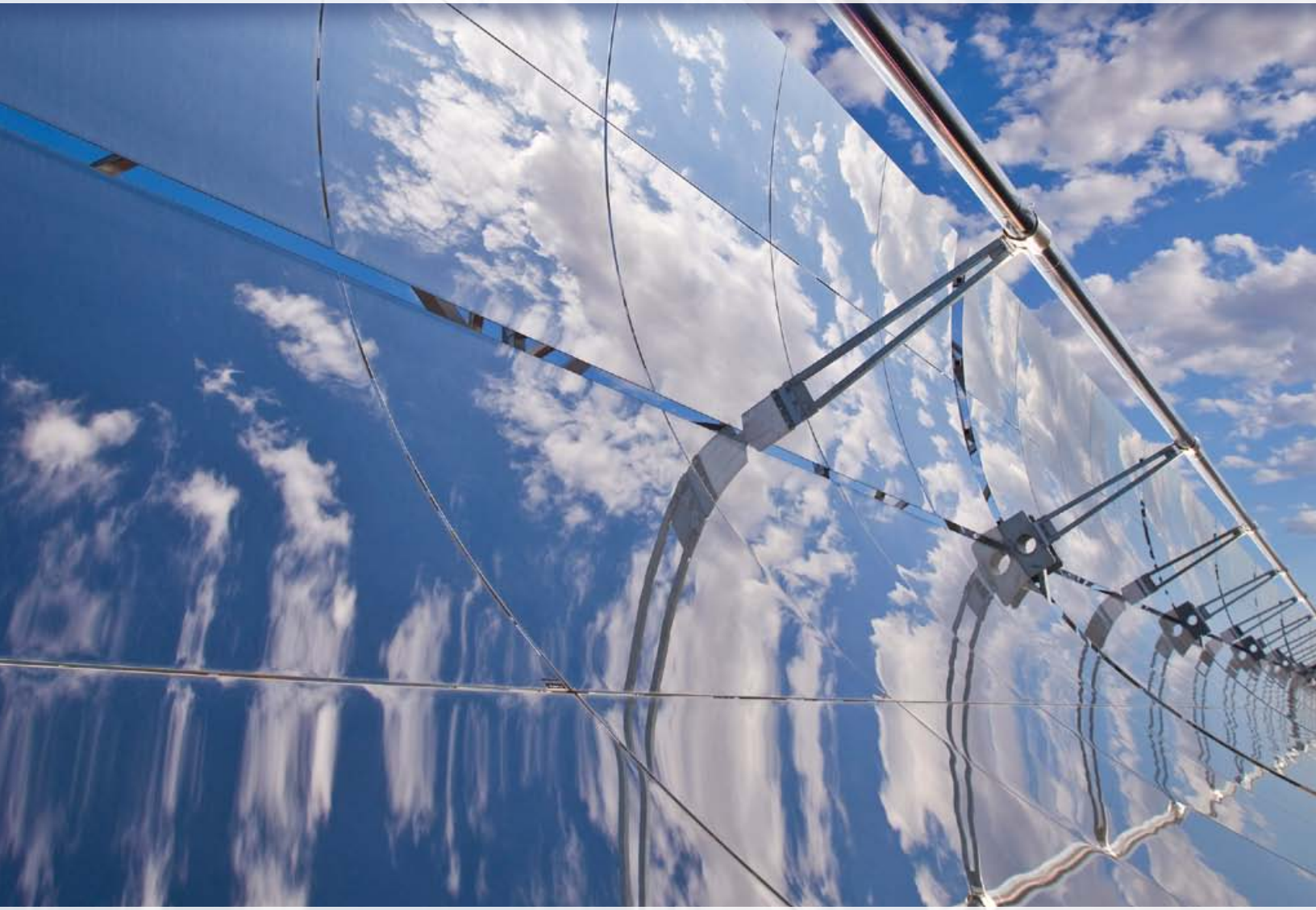
RENEWABLE ENERGY SOURCES AND CLIMATE CHANGE MITIGATION

SUMMARY FOR POLICYMAKERS AND TECHNICAL SUMMARY



SPECIAL REPORT OF THE
INTERGOVERNMENTAL PANEL
ON CLIMATE CHANGE

ipcc

WMO UNEP

Special Report on Renewable Energy Sources and Climate Change Mitigation

Summary for Policymakers

A Report of Working Group III of the IPCC

and

Technical Summary

A Report accepted by Working Group III of the IPCC

but not approved in detail

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I Foreword and Preface

Foreword

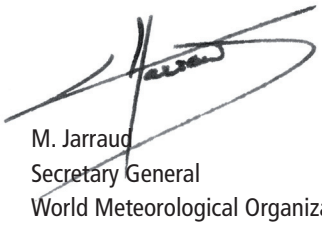
The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) provides a comprehensive review concerning these sources and technologies, the relevant costs and benefits, and their potential role in a portfolio of mitigation options.

For the first time, an inclusive account of costs and greenhouse gas emissions across various technologies and scenarios confirms the key role of renewable sources, irrespective of any tangible climate change mitigation agreement.

As an intergovernmental body established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), the IPCC has successfully provided policymakers over the ensuing period with the most authoritative and objective scientific and technical assessments, which, while clearly policy relevant, never claimed to be policy prescriptive. Moreover, this Special Report should be considered especially significant at a time when Governments are pondering the role of renewable energy resources in the context of their respective climate change mitigation efforts.

The SRREN was made possible thanks to the commitment and dedication of hundreds of experts from various regions and disciplines. We would like to express our deep gratitude to Prof. Ottmar Edenhofer, Dr. Ramon Pichs-Madruga, and Dr. Youba Sokona, for their untiring leadership throughout the SRREN development process, as well as to all Coordinating Lead Authors, Lead Authors, Contributing Authors, Review Editors and Reviewers, and to the staff of the Working Group III Technical Support Unit.

We greatly value Germany's generous support and dedication to the SRREN, as evidenced in particular by its hosting of the Working Group III Technical Support Unit. Moreover, we wish to express our appreciation to the United Arab Emirates, for hosting the plenary session which approved the report; as well as to Brazil, Norway, the United Kingdom and Mexico, which hosted the successive Lead Authors meetings; to all sponsors which contributed to the IPCC work through their financial and logistical support; and finally to the IPCC Chairman, Dr. R. K. Pachauri, for his leadership throughout the SRREN development process.



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Preface

The Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) of the IPCC Working Group III provides an assessment and thorough analysis of renewable energy technologies and their current and potential role in the mitigation of greenhouse gas emissions. The results presented here are based on an extensive assessment of scientific literature, including specifics of individual studies, but also an aggregate across studies analyzed for broader conclusions. The report combines information on technology specific studies with results of large-scale integrated models, and provides policy-relevant (but not policy-prescriptive) information to decision makers on the characteristics and technical potentials of different resources; the historical development of the technologies; the challenges of their integration and social and environmental impacts of their use; as well as a comparison in levelized cost of energy for commercially available renewable technologies with recent non-renewable energy costs. Further, the role of renewable energy sources in pursuing GHG concentration stabilization levels discussed in this report and the presentation and analysis of the policies available to assist the development and deployment of renewable energy technologies in climate change mitigation and/or other goals answer important questions detailed in the original scoping of the report.

The process

This report has been prepared in accordance with the rules and procedures established by the IPCC and used for previous assessment reports. After a scoping meeting in Lübeck, Germany from the 20th to the 25th of January, 2008, the outline of the report was approved at the 28th IPCC Plenary held in Budapest, Hungary on the 9th and 10th of April, 2008. Soon afterward, an author team of 122 Lead Authors (33 from developing countries, 4 from EIT countries, and 85 from industrialized countries), 25 Review Editors and 132 contributing authors was formed.

The IPCC review procedure was followed, in which drafts produced by the authors were subject to two reviews. 24,766 comments from more than 350 expert reviewers and governments and international organizations were processed. Review Editors for each chapter have ensured that all substantive government and expert review comments received appropriate consideration.

The Summary for Policy Makers was approved line-by-line and the Final Draft of the report was accepted at the 11th Session of the Third Working Group held in Abu Dhabi, United Arab Emirates from the 5th to the 8th of May, 2011. The Special Report was accepted in its entirety at the 33rd IPCC Plenary Session held also in Abu Dhabi from the 10th to the 13th of May, 2011.

Structure of the Special Report

The SRREN consists of three categories of chapters: one introductory chapter; six technology specific chapters (Chapters 2-7); and four chapters that cover integrative issues across technologies (Chapters 8-11).

Chapter 1 is the introductory chapter designed to place renewable energy technologies within the broader framework of climate change mitigation options and identify characteristics common to renewable energy technologies.

Each of the technology chapters (2-7) provides information on the available resource potential, the state of technological and market development and the environmental and social impacts for each renewable energy source including bioenergy, direct solar energy, geothermal energy, hydropower, ocean energy and wind energy. In addition, prospects for future technological innovation and cost reductions are discussed, and the chapters end with a discussion on possible future deployment.

Chapter 8 is the first of the integrative chapters and discusses how renewable energy technologies are currently integrated into energy distribution systems, and how they may be integrated in the future. Development pathways for the strategic use of renewable technologies in the transport, buildings, industry and agricultural sectors are also discussed.

Renewable energy in the context of sustainable development is covered in Chapter 9. This includes the social, environmental and economic impacts of renewable energy sources, including the potential for improved energy access and a secure supply of energy. Specific barriers for renewable energy technologies are also covered.

In a review of over 160 scenarios, Chapter 10 investigates how renewable energy technologies may contribute to varying greenhouse gas emission reduction scenarios, ranging from business-as-usual scenarios to those reflecting ambitious GHG concentration stabilization levels. Four scenarios are analyzed in depth and the costs of extensive deployment of renewable energy technologies are also discussed.

The last chapter of the report, Chapter 11, describes the current trends in renewable energy support policies, as well as trends in financing and investment in renewable energy technologies. It reviews current experiences with RE policies, including effectiveness and efficiency measures, and discusses the influence of an enabling environment on the success of policies.

While the authors of the report included the most recent literature available at the time of publication, readers should be aware that topics covered in this Special Report may be subject to further rapid development. This includes state of development of some renewable energy technologies, as well as the state of knowledge of integration challenges, mitigation costs, co-benefits, environmental and social impacts, policy approaches and financing options. The boundaries and names shown and the designations used on any geographic maps in this report do not imply official endorsement or acceptance by the United Nations. In the geographic maps developed for the SRREN, the dotted line in Jammu and Kashmir represents approximately the Line of Control agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties.

Acknowledgements

Production of this Special Report was a major enterprise, in which many people from around the world were involved, with a wide variety of contributions. We wish to thank the generous contributions by the governments and institutions involved, which enabled the authors, Review Editors and Government and Expert Reviewers to participate in this process.

We are especially grateful for the contribution and support of the German Government, in particular the Bundesministerium für Bildung und Forschung (BMBF), in funding the Working Group III Technical Support Unit (TSU). Coordinating this funding, Gregor Laumann and Christiane Textor of the Deutsches Zentrum für Luft- und Raumfahrt (DLR) were always ready to dedicate time and energy to the needs of the team. We would also like to express our gratitude to the Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU). In addition, the Potsdam Institute for Climate Impact Research (PIK) kindly hosted and housed the TSU offices.

We would very much like to thank the governments of Brazil, Norway, the United Kingdom and Mexico, who, in collaboration with local institutions, hosted the crucial lead author meetings in São José dos Campos (January 2009), Oslo (September 2009), Oxford (March 2010) and Mexico City (September 2010). In addition, we would like to thank the government of the United States and the Institute for Sustainability, with the Founder Society Technologies for Carbon Management Project for hosting the SRREN Expert Review meeting in Washington D.C.(February 2010). Finally, we

express our appreciation to PIK for welcoming the SRREN Coordinating Lead Authors on their campus for a concluding meeting (January 2011).

This Special Report is only possible thanks to the expertise, hard work and commitment to excellence shown throughout by our Coordinating Lead Authors and Lead Authors, with important assistance by many Contributing Authors. We would also like to express our appreciation to the Government and Expert Reviewers, acknowledging the time and energy invested to provide constructive and useful comments to the various drafts. Our Review Editors were also critical in the SRREN process, supporting the author team with processing the comments and assuring an objective discussion of relevant issues.

It is a pleasure to acknowledge the tireless work of the staff of the Working Group III Technical Support Unit, Patrick Matschoss, Susanne Kadner, Kristin Seyboth, Timm Zwickel, Patrick Eickemeier, Gerrit Hansen, Steffen Schloemer, Christoph von Stechow, Benjamin Kriemann, Annegret Kuhnigk, Anna Adler and Nina Schuetz, who were assisted by Marilyn Anderson, Lelani Arris, Andrew Ayres, Marlen Goerner, Daniel Mahringer and Ashley Renders. Brigitte Knopf, in her role as Senior Advisor to the TSU, consistently provided valuable input and direction. Graphics support by Kay Schröder and his team at Daily-Interactive.com Digitale Kommunikation is gratefully appreciated, as is the layout work by Valarie Morris and her team at Arroyo Writing, LLC.

The Working Group III Bureau – consisting of Antonina Ivanova Boncheva (Mexico), Carlo Carraro (Italy), Suzana Kahn Ribeiro (Brazil), Jim Skea (UK), Francis Yamba (Zambia), and Taha Zatari (Saudi Arabia) and prior to his elevation to IPCC Vice Chair, Ismail A.R. Elgizouli (Sudan) – provided continuous and constructive support to the Working Group III Co-Chairs throughout the SRREN process.

We would like to thank the Renate Christ, Secretary of the IPCC, and the Secretariat staff Gaetano Leone, Mary Jean Burer, Sophie Schlingemann, Judith Ewa, Jesbin Baidya, Joelle Fernandez, Annie Courtin, Laura Biagioni, Amy Smith Aasdam, and Rockaya Aidara, who provided logistical support for government liaison and travel of experts from developing and transitional economy countries.

Our special acknowledgement to Dr. Rajendra Pachauri, Chairman of the IPCC, for his contribution and support during the preparation of this IPCC Special Report.

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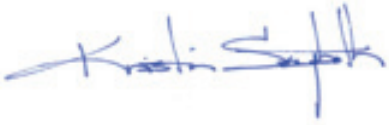

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This report is dedicated to

Wolfram Krewitt, Germany
Coordinating Lead Author in Chapter 8

Wolfram Krewitt passed away October 8th, 2009. He worked at the Deutsches Zentrum für Luft- und Raumfahrt (DLR) in Stuttgart, Germany.

Raymond Wright, Jamaica
Lead Author in Chapter 10

Raymond Wright passed away July 7th, 2011. He worked at the Petroleum Corporation of Jamaica (PCJ) in Kingston, Jamaica.

Wolfram Krewitt made a significant contribution to this Special Report and his vision for Chapter 8 (Integration of Renewable Energy into Present and Future Energy Systems) remains embedded in the text for which he is acknowledged. Raymond Wright was a critical member of the Chapter 10 (Mitigation Potential and Costs) author team who consistently offered precise insights to the Special Report, ensuring balance and credibility. Both authors were talented, apt and dedicated members of the IPCC author team - their passing represents a deep loss for the international scientific communities working in climate and energy issues. Wolfram Krewitt and Raymond Wright are dearly remembered by their fellow authors.

II Summaries

SPM

Summary for Policymakers

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1. Introduction

The Working Group III Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) presents an assessment of the literature on the scientific, technological, environmental, economic and social aspects of the contribution of six renewable energy (RE) sources to the mitigation of climate change. It is intended to provide policy relevant information to governments, intergovernmental processes and other interested parties. This Summary for Policymakers provides an overview of the SRREN, summarizing the essential findings.

The SRREN consists of 11 chapters. Chapter 1 sets the context for RE and climate change; Chapters 2 through 7 provide information on six RE technologies, and Chapters 8 through 11 address integrative issues (see Figure SPM.1).

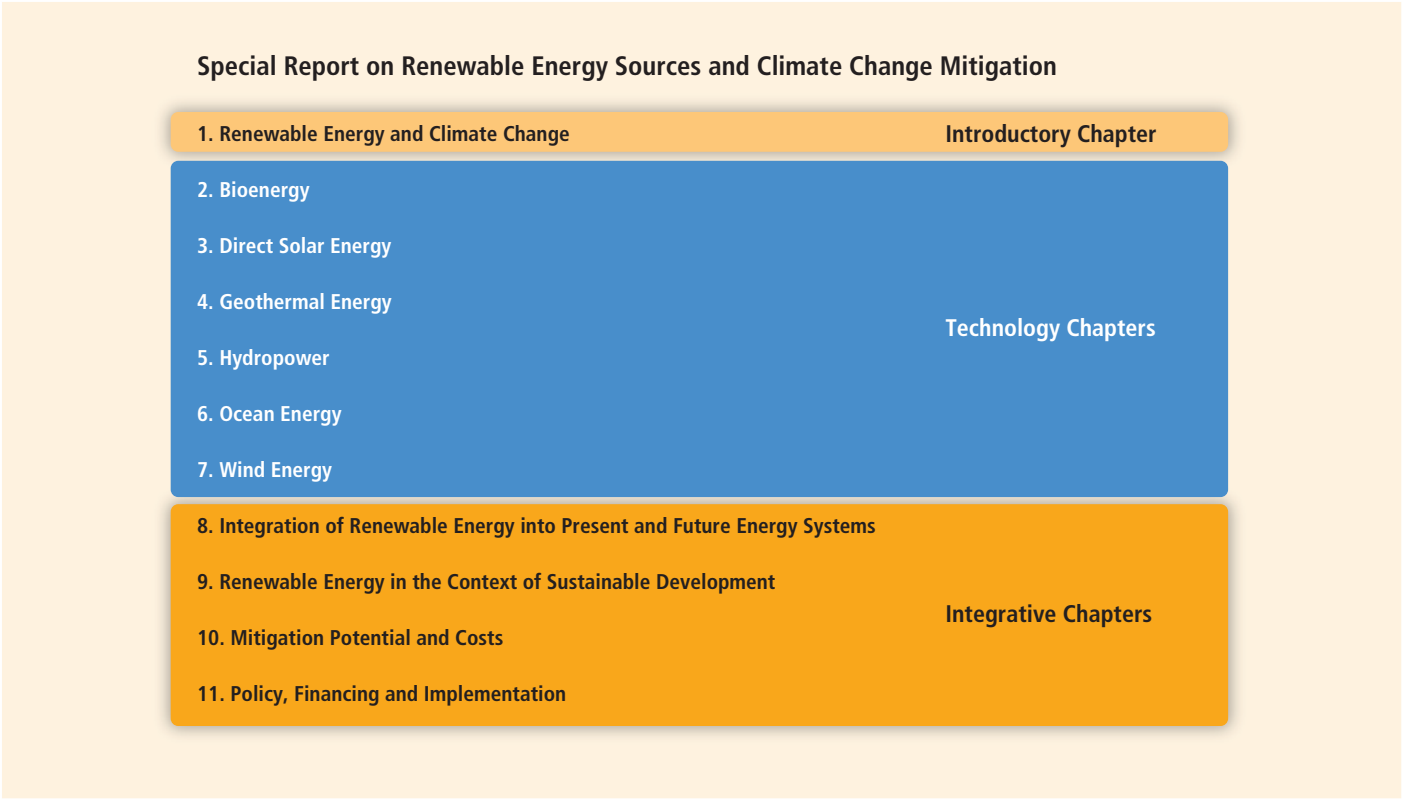


Figure SPM.1 | Structure of the SRREN. [Figure 1.1, 1.1.2]

References to chapters and sections are indicated with corresponding chapter and section numbers in square brackets. An explanation of terms, acronyms and chemical symbols used in this SPM can be found in the glossary of the SRREN (Annex I). Conventions and methodologies for determining costs, primary energy and other topics of analysis can be found in Annex II and Annex III. This report communicates uncertainty where relevant.[1]

1 This report communicates uncertainty, for example, by showing the results of sensitivity analyses and by quantitatively presenting ranges in cost numbers as well as ranges in the scenario results. This report does not apply formal IPCC uncertainty terminology because at the time of the approval of this report, IPCC uncertainty guidance was in the process of being revised.

2. Renewable energy and climate change

Demand for energy and associated services, to meet social and economic development and improve human welfare and health, is increasing. All societies require energy services to meet basic human needs (e.g., lighting, cooking, space comfort, mobility and communication) and to serve productive processes. [1.1.1, 9.3.2] Since approximately 1850, global use of fossil fuels (coal, oil and gas) has increased to dominate energy supply, leading to a rapid growth in carbon dioxide (CO_2) emissions. [Figure 1.6]

Greenhouse gas (GHG) emissions resulting from the provision of energy services have contributed significantly to the historic increase in atmospheric GHG concentrations. The IPCC Fourth Assessment Report (AR4) concluded that "Most of the observed increase in global average temperature since the mid-20th century is very likely[2] due to the observed increase in anthropogenic greenhouse gas concentrations."

Recent data confirm that consumption of fossil fuels accounts for the majority of global anthropogenic GHG emissions.[3] Emissions continue to grow and CO_2 concentrations had increased to over 390 ppm, or 39% above preindustrial levels, by the end of 2010. [1.1.1, 1.1.3]

There are multiple options for lowering GHG emissions from the energy system while still satisfying the global demand for energy services. [1.1.3, 10.1] Some of these possible options, such as energy conservation and efficiency, fossil fuel switching, RE, nuclear and carbon capture and storage (CCS) were assessed in the AR4. A comprehensive evaluation of any portfolio of mitigation options would involve an evaluation of their respective mitigation potential as well as their contribution to sustainable development and all associated risks and costs. [1.1.6] This report will concentrate on the role that the deployment of RE technologies can play within such a portfolio of mitigation options.

As well as having a large potential to mitigate climate change, RE can provide wider benefits. RE may, if implemented properly, contribute to social and economic development, energy access, a secure energy supply, and reducing negative impacts on the environment and health. [9.2, 9.3]

Under most conditions, increasing the share of RE in the energy mix will require policies to stimulate changes in the energy system. Deployment of RE technologies has increased rapidly in recent years, and their share is projected to increase substantially under most ambitious mitigation scenarios [1.1.5, 10.2]. Additional policies would be required to attract the necessary increases in investment in technologies and infrastructure. [11.4.3, 11.5, 11.6.1, 11.7.5]

3. Renewable energy technologies and markets

RE comprises a heterogeneous class of technologies (Box SPM.1). Various types of RE can supply electricity, thermal energy and mechanical energy, as well as produce fuels that are able to satisfy multiple energy service needs [1.2]. Some RE technologies can be deployed at the point of use (decentralized) in rural and urban environments, whereas others are primarily deployed within large (centralized) energy networks [1.2, 8.2, 8.3, 9.3.2]. Though a growing number of RE technologies are technically mature and are being deployed at significant scale, others are in an earlier phase of technical maturity and commercial deployment or fill specialized niche markets [1.2]. The energy output of

2 According to the formal uncertainty language used in the AR4, the term 'very likely' refers to a >90% assessed probability of occurrence.

3 The contributions of individual anthropogenic GHGs to total emissions in 2004, reported in AR4, expressed as CO_2eq were: CO_2 from fossil fuels (56.6%), CO_2 from deforestation, decay of biomass etc. (17.3%), CO_2 from other (2.8%), methane (14.3%), nitrous oxide (7.9%) and fluorinated gases (1.1%) [Figure 1.1b, AR4, WG III, Chapter 1. For further information on sectoral emissions, including forestry, see also Figure 1.3b and associated footnotes.]

RE technologies can be (i) variable and—to some degree—unpredictable over differing time scales (from minutes to years), (ii) variable but predictable, (iii) constant, or (iv) controllable. [8.2, 8.3]

Box SPM.1 | Renewable energy sources and technologies considered in this report.

Bioenergy can be produced from a variety of biomass feedstocks, including forest, agricultural and livestock residues; short-rotation forest plantations; energy crops; the organic component of municipal solid waste; and other organic waste streams. Through a variety of processes, these feedstocks can be directly used to produce electricity or heat, or can be used to create gaseous, liquid, or solid fuels. The range of bioenergy technologies is broad and the technical maturity varies substantially. Some examples of commercially available technologies include small- and large-scale boilers, domestic pellet-based heating systems, and ethanol production from sugar and starch. Advanced biomass integrated gasification combined-cycle power plants and lignocellulose-based transport fuels are examples of technologies that are at a pre-commercial stage, while liquid biofuel production from algae and some other biological conversion approaches are at the research and development (R&D) phase. Bioenergy technologies have applications in centralized and decentralized settings, with the traditional use of biomass in developing countries being the most widespread current application.[4] Bioenergy typically offers constant or controllable output. Bioenergy projects usually depend on local and regional fuel supply availability, but recent developments show that solid biomass and liquid biofuels are increasingly traded internationally. [1.2, 2.1, 2.3, 2.6, 8.2, 8.3]

Direct solar energy technologies harness the energy of solar irradiance to produce electricity using photovoltaics (PV) and concentrating solar power (CSP), to produce thermal energy (heating or cooling, either through passive or active means), to meet direct lighting needs and, potentially, to produce fuels that might be used for transport and other purposes. The technology maturity of solar applications ranges from R&D (e.g., fuels produced from solar energy), to relatively mature (e.g., CSP), to mature (e.g., passive and active solar heating, and wafer-based silicon PV). Many but not all of the technologies are modular in nature, allowing their use in both centralized and decentralized energy systems. Solar energy is variable and, to some degree, unpredictable, though the temporal profile of solar energy output in some circumstances correlates relatively well with energy demands. Thermal energy storage offers the option to improve output control for some technologies such as CSP and direct solar heating. [1.2, 3.1, 3.3, 3.5, 3.7, 8.2, 8.3]

Geothermal energy utilizes the accessible thermal energy from the Earth's interior. Heat is extracted from geothermal reservoirs using wells or other means. Reservoirs that are naturally sufficiently hot and permeable are called hydrothermal reservoirs, whereas reservoirs that are sufficiently hot but that are improved with hydraulic stimulation are called enhanced geothermal systems (EGS). Once at the surface, fluids of various temperatures can be used to generate electricity or can be used more directly for applications that require thermal energy, including district heating or the use of lower-temperature heat from shallow wells for geothermal heat pumps used in heating or cooling applications. Hydrothermal power plants and thermal applications of geothermal energy are mature technologies, whereas EGS projects are in the demonstration and pilot phase while also undergoing R&D. When used to generate electricity, geothermal power plants typically offer constant output. [1.2, 4.1, 4.3, 8.2, 8.3]

Hydropower harnesses the energy of water moving from higher to lower elevations, primarily to generate electricity. Hydropower projects encompass dam projects with reservoirs, run-of-river and in-stream projects and cover a continuum in project scale. This variety gives hydropower the ability to meet large centralized urban needs as well as decentralized rural needs. Hydropower technologies are mature. Hydropower projects exploit a resource that varies temporally. However, the controllable output provided by hydropower facilities that have reservoirs can be used to meet peak electricity demands and help to balance electricity systems that have large amounts of variable RE generation. The operation of hydropower reservoirs often reflects their multiple uses, for example, drinking water, irrigation, flood and drought control, and navigation, as well as energy supply. [1.2, 5.1, 5.3, 5.5, 5.10, 8.2]

4 Traditional biomass is defined by the International Energy Agency (IEA) as biomass consumption in the residential sector in developing countries and refers to the often unsustainable use of wood, charcoal, agricultural residues, and animal dung for cooking and heating. All other biomass use is defined as modern [Annex I].

Ocean energy derives from the potential, kinetic, thermal and chemical energy of seawater, which can be transformed to provide electricity, thermal energy, or potable water. A wide range of technologies are possible, such as barrages for tidal range, submarine turbines for tidal and ocean currents, heat exchangers for ocean thermal energy conversion, and a variety of devices to harness the energy of waves and salinity gradients. Ocean technologies, with the exception of tidal barrages, are at the demonstration and pilot project phases and many require additional R&D. Some of the technologies have variable energy output profiles with differing levels of predictability (e.g., wave, tidal range and current), while others may be capable of near-constant or even controllable operation (e.g., ocean thermal and salinity gradient). [1.2, 6.1, 6.2, 6.3, 6.4, 6.6, 8.2]

Wind energy harnesses the kinetic energy of moving air. The primary application of relevance to climate change mitigation is to produce electricity from large wind turbines located on land (onshore) or in sea- or freshwater (offshore). Onshore wind energy technologies are already being manufactured and deployed on a large scale. Offshore wind energy technologies have greater potential for continued technical advancement. Wind electricity is both variable and, to some degree, unpredictable, but experience and detailed studies from many regions have shown that the integration of wind energy generally poses no insurmountable technical barriers. [1.2, 7.1, 7.3, 7.5, 7.7, 8.2]

On a global basis, it is estimated that RE accounted for 12.9% of the total 492 Exajoules (EJ)[5] of primary energy supply in 2008 (Box SPM.2 and Figure SPM.2). The largest RE contributor was biomass (10.2%), with the majority (roughly 60%) being traditional biomass used in cooking and heating applications in developing countries but with rapidly increasing use of modern biomass as well.[6] Hydropower represented 2.3%, whereas other RE sources accounted for 0.4%. [1.1.5] In 2008, RE contributed approximately 19% of global electricity supply (16% hydropower, 3% other RE) and biofuels contributed 2% of global road transport fuel supply. Traditional biomass (17%), modern biomass (8%), solar thermal and geothermal energy (2%) together fuelled 27% of the total global demand for heat. The contribution of RE to primary energy supply varies substantially by country and region. [1.1.5, 1.3.1, 8.1]

Deployment of RE has been increasing rapidly in recent years (Figure SPM.3). Various types of government policies, the declining cost of many RE technologies, changes in the prices of fossil fuels, an increase of energy demand and other factors have encouraged the continuing increase in the use of RE. [1.1.5, 9.3, 10.5, 11.2, 11.3] Despite global financial challenges, RE capacity continued to grow rapidly in 2009 compared to the cumulative installed capacity from the previous year, including wind power (32% increase, 38 Gigawatts (GW) added), hydropower (3%, 31 GW added), grid-connected photovoltaics (53%, 7.5 GW added), geothermal power (4%, 0.4 GW added), and solar hot water/heating (21%, 31 GW_{th} added). Biofuels accounted for 2% of global road transport fuel demand in 2008 and nearly 3% in 2009. The annual production of ethanol increased to 1.6 EJ (76 billion litres) by the end of 2009 and biodiesel to 0.6 EJ (17 billion litres). [1.1.5, 2.4, 3.4, 4.4, 5.4, 7.4]

Of the approximate 300 GW of new electricity generating capacity added globally over the two-year period from 2008 to 2009, 140 GW came from RE additions. Collectively, developing countries host 53% of global RE electricity generation capacity [1.1.5]. At the end of 2009, the use of RE in hot water/heating markets included modern biomass (270 GW_{th}), solar (180 GW_{th}), and geothermal (60 GW_{th}). The use of decentralized RE (excluding traditional biomass) in meeting rural energy needs at the household or village level has also increased, including hydropower stations, various modern biomass options, PV, wind or hybrid systems that combine multiple technologies. [1.1.5, 2.4, 3.4, 4.4, 5.4]

5 1 Exajoule = 10^{18} joules = 23.88 million tonnes of oil equivalent (Mtoe).

6 In addition to this 60% share of traditional biomass, there is biomass use estimated to amount to 20 to 40% not reported in official primary energy databases, such as dung, unaccounted production of charcoal, illegal logging, fuelwood gathering, and agricultural residue use. [2.1, 2.5]

Box SPM.2 | Accounting for primary energy in the SRREN.

There is no single, unambiguous accounting method for calculating primary energy from non-combustible energy sources such as non-combustible RE sources and nuclear energy. The SRREN adopts the 'direct equivalent' method for accounting for primary energy supply. In this method, fossil fuels and bioenergy are accounted for based on their heating value while non-combustible energy sources, including nuclear energy and all non-combustible RE, are accounted for based on the secondary energy that they produce. This may lead to an understatement of the contribution of non-combustible RE and nuclear compared to bioenergy and fossil fuels by a factor of roughly 1.2 up to 3. The selection of the accounting method also impacts the relative shares of different individual energy sources. Comparisons in the data and figures presented in the SRREN between fossil fuels and bioenergy on the one hand, and non-combustible RE and nuclear energy on the other, reflect this accounting method. [1.1.9, Annex II.4]

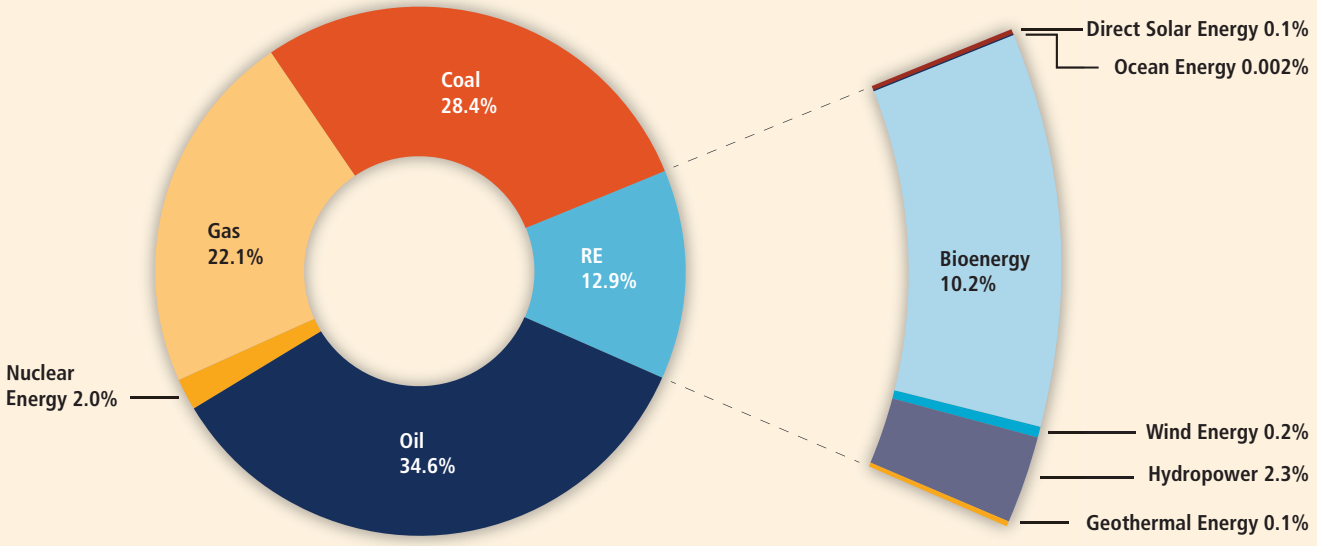


Figure SPM.2 | Shares of energy sources in total global primary energy supply in 2008 (492 EJ). Modern biomass contributes 38% of the total biomass share. [Figure 1.10, 1.1.5]

Note: Underlying data for figure have been converted to the 'direct equivalent' method of accounting for primary energy supply. [Box SPM.2, 1.1.9, Annex II.4]

The global technical potential[7] of RE sources will not limit continued growth in the use of RE. A wide range of estimates is provided in the literature, but studies have consistently found that the total global technical potential for RE is substantially higher than global energy demand (Figure SPM.4) [1.2.2, 10.3, Annex II]. The technical potential for solar energy is the highest among the RE sources, but substantial technical potential exists for all six RE sources. Even in regions with relatively low levels of technical potential for any individual RE source, there are typically significant opportunities for increased deployment compared to current levels. [1.2.2, 2.2, 2.8, 3.2, 4.2, 5.2, 6.2, 6.4, 7.2, 8.2, 8.3, 10.3] In the longer term and at higher deployment levels, however, technical potentials indicate a limit to the

7 Definitions of technical potential often vary by study. 'Technical potential' is used in the SRREN as the amount of RE output obtainable by full implementation of demonstrated technologies or practices. No explicit reference to costs, barriers or policies is made. Technical potentials reported in the literature and assessed in the SRREN, however, may have taken into account practical constraints and when explicitly stated they are generally indicated in the underlying report. [Annex I]

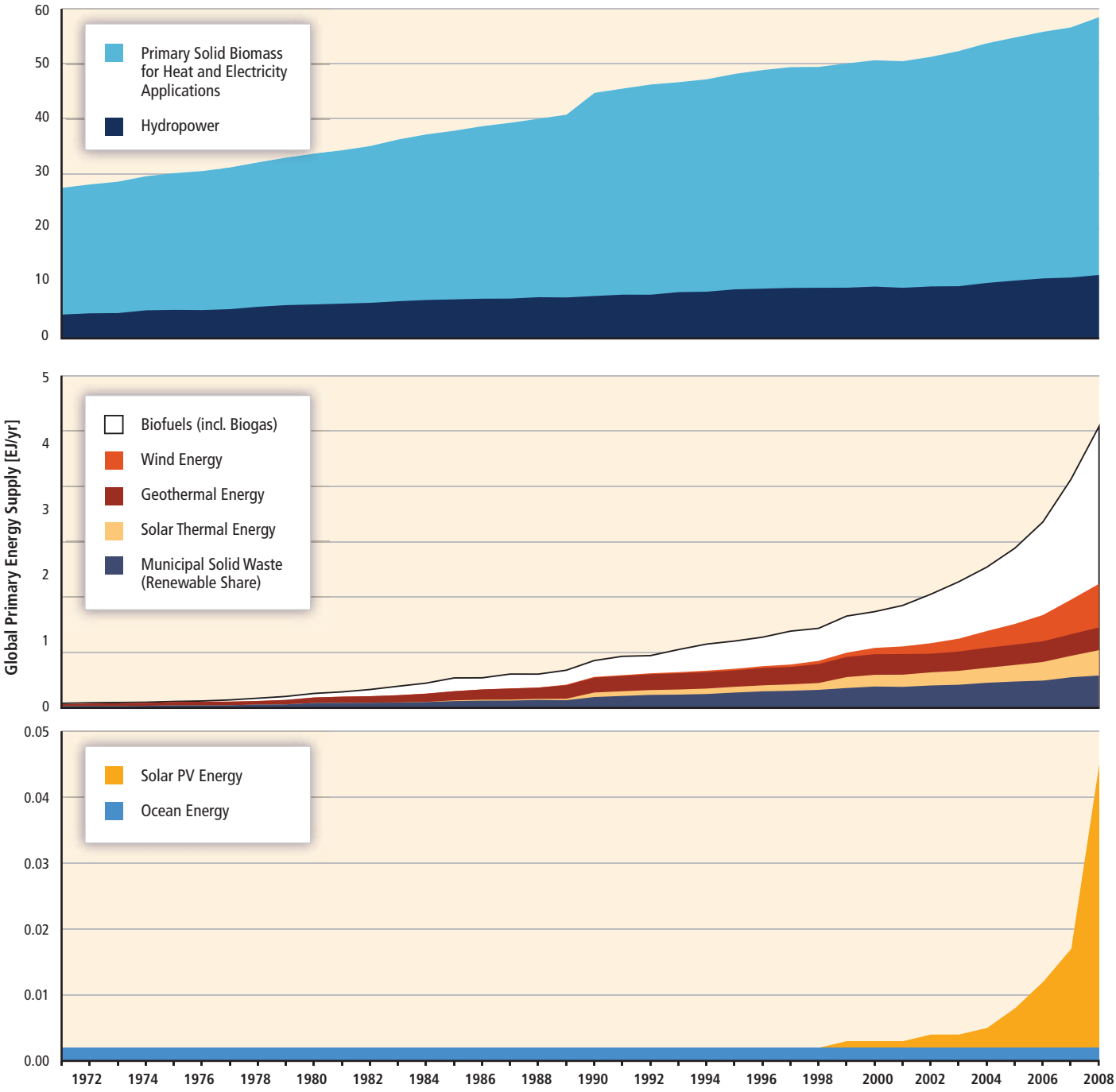
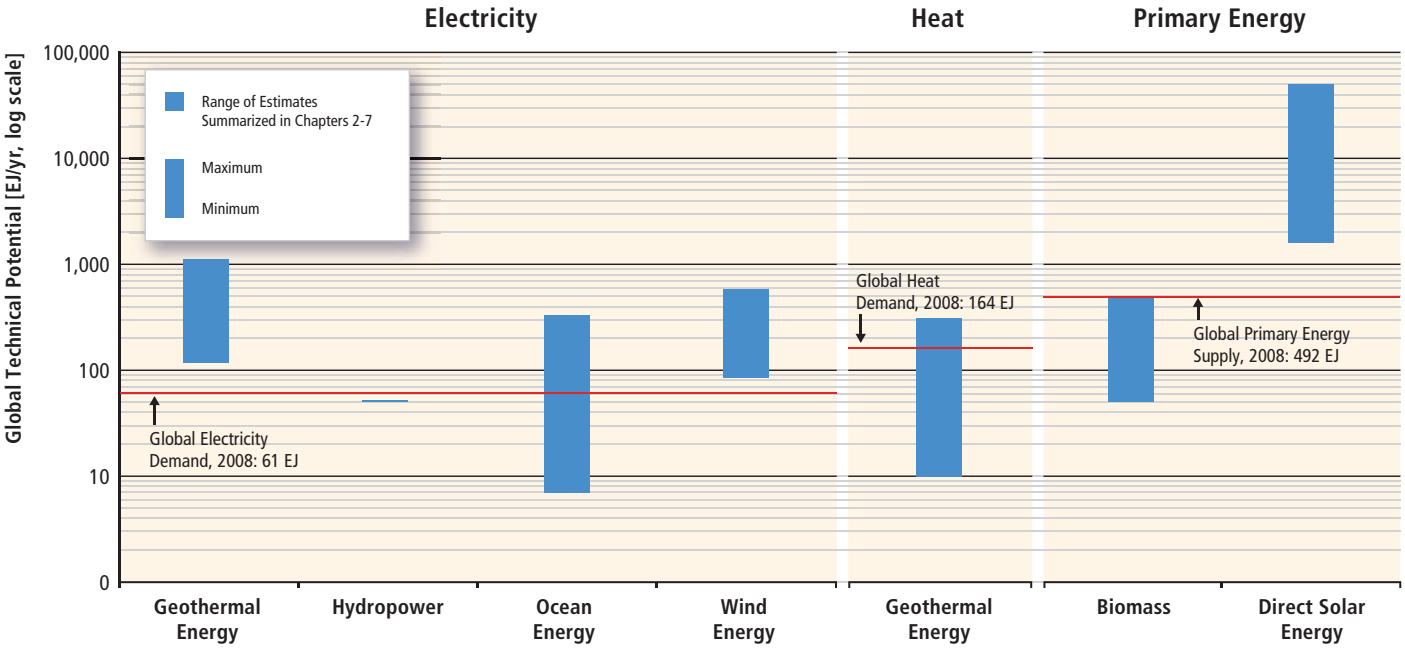


Figure SPM.3 | Historical development of global primary energy supply from renewable energy from 1971 to 2008. [Figure 1.12, 1.1.5]

Notes: Technologies are referenced to separate vertical units for display purposes only. Underlying data for figure has been converted to the 'direct equivalent' method of accounting for primary energy supply [Box SPM.2, 1.1.9, Annex II.4], except that the energy content of biofuels is reported in secondary energy terms (the primary biomass used to produce the biofuel would be higher due to conversion losses. [2.3, 2.4])

contribution of some individual RE technologies. Factors such as sustainability concerns [9.3], public acceptance [9.5], system integration and infrastructure constraints [8.2], or economic factors [10.3] may also limit deployment of RE technologies.

Climate change will have impacts on the size and geographic distribution of the technical potential for RE sources, but research into the magnitude of these possible effects is nascent. Because RE sources are, in many cases, dependent on the climate, global climate change will affect the RE resource base, though the precise nature and magnitude of these impacts is uncertain. The future technical potential for bioenergy could be influenced by climate change through impacts on biomass production such as altered soil conditions, precipitation, crop productivity and other factors. The overall impact of a global mean temperature change of less than 2°C on the technical potential of bioenergy is expected to be relatively small on a global basis. However, considerable regional differences could be expected and uncertainties are larger and more difficult to assess compared to other RE options due to the large number of feedback mechanisms involved. [2.2, 2.6] For solar energy, though climate change is expected to influence the distribution and variability of cloud cover, the impact of these changes on overall technical potential is expected to be small [3.2]. For hydropower the overall impacts on the global technical potential is expected to be slightly positive. However, results also indicate the possibility of substantial variations across regions and even within countries. [5.2] Research to date suggests that climate change is not expected to greatly impact the global technical potential for wind energy development but changes in the regional distribution of the wind energy resource may be expected [7.2]. Climate change is not anticipated to have significant impacts on the size or geographic distribution of geothermal or ocean energy resources. [4.2, 6.2]



Range of Estimates of Global Technical Potentials

Max (in EJ/yr)	**1109**	**52**	**331**	**580**	**312**	**500**	**49837**
Min (in EJ/yr)	**118**	**50**	**7**	**85**	**10**	**50**	**1575**

Figure SPM.4 | Ranges of global technical potentials of RE sources derived from studies presented in Chapters 2 through 7. Biomass and solar are shown as primary energy due to their multiple uses; note that the figure is presented in logarithmic scale due to the wide range of assessed data. [Figure 1.17, 1.2.3]

Notes: Technical potentials reported here represent total worldwide potentials for annual RE supply and do not deduct any potential that is already being utilized. Note that RE electricity sources could also be used for heating applications, whereas biomass and solar resources are reported only in primary energy terms but could be used to meet various energy service needs. Ranges are based on various methods and apply to different future years; consequently, the resulting ranges are not strictly comparable across technologies. For the data behind Figure SPM.4 and additional notes that apply, see Chapter 1 Annex, Table A.1.1 (as well as the underlying chapters).

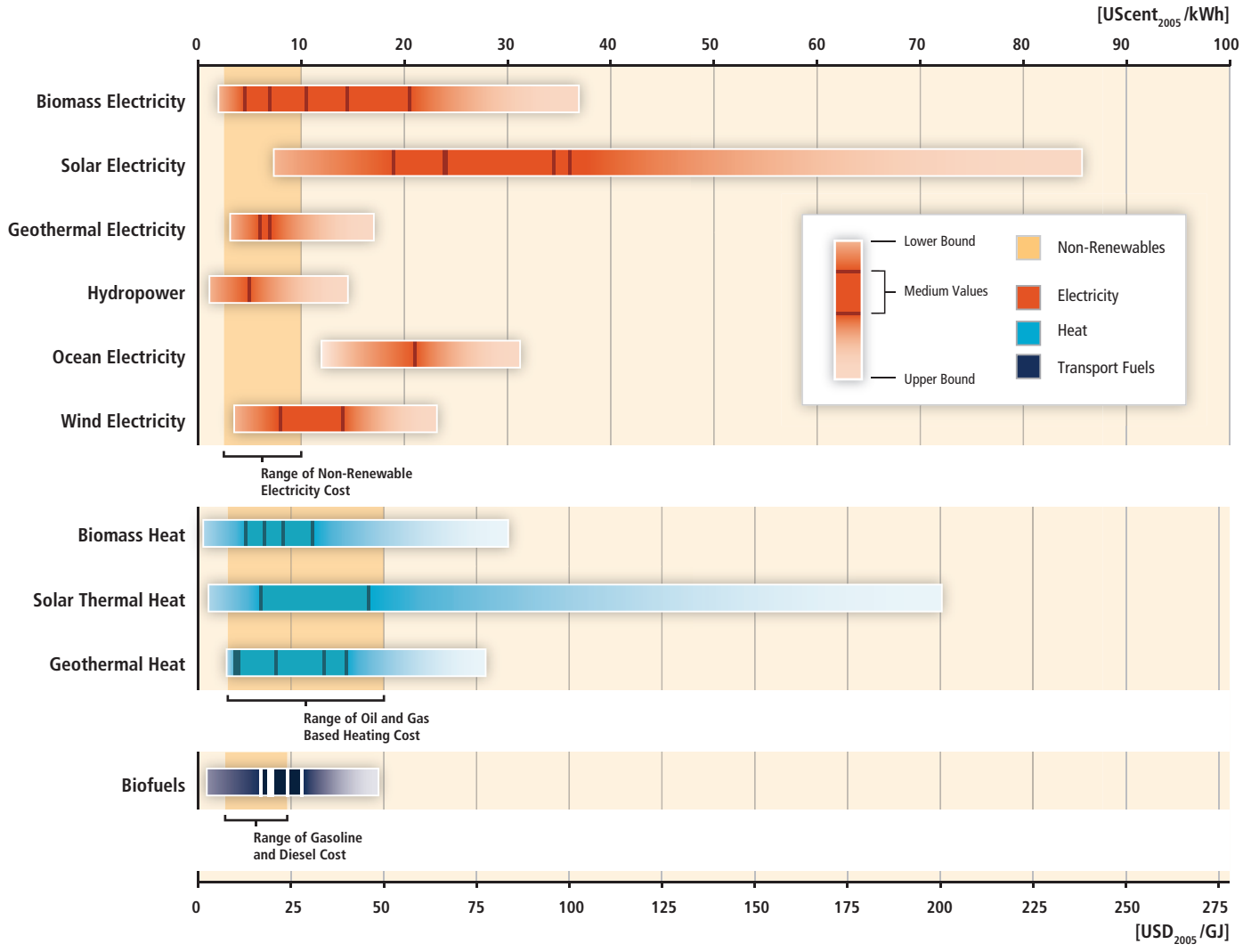
The levelized cost of energy[8] for many RE technologies is currently higher than existing energy prices, though in various settings RE is already economically competitive. Ranges of recent levelized costs of energy for selected commercially available RE technologies are wide, depending on a number of factors including, but not limited to, technology characteristics, regional variations in cost and performance, and differing discount rates (Figure SPM.5). [1.3.2, 2.3, 2.7, 3.8, 4.8, 5.8, 6.7, 7.8, 10.5, Annex III] Some RE technologies are broadly competitive with existing market energy prices. Many of the other RE technologies can provide competitive energy services in certain circumstances, for example, in regions with favourable resource conditions or that lack the infrastructure for other low-cost energy supplies. In most regions of the world, policy measures are still required to ensure rapid deployment of many RE sources. [2.3, 2.7, 3.8, 4.7, 5.8, 6.7, 7.8, 10.5]

Monetizing the external costs of energy supply would improve the relative competitiveness of RE. The same applies if market prices increase due to other reasons (Figure SPM.5). [10.6] The levelized cost of energy for a technology is not the sole determinant of its value or economic competitiveness. The attractiveness of a specific energy supply option depends also on broader economic as well as environmental and social aspects, and the contribution that the technology provides to meeting specific energy services (e.g., peak electricity demands) or imposes in the form of ancillary costs on the energy system (e.g., the costs of integration). [8.2, 9.3, 10.6]

The cost of most RE technologies has declined and additional expected technical advances would result in further cost reductions. Significant advances in RE technologies and associated long-term cost reductions have been demonstrated over the last decades, though periods of rising prices have sometimes been experienced (due to, for example, increasing demand for RE in excess of available supply) (Figure SPM.6). The contribution of different drivers (e.g., R&D, economies of scale, deployment-oriented learning, and increased market competition among RE suppliers) is not always understood in detail. [2.7, 3.8, 7.8, 10.5] Further cost reductions are expected, resulting in greater potential deployment and consequent climate change mitigation. Examples of important areas of potential technological advancement include: new and improved feedstock production and supply systems, biofuels produced via new processes (also called next-generation or advanced biofuels, e.g., lignocellulosic) and advanced biorefining [2.6]; advanced PV and CSP technologies and manufacturing processes [3.7]; enhanced geothermal systems (EGS) [4.6]; multiple emerging ocean technologies [6.6]; and foundation and turbine designs for offshore wind energy [7.7]. Further cost reductions for hydropower are expected to be less significant than some of the other RE technologies, but R&D opportunities exist to make hydropower projects technically feasible in a wider range of locations and to improve the technical performance of new and existing projects. [5.3, 5.7, 5.8]

A variety of technology-specific challenges (in addition to cost) may need to be addressed to enable RE to significantly upscale its contribution to reducing GHG emissions. For the increased and sustainable use of bioenergy, proper design, implementation and monitoring of sustainability frameworks can minimize negative impacts and maximize benefits with regard to social, economic and environmental issues [SPM.5, 2.2, 2.5, 2.8]. For solar energy, regulatory and institutional barriers can impede deployment, as can integration and transmission issues [3.9]. For geothermal energy, an important challenge would be to prove that enhanced geothermal systems (EGS) can be deployed economically, sustainably and widely [4.5, 4.6, 4.7, 4.8]. New hydropower projects can have ecological and social impacts that are very site specific, and increased deployment may require improved sustainability assessment tools, and regional and multi-party collaborations to address energy and water needs [5.6, 5.9, 5.10]. The deployment of ocean energy could benefit from testing centres for demonstration projects, and from dedicated policies and regulations that encourage early deployment [6.4]. For wind energy, technical and institutional solutions to transmission constraints and operational integration concerns may be especially important, as might public acceptance issues relating primarily to landscape impacts. [7.5, 7.6, 7.9]

8 The levelized cost of energy represents the cost of an energy generating system over its lifetime; it is calculated as the per-unit price at which energy must be generated from a specific source over its lifetime to break even. It usually includes all private costs that accrue upstream in the value chain, but does not include the downstream cost of delivery to the final customer; the cost of integration, or external environmental or other costs. Subsidies and tax credits are also not included.



Notes: Medium values are shown for the following subcategories, sorted in the order as they appear in the respective ranges (from left to right):

Electricity	Heat	Transport Fuels
Biomass: 1. Cofiring 2. Small scale combined heat and power, CHP (Gasification internal combustion engine) 3. Direct dedicated stoker & CHP 4. Small scale CHP (steam turbine) 5. Small scale CHP (organic Rankine cycle)	**Biomass Heat:** 1. Municipal solid waste based CHP 2. Anaerobic digestion based CHP 3. Steam turbine CHP 4. Domestic pellet heating system	**Biofuels:** 1. Corn ethanol 2. Soy biodiesel 3. Wheat ethanol 4. Sugarcane ethanol 5. Palm oil biodiesel
Solar Electricity: 1. Concentrating solar power 2. Utility-scale PV (1-axis and fixed tilt) 3. Commercial rooftop PV 4. Residential rooftop PV	**Solar Thermal Heat:** 1. Domestic hot water systems in China 2. Water and space heating	
Geothermal Electricity: 1. Condensing flash plant 2. Binary cycle plant	**Geothermal Heat:** 1. Greenhouses 2. Uncovered aquaculture ponds 3. District heating 4. Geothermal heat pumps 5. Geothermal building heating	
Hydropower: 1. All types		
Ocean Electricity: 1. Tidal barrage		
Wind Electricity: 1. Onshore 2. Offshore		

The lower range of the levelized cost of energy for each RE technology is based on a combination of the most favourable input-values, whereas the upper range is based on a combination of the least favourable input values. Reference ranges in the figure background for non-renewable electricity options are indicative of the levelized cost of centralized non-renewable electricity generation. Reference ranges for heat are indicative of recent costs for oil and gas based heat supply options. Reference ranges for transport fuels are based on recent crude oil spot prices of USD 40 to 130/barrel and corresponding diesel and gasoline costs, excluding taxes.

Figure SPM.5 | Range in recent levelized cost of energy for selected commercially available RE technologies in comparison to recent non-renewable energy costs. Technology sub-categories and discount rates were aggregated for this figure. For related figures with less or no such aggregation, see [1.3.2, 10.5, Annex III].

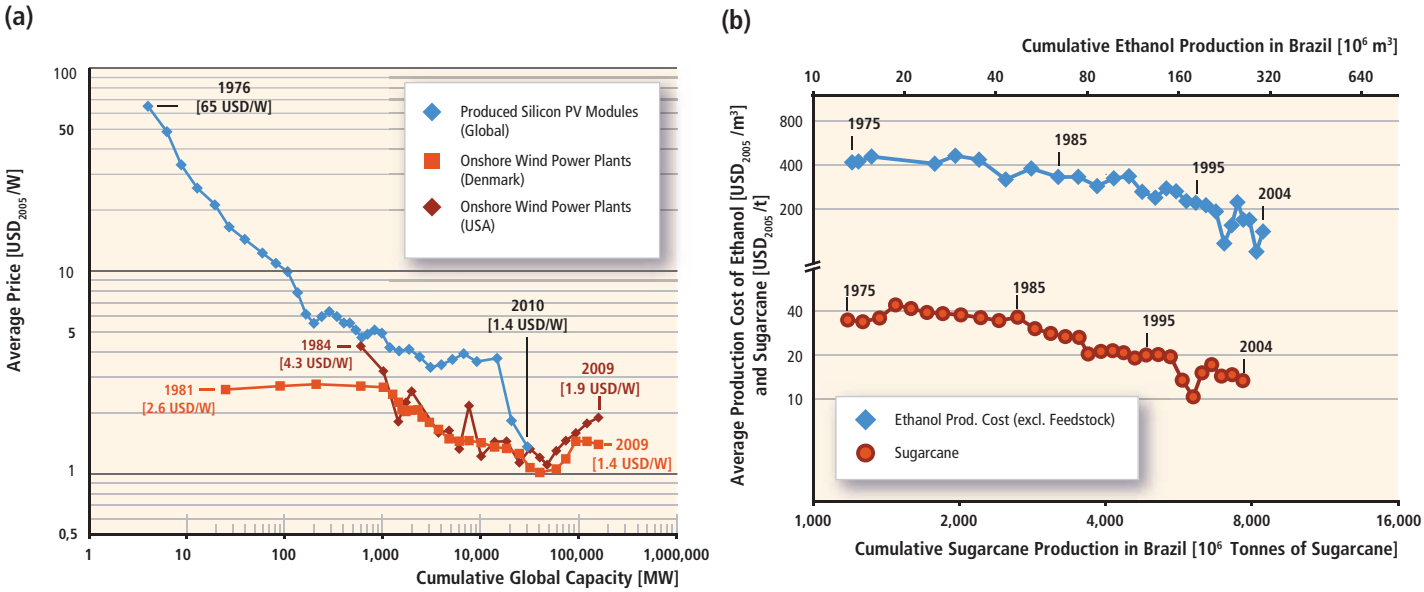


Figure SPM.6 | Selected experience curves in logarithmic scale for (a) the price of silicon PV modules and onshore wind power plants per unit of capacity; and (b) the cost of sugarcane-based ethanol production [data from Figure 3.17, 3.8.3, Figure 7.20, 7.8.2, Figure 2.21, 2.7.2].

Notes: Depending on the setting, cost reductions may occur at various geographic scales. The country-level examples provided here derive from the published literature. No global dataset of wind power plant prices or costs is readily available. Reductions in the cost or price of a technology per unit of capacity understate reductions in the levelized cost of energy of that technology when performance improvements occur. [7.8.4, 10.5]

4. Integration into present and future energy systems

Various RE resources are already being successfully integrated into energy supply systems [8.2] and into end-use sectors [8.3] (Figure SPM.7).

The characteristics of different RE sources can influence the scale of the integration challenge. Some RE resources are widely distributed geographically. Others, such as large-scale hydropower, can be more centralized but have integration options constrained by geographic location. Some RE resources are variable with limited predictability. Some have lower physical energy densities and different technical specifications from fossil fuels. Such characteristics can constrain ease of integration and invoke additional system costs particularly when reaching higher shares of RE. [8.2]

Integrating RE into most existing energy supply systems and end-use sectors at an accelerated rate—leading to higher shares of RE—is technologically feasible, though will result in a number of additional challenges. Increased shares of RE are expected within an overall portfolio of low GHG emission technologies [10.3, Tables 10.4-10.6]. Whether for electricity, heating, cooling, gaseous fuels or liquid fuels, including integration directly into end-use sectors, the RE integration challenges are contextual and site specific and include the adjustment of existing energy supply systems. [8.2, 8.3]

The costs and challenges of integrating increasing shares of RE into an existing energy supply system depend on the current share of RE, the availability and characteristics of RE resources, the system characteristics, and how the system evolves and develops in the future.

- RE can be integrated into all types of *electricity* systems, from large inter-connected continental-scale grids [8.2.1] down to small stand-alone systems and individual buildings [8.2.5]. Relevant system characteristics include the generation mix and its flexibility, network infrastructure, energy market designs and institutional rules, demand location, demand profiles, and control and communication capability. Wind, solar PV energy and CSP without

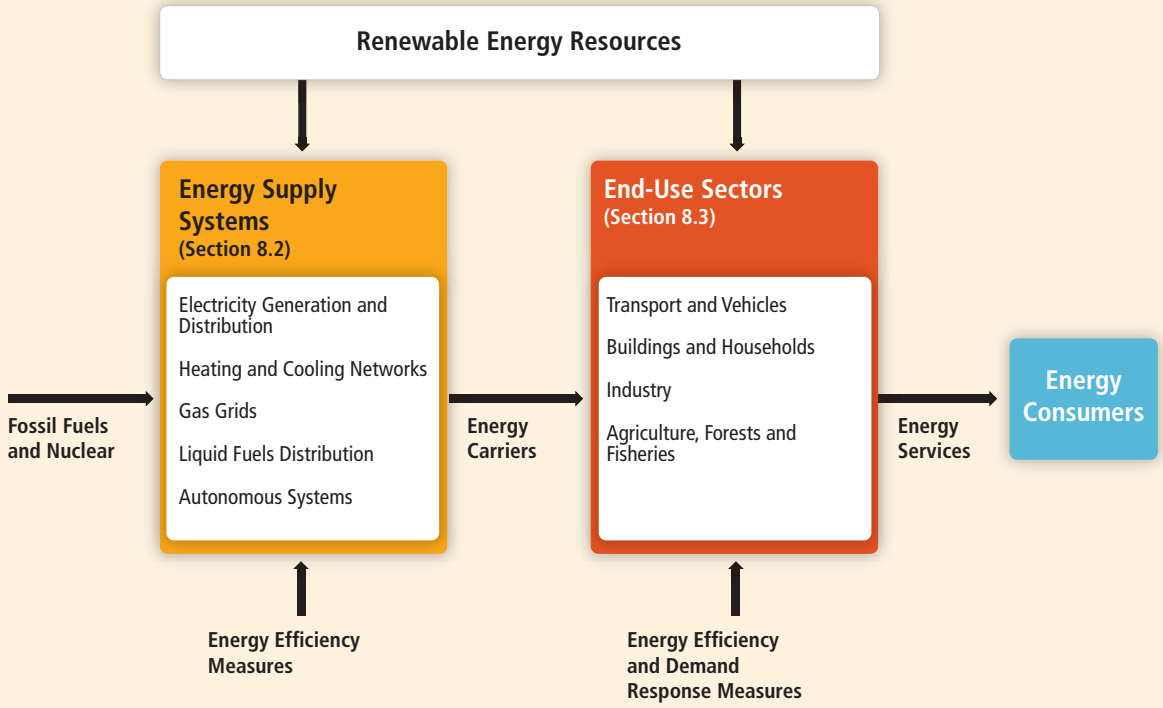


Figure SPM.7 | Pathways for RE integration to provide energy services, either into energy supply systems or on-site for use by the end-use sectors. [Figure 8.1, 8.1]

storage can be more difficult to integrate than dispatchable[9] hydropower, bioenergy, CSP with storage and geothermal energy.

As the penetration of variable RE sources increases, maintaining system reliability may become more challenging and costly. Having a portfolio of complementary RE technologies is one solution to reduce the risks and costs of RE integration. Other solutions include the development of complementary flexible generation and the more flexible operation of existing schemes; improved short-term forecasting, system operation and planning tools; electricity demand that can respond in relation to supply availability; energy storage technologies (including storage-based hydropower); and modified institutional arrangements. Electricity network transmission (including interconnections between systems) and/or distribution infrastructure may need to be strengthened and extended, partly because of the geographical distribution and fixed remote locations of many RE resources. [8.2.1]

- *District heating systems* can use low-temperature thermal RE inputs such as solar and geothermal heat, or biomass, including sources with few competing uses such as refuse-derived fuels. *District cooling* can make use of cold natural waterways. Thermal storage capability and flexible cogeneration can overcome supply and demand variability challenges as well as provide demand response for electricity systems. [8.2.2]

9 Electricity plants that can schedule power generation as and when required are classed as dispatchable [8.2.1.1, Annex I]. Variable RE technologies are partially dispatchable (i.e., only when the RE resource is available). CSP plants are classified as dispatchable when heat is stored for use at night or during periods of low sunshine.

- In *gas distribution grids*, injecting biomethane, or in the future, RE-derived hydrogen and synthetic natural gas, can be achieved for a range of applications but successful integration requires that appropriate gas quality standards are met and pipelines upgraded where necessary. [8.2.3]

- *Liquid fuel systems* can integrate biofuels for transport applications or for cooking and heating applications. Pure (100%) biofuels, or more usually those blended with petroleum-based fuels, usually need to meet technical standards consistent with vehicle engine fuel specifications. [8.2.4, 8.3.1]

There are multiple pathways for increasing the shares of RE across all end-use sectors. The ease of integration varies depending on region, characteristics specific to the sector and the technology.

- For *transport*, liquid and gaseous biofuels are already and are expected to continue to be integrated into the fuel supply systems of a growing number of countries. Integration options may include decentralized on-site or centralized production of RE hydrogen for fuel cell vehicles and RE electricity for rail and electric vehicles [8.2.1, 8.2.3] depending on infrastructure and vehicle technology developments. [8.3.1] Future demand for electric vehicles could also enhance flexible electricity generation systems. [8.2.1, 8.3.1]

- In the *building* sector, RE technologies can be integrated into both new and existing structures to produce electricity, heating and cooling. Supply of surplus energy may be possible, particularly for energy efficient building designs. [8.3.2] In developing countries, the integration of RE supply systems is feasible for even modest dwellings. [8.3.2, 9.3.2]

- Agriculture as well as food and fibre process *industries* often use biomass to meet direct heat and power demands on-site. They can also be net exporters of surplus fuels, heat, and electricity to adjacent supply systems. [8.3.3, 8.3.4] Increasing the integration of RE for use by industries is an option in several sub-sectors, for example through electro-thermal technologies or, in the longer term, by using RE hydrogen. [8.3.3]

The costs associated with RE integration, whether for electricity, heating, cooling, gaseous or liquid fuels, are contextual, site-specific and generally difficult to determine. They may include additional costs for network infrastructure investment, system operation and losses, and other adjustments to the existing energy supply systems as needed. The available literature on integration costs is sparse and estimates are often lacking or vary widely.

In order to accommodate high RE shares, energy systems will need to evolve and be adapted. [8.2, 8.3] Long-term integration efforts could include investment in enabling infrastructure; modification of institutional and governance frameworks; attention to social aspects, markets and planning; and capacity building in anticipation of RE growth. [8.2, 8.3] Furthermore, integration of less mature technologies, including biofuels produced through new processes (also called advanced biofuels or next-generation biofuels), fuels generated from solar energy, solar cooling, ocean energy technologies, fuel cells and electric vehicles, will require continuing investments in research, development and demonstration (RD&D), capacity building and other supporting measures. [2.6, 3.7, 11.5, 11.6, 11.7]

RE could shape future energy supply and end-use systems, in particular for electricity, which is expected to attain higher shares of RE earlier than either the heat or transport fuel sectors at the global level [10.3]. Parallel developments in electric vehicles [8.3.1], increased heating and cooling using electricity (including heat pumps) [8.2.2, 8.3.2, 8.3.3], flexible demand response services (including the use of smart meters) [8.2.1], energy storage and other technologies could be associated with this trend.

As infrastructure and energy systems develop, in spite of the complexities, there are few, if any, fundamental technological limits to integrating a portfolio of RE technologies to meet a majority share of total

energy demand in locations where suitable RE resources exist or can be supplied. However, the actual rate of integration and the resulting shares of RE will be influenced by factors such as costs, policies, environmental issues and social aspects. [8.2, 8.3, 9.3, 9.4, 10.2, 10.5]

5. Renewable energy and sustainable development

Historically, economic development has been strongly correlated with increasing energy use and growth of GHG emissions, and RE can help decouple that correlation, contributing to sustainable development (SD). Though the exact contribution of RE to SD has to be evaluated in a country-specific context, RE offers the opportunity to contribute to social and economic development, energy access, secure energy supply, climate change mitigation, and the reduction of negative environmental and health impacts. [9.2] Providing access to modern energy services would support the achievement of the Millennium Development Goals. [9.2.2, 9.3.2]

- **RE can contribute to social and economic development.** Under favorable conditions, cost savings in comparison to non-RE use exist, in particular in remote and in poor rural areas lacking centralized energy access. [9.3.1, 9.3.2.] Costs associated with energy imports can often be reduced through the deployment of domestic RE technologies that are already competitive. [9.3.3] RE can have a positive impact on job creation although the studies available differ with respect to the magnitude of net employment. [9.3.1]

- **RE can help accelerate access to energy, particularly for the 1.4 billion people without access to electricity and the additional 1.3 billion using traditional biomass.** Basic levels of access to modern energy services can provide significant benefits to a community or household. In many developing countries, decentralized grids based on RE and the inclusion of RE in centralized energy grids have expanded and improved energy access. In addition, non-electrical RE technologies also offer opportunities for modernization of energy services, for example, using solar energy for water heating and crop drying, biofuels for transportation, biogas and modern biomass for heating, cooling, cooking and lighting, and wind for water pumping. [9.3.2, 8.1] The number of people without access to modern energy services is expected to remain unchanged unless relevant domestic policies are implemented, which may be supported or complemented by international assistance as appropriate. [9.3.2, 9.4.2]

- **RE options can contribute to a more secure energy supply, although specific challenges for integration must be considered.** RE deployment might reduce vulnerability to supply disruption and market volatility if competition is increased and energy sources are diversified. [9.3.3, 9.4.3] Scenario studies indicate that concerns regarding secure energy supply could continue in the future without technological improvements within the transport sector. [2.8, 9.4.1.1, 9.4.3.1, 10.3] The variable output profiles of some RE technologies often necessitate technical and institutional measures appropriate to local conditions to assure energy supply reliability. [8.2, 9.3.3]

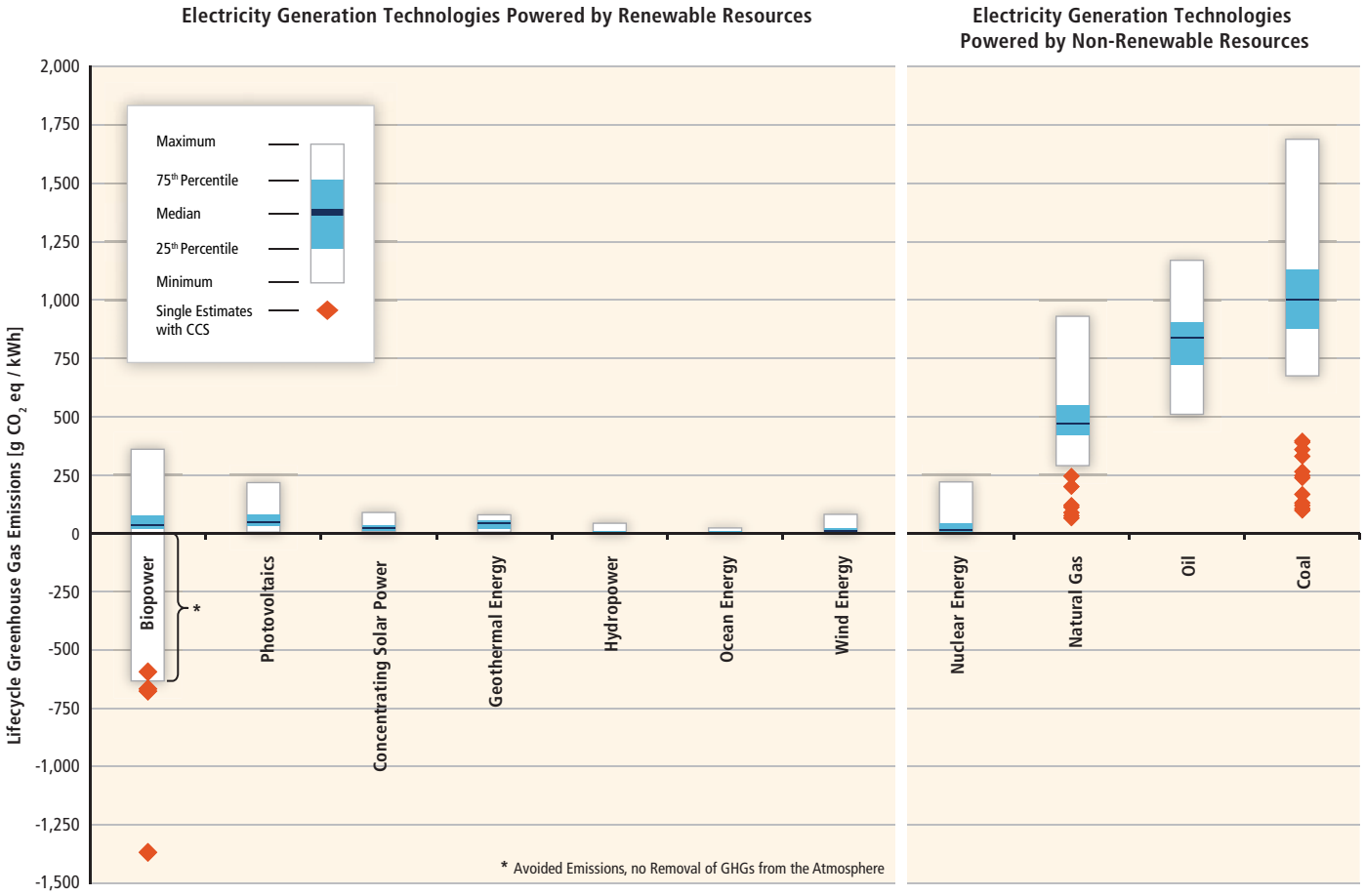
- **In addition to reduced GHG emissions, RE technologies can provide other important environmental benefits. Maximizing these benefits depends on the specific technology, management, and site characteristics associated with each RE project.**

  - **Lifecycle assessments (LCA) for electricity generation indicate that GHG emissions from RE technologies are, in general, significantly lower than those associated with fossil fuel options, and in a range of conditions, less than fossil fuels employing CCS.** The median values for all RE range from 4 to 46 g CO_2eq/kWh while those for fossil fuels range from 469 to 1,001 g CO_2eq/kWh (excluding land use change emissions) (Figure SPM.8).

  - **Most current bioenergy systems, including liquid biofuels, result in GHG emission reductions, and most biofuels produced through new processes (also called advanced biofuels or next-generation biofuels) could provide higher GHG mitigation. The GHG balance may be affected by land use**

changes and corresponding emissions and removals. Bioenergy can lead to avoided GHG emissions from residues and wastes in landfill disposals and co-products; the combination of bioenergy with CCS may provide for further reductions (see Figure SPM.8). The GHG implications related to land management and land use changes in carbon stocks have considerable uncertainties. [2.2, 2.5, 9.3.4.1]

- **The sustainability of bioenergy, in particular in terms of lifecycle GHG emissions, is influenced by land and biomass resource management practices.** Changes in land and forest use or management that, according to a considerable number of studies, could be brought about *directly* or *indirectly* by biomass production for use as fuels, power or heat, can decrease or increase terrestrial carbon stocks. The same studies also



Count of Estimates	222(+4)	124	42	8	28	10	126	125	83(+7)	24	169(+12)
Count of References	52(+0)	26	13	6	11	5	49	32	36(+4)	10	50(+10)

Figure SPM.8 | Estimates of lifecycle GHG emissions (g CO_2eq/kWh) for broad categories of electricity generation technologies, plus some technologies integrated with CCS. Land use-related net changes in carbon stocks (mainly applicable to biopower and hydropower from reservoirs) and land management impacts are excluded; negative estimates[10] for biopower are based on assumptions about avoided emissions from residues and wastes in landfill disposals and co-products. References and methods for the review are reported in Annex II. The number of estimates is greater than the number of references because many studies considered multiple scenarios. Numbers reported in parentheses pertain to additional references and estimates that evaluated technologies with CCS. Distributional information relates to estimates currently available in LCA literature, not necessarily to underlying theoretical or practical extrema, or the true central tendency when considering all deployment conditions. [Figure 9.8, 9.3.4.1]

10 'Negative estimates' within the terminology of lifecycle assessments presented in the SRREN refer to avoided emissions. Unlike the case of bioenergy combined with CCS, avoided emissions do not remove GHGs from the atmosphere.

show that indirect changes in terrestrial carbon stocks have considerable uncertainties, are not directly observable, are complex to model and are difficult to attribute to a single cause. Proper governance of land use, zoning, and choice of biomass production systems are key considerations for policy makers. [2.4.5, 2.5.1, 9.3.4, 9.4.4] Policies are in place that aim to ensure that the benefits from bioenergy, such as rural development, overall improvement of agricultural management and the contribution to climate change mitigation, are realized; their effectiveness has not been assessed. [2.2, 2.5, 2.8]

- **RE technologies, in particular non-combustion based options, can offer benefits with respect to air pollution and related health concerns.** [9.3.4.3, 9.4.4.1] Improving traditional biomass use can significantly reduce local and indoor air pollution (alongside GHG emissions, deforestation and forest degradation) and lower associated health impacts, particularly for women and children in developing countries. [2.5.4, 9.3.4.4]

- **Water availability could influence choice of RE technology.** Conventional water-cooled thermal power plants may be especially vulnerable to conditions of water scarcity and climate change. In areas where water scarcity is already a concern, non-thermal RE technologies or thermal RE technologies using dry cooling can provide energy services without additional stress on water resources. Hydropower and some bioenergy systems are dependent on water availability, and can either increase competition or mitigate water scarcity. Many impacts can be mitigated by siting considerations and integrated planning. [2.5.5.1, 5.10, 9.3.4.4]

- **Site-specific conditions will determine the degree to which RE technologies impact biodiversity.** RE-specific impacts on biodiversity may be positive or negative. [2.5, 3.6, 4.5, 5.6, 6.5, , 9.3.4.6]

- **RE technologies have low fatality rates.** Accident risks of RE technologies are not negligible, but their often decentralized structure strongly limits the potential for disastrous consequences in terms of fatalities. However, dams associated with some hydropower projects may create a specific risk depending on site-specific factors. [9.3.4.7]

6. Mitigation potentials and costs

A significant increase in the deployment of RE by 2030, 2050 and beyond is indicated in the majority of the 164 scenarios reviewed in this Special Report.[11] In 2008, total RE production was roughly 64 EJ/yr (12.9% of total primary energy supply) with more than 30 EJ/yr of this being traditional biomass. More than 50% of the scenarios project levels of RE deployment in 2050 of more than 173 EJ/yr reaching up to over 400 EJ/yr in some cases (Figure SPM.9). Given that traditional biomass use decreases in most scenarios, a corresponding increase in the production level of RE (excluding traditional biomass) anywhere from roughly three-fold to more than ten-fold is projected. The global primary energy supply share of RE differs substantially among the scenarios. More than half of the scenarios show a contribution from RE in excess of a 17% share of primary energy supply in 2030 rising to more than 27% in 2050. The scenarios with the highest RE shares reach approximately 43% in 2030 and 77% in 2050. [10.2, 10.3]

RE can be expected to expand even under baseline scenarios. Most baseline scenarios show RE deployments significantly above the 2008 level of 64 EJ/yr and up to 120 EJ/yr by 2030. By 2050, many baseline scenarios reach RE deployment levels of more than 100 EJ/yr and in some cases up to about 250 EJ/yr (Figure SPM.9). These baseline deployment levels result from a range of assumptions, including, for example, continued demand growth for energy services throughout the century, the ability of RE to contribute to increased energy access and the limited long-term

11 For this purpose a review of 164 global scenarios from 16 different large-scale integrated models was conducted. Although the set of scenarios allows for a meaningful assessment of uncertainty, the reviewed 164 scenarios do not represent a fully random sample suitable for rigorous statistical analysis and do not represent always the full RE portfolio (e.g., so far ocean energy is only considered in a few scenarios) [10.2.2]. For more specific analysis, a subset of 4 illustrative scenarios from the set of 164 was used. They represent a span from a baseline scenario without specific mitigation targets to three scenarios representing different CO_2 stabilization levels. [10.3]

availability of fossil resources. Other assumptions (e.g., improved costs and performance of RE technologies) render RE technologies increasingly economically competitive in many applications even in the absence of climate policy. [10.2]

RE deployment significantly increases in scenarios with low GHG stabilization concentrations. Low GHG stabilization scenarios lead on average to higher RE deployment compared to the baseline. However, for any given long-term GHG concentration goal, the scenarios exhibit a wide range of RE deployment levels (Figure SPM.9). In scenarios that stabilize the atmospheric CO_2 concentrations at a level of less than 440 ppm, the median RE deployment level in 2050 is 248 EJ/yr (139 in 2030), with the highest levels reaching 428 EJ/yr by 2050 (252 in 2030). [10.2]

Many combinations of low-carbon energy supply options and energy efficiency improvements can contribute to given low GHG concentration levels, with RE becoming the dominant low-carbon energy supply option by 2050 in the majority of scenarios. This wide range of results originates in assumptions about factors such as developments in RE technologies (including bioenergy with CCS) and their associated resource bases and costs; the comparative attractiveness of other mitigation options (e.g., end-use energy efficiency, nuclear energy, fossil energy with CCS); patterns of consumption and production; fundamental drivers of energy services demand (including future population and economic growth); the ability to integrate variable RE sources into power grids; fossil fuel resources; specific policy approaches to mitigation; and emissions trajectories towards long-term concentration levels. [10.2]

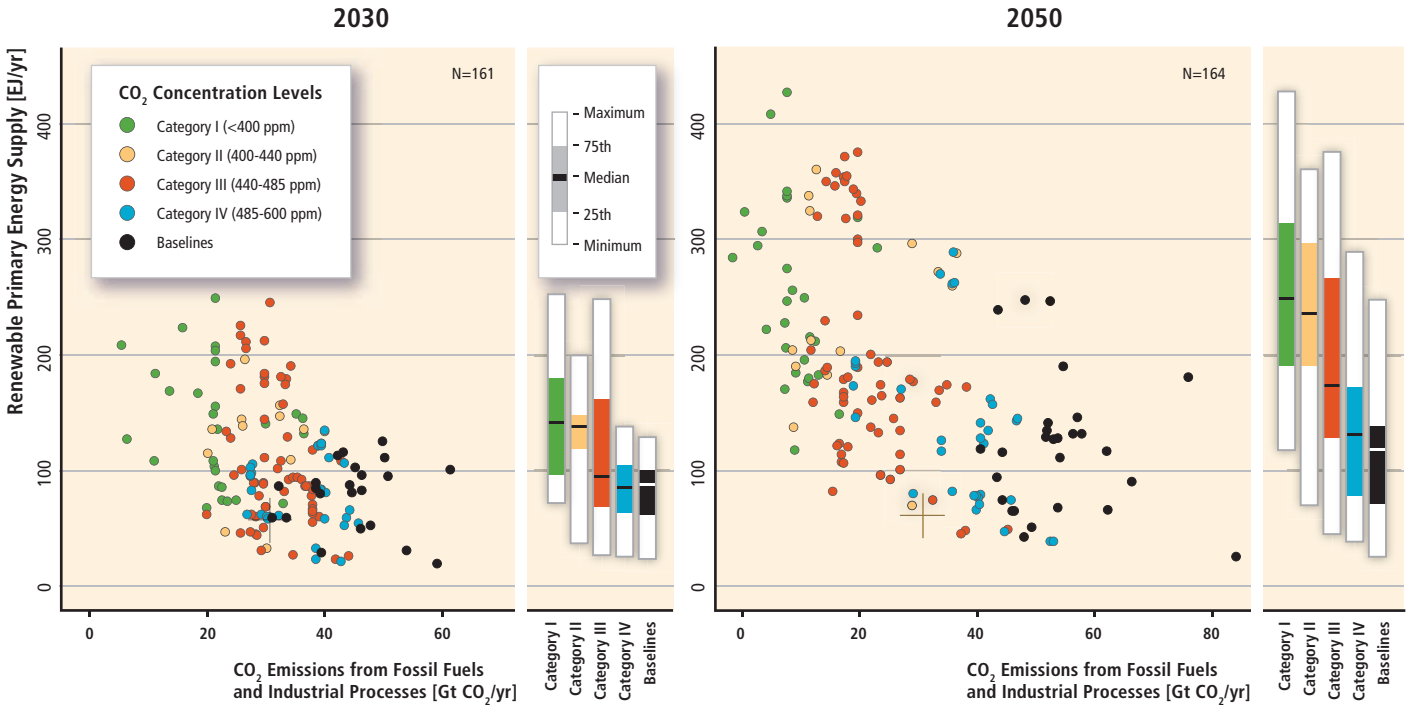


Figure SPM.9 | Global RE primary energy supply (direct equivalent) from 164 long-term scenarios versus fossil and industrial CO_2 emissions in 2030 and 2050. Colour coding is based on categories of atmospheric CO_2 concentration stabilization levels that are defined consistently with those in the AR4. The panels to the right of the scatterplots show the deployment levels of RE in each of the atmospheric CO_2 concentration categories. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. The grey crossed lines show the relationship in 2007. [Figure 10.2, 10.2.2.2]

Notes: For data reporting reasons only 161 scenarios are included in the 2030 results shown here, as opposed to the full set of 164 scenarios. RE deployment levels below those of today are a result of model output and differences in the reporting of traditional biomass. For details on the use of the 'direct equivalent' method of accounting for primary energy supply and the implied care needed in the interpretation of scenario results, see Box SPM.2. Note that categories V and above are not included and category IV is extended to 600 ppm from 570 ppm, because all stabilization scenarios lie below 600 ppm CO_2 in 2100 and because the lowest baseline scenarios reach concentration levels of slightly more than 600 ppm by 2100.

The scenario review in this Special Report indicates that RE has a large potential to mitigate GHG emissions. Four illustrative scenarios span a range of global cumulative CO_2 savings between 2010 and 2050, from about 220 to 560 Gt CO_2 compared to about 1,530 Gt cumulative fossil and industrial CO_2 emissions in the IEA World Energy Outlook 2009 Reference Scenario during the same period. The precise attribution of mitigation potentials to RE depends on the role scenarios attribute to specific mitigation technologies, on complex system behaviours and, in particular, on the energy sources that RE displaces. Therefore, attribution of precise mitigation potentials to RE should be viewed with appropriate caution. [10.2, 10.3, 10.4]

Scenarios generally indicate that growth in RE will be widespread around the world. Although the precise distribution of RE deployment among regions varies substantially across scenarios, the scenarios are largely consistent in indicating widespread growth in RE deployment around the globe. In addition, the total RE deployment is higher over the long term in the group of non-Annex I countries[12] than in the group of Annex I countries in most scenarios (Figure SPM.10). [10.2, 10.3]

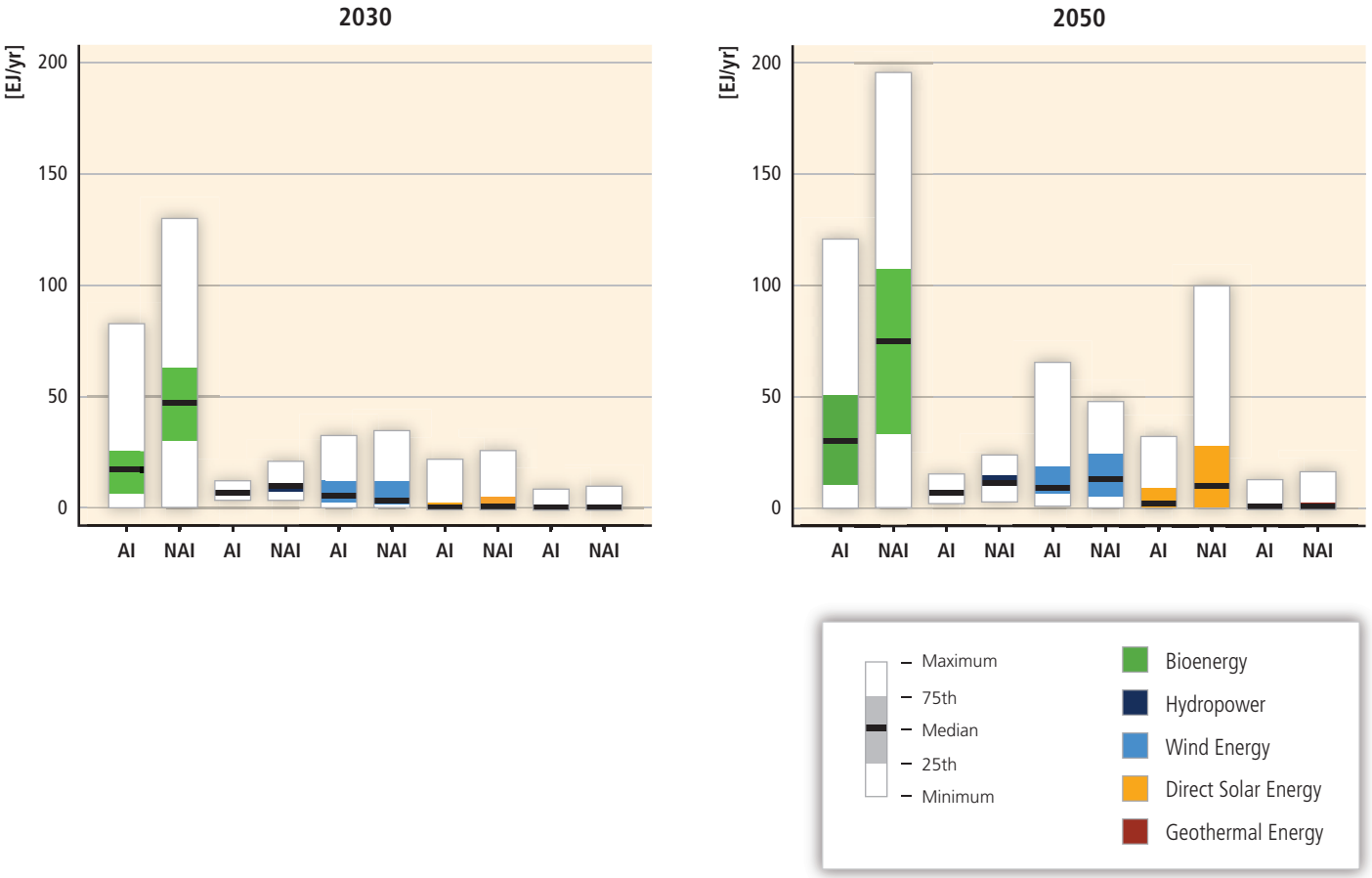


Figure SPM.10 | Global RE primary energy supply (direct equivalent) by source in the group of Annex I (AI) and the group of Non-Annex I (NAI) countries in 164 long-term scenarios by 2030 and 2050. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. [Figure 10.8, 10.2.2.5]

Notes: For details on the use of the 'direct equivalent' method of accounting for primary energy supply and the implied care needed in the interpretation of scenario results, see Box SPM.2. More specifically, the ranges of secondary energy provided from bioenergy, wind energy and direct solar energy can be considered of comparable magnitude in their higher penetration scenarios in 2050. Ocean energy is not presented here as only very few scenarios consider this RE technology.

12 The terms 'Annex I' and 'non-Annex I' are categories of countries that derive from the United Nations Framework Convention on Climate Change (UNFCCC).

Scenarios do not indicate an obvious single dominant RE technology at a global level; in addition, the global overall technical potentials do not constrain the future contribution of RE. Although the contribution of RE technologies varies across scenarios, modern biomass, wind and direct solar commonly make up the largest contributions of RE technologies to the energy system by 2050 (Figure SPM.11). All scenarios assessed confirm that technical potentials will not be the limiting factors for the expansion of RE at a global scale. Despite significant technological and regional differences, in the four illustrative scenarios less than 2.5% of the global available technical RE potential is used. [10.2, 10.3]

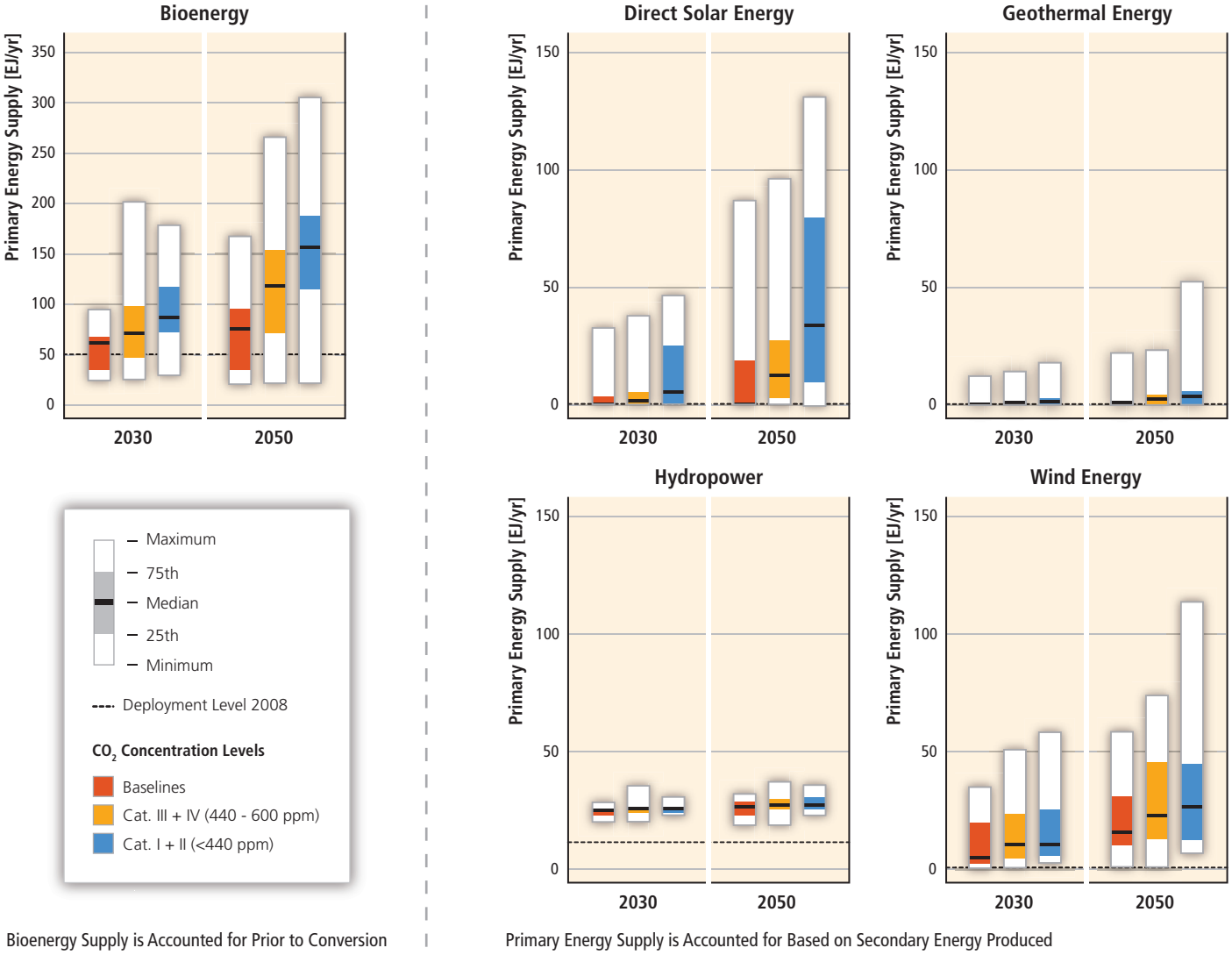


Figure SPM.11 | Global primary energy supply (direct equivalent) of bioenergy, wind, direct solar, hydro, and geothermal energy in 164 long-term scenarios in 2030 and 2050, and grouped by different categories of atmospheric CO_2 concentration level that are defined consistently with those in the AR4. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. [Excerpt from Figure 10.9, 10.2.2.5]

Notes: For details on the use of the 'direct equivalent' method of accounting for primary energy supply and the implied care needed in the interpretation of scenario results, see Box SPM.2. More specifically, the ranges of secondary energy provided from bioenergy, wind energy and direct solar energy can be considered of comparable magnitude in their higher penetration scenarios in 2050. Ocean energy is not presented here as only very few scenarios consider this RE technology. Note that categories V and above are not included and category IV is extended to 600 ppm from 570 ppm, because all stabilization scenarios lie below 600 ppm CO_2 in 2100 and because the lowest baselines scenarios reach concentration levels of slightly more than 600 ppm by 2100.

Individual studies indicate that if RE deployment is limited, mitigation costs increase and low GHG concentration stabilizations may not be achieved. A number of studies have pursued scenario sensitivities that assume constraints on the deployment of individual mitigation options, including RE as well as nuclear and fossil energy with CCS. There is little agreement on the precise magnitude of the cost increase. [10.2]

A transition to a low-GHG economy with higher shares of RE would imply increasing investments in technologies and infrastructure. The four illustrative scenarios analyzed in detail in the SRREN estimate global cumulative RE investments (in the power generation sector only) ranging from USD_{2005} 1,360 to 5,100 billion for the decade 2011 to 2020, and from USD_{2005} 1,490 to 7,180 billion for the decade 2021 to 2030. The lower values refer to the IEA World Energy Outlook 2009 Reference Scenario and the higher ones to a scenario that seeks to stabilize atmospheric CO_2 (only) concentration at 450 ppm. The annual averages of these investment needs are all smaller than 1% of the world's gross domestic product (GDP). Beyond differences in the design of the models used to investigate these scenarios, the range can be explained mainly by differences in GHG concentrations assessed and constraints imposed on the set of admissible mitigation technologies. Increasing the installed capacity of RE power plants will reduce the amount of fossil and nuclear fuels that otherwise would be needed in order to meet a given electricity demand. In addition to investment, operation and maintenance (O&M) and (where applicable) feedstock costs related to RE power plants, any assessment of the overall economic burden that is associated with their application will have to consider avoided fuel and substituted investment costs as well. Even without taking the avoided costs into account, the lower range of the RE power investments discussed above is lower than the respective investments reported for 2009. The higher values of the annual averages of the RE power sector investment approximately correspond to a five-fold increase in the current global investments in this field. [10.5, 11.2.2]

7. Policy, implementation and financing

An increasing number and variety of RE policies—motivated by many factors—have driven escalated growth of RE technologies in recent years. [1.4, 11.2, 11.5, 11.6] Government policies play a crucial role in accelerating the deployment of RE technologies. Energy access and social and economic development have been the primary drivers in most developing countries whereas secure energy supply and environmental concerns have been most important in developed countries [9.3, 11.3]. The focus of policies is broadening from a concentration primarily on RE electricity to include RE heating and cooling and transportation. [11.2, 11.5]

RE-specific policies for research, development, demonstration and deployment help to level the playing field for RE. Policies include regulations such as feed-in-tariffs, quotas, priority grid access, building mandates, biofuel blending requirements, and bioenergy sustainability criteria. [2.4.5.2, 2.ES, TS.2.8.1] Other policy categories are fiscal incentives such as tax policies and direct government payments such as rebates and grants; and public finance mechanisms such as loans and guarantees. Wider policies aimed at reducing GHG emissions such as carbon pricing mechanisms may also support RE.

Policies can be sector specific, can be implemented at the local, state/provincial, national and in some cases regional level, and can be complemented by bilateral, regional and international cooperation. [11.5]
Policies have promoted an increase in RE capacity installations by helping to overcome various barriers. [1.4, 11.1, 11.4, 11.5, 11.6] Barriers to RE deployment include:

- Institutional and policy barriers related to existing industry, infrastructure and regulation of the energy system;
- Market failures, including non-internalized environmental and health costs, where applicable;

- Lack of general information and access to data relevant to the deployment of RE, and lack of technical and knowledge capacity; and

- Barriers related to societal and personal values and affecting the perception and acceptance of RE technologies. [1.4, 9.5.1, 9.5.2.1]

Public R&D investments in RE technologies are most effective when complemented by other policy instruments, particularly deployment policies that simultaneously enhance demand for new technologies. Together, R&D and deployment policies create a positive feedback cycle, inducing private sector investment. Enacting deployment policies early in the development of a given technology can accelerate learning by inducing private R&D, which in turn further reduces costs and provides additional incentives for using the technology. [11.5.2]

Some policies have been shown to be effective and efficient in rapidly increasing RE deployment. However, there is no one-size-fits-all policy. Experience shows that different policies or combinations of policies can be more effective and efficient depending on factors such as the level of technological maturity, affordable capital, ease of integration into the existing system and the local and national RE resource base. [11.5]

- Several studies have concluded that some feed in tariffs have been effective and efficient at promoting RE electricity, mainly due to the combination of long-term fixed price or premium payments, network connections, and guaranteed purchase of all RE electricity generated. Quota policies can be effective and efficient if designed to reduce risk; for example, with long-term contracts. [11.5.4]

- An increasing number of governments are adopting fiscal incentives for RE heating and cooling. Obligations to use RE heat are gaining attention for their potential to encourage growth independent of public financial support. [11.5.5]

- In the transportation sector, RE fuel mandates or blending requirements are key drivers in the development of most modern biofuel industries. Other policies include direct government payments or tax reductions. Policies have influenced the development of an international biofuel trade. [11.5.6]

The flexibility to adjust as technologies, markets and other factors evolve is important. The details of design and implementation are critical in determining the effectiveness and efficiency of a policy. [11.5]. Policy frameworks that are transparent and sustained can reduce investment risks and facilitate deployment of RE and the evolution of low-cost applications. [11.5, 11.6]

'Enabling' policies support RE development and deployment. A favourable, or enabling, environment for RE can be created by addressing the possible interactions of a given policy with other RE policies as well as with energy and non-energy policies (e.g., those targeting agriculture, transportation, water management and urban planning); by easing the ability of RE developers to obtain finance and to successfully site a project; by removing barriers for access to networks and markets for RE installations and output; by increasing education and awareness through dedicated communication and dialogue initiatives; and by enabling technology transfer. In turn, the existence of an 'enabling' environment can increase the efficiency and effectiveness of policies to promote RE. [9.5.1.1, 11.6]

Two separate market failures create the rationale for the additional support of innovative RE technologies that have high potential for technological development, even if an emission market (or GHG pricing policy in general) exists. The first market failure refers to the external cost of GHG emissions. The second market failure is in the field of innovation: if firms underestimate the future benefits of investments into learning RE technologies or if they

cannot appropriate these benefits, they will invest less than is optimal from a macroeconomic perspective. In addition to GHG pricing policies, RE-specific policies may be appropriate from an economic point of view if the related opportunities for technological development are to be addressed (or if other goals beyond climate mitigation are pursued). Potentially adverse consequences such as lock-in, carbon leakage and rebound effects should be taken into account in the design of a portfolio of policies. [11.1.1, 11.5.7.3]

The literature indicates that long-term objectives for RE and flexibility to learn from experience would be critical to achieve cost-effective and high penetrations of RE. This would require systematic development of policy frameworks that reduce risks and enable attractive returns that provide stability over a time frame relevant to the investment. An appropriate and reliable mix of policy instruments, including energy efficiency policies, is even more important where energy infrastructure is still developing and energy demand is expected to increase in the future. [11.5, 11.6, 11.7]

8. Advancing knowledge about renewable energy

Enhanced scientific and engineering knowledge should lead to performance improvements and cost reductions in RE technologies. Additional knowledge related to RE and its role in GHG emissions reductions remains to be gained in a number of broad areas including: [for details, see Table 1.1]

- Future cost and timing of RE deployment;
- Realizable technical potential for RE at all geographical scales;
- Technical and institutional challenges and costs of integrating diverse RE technologies into energy systems and markets;
- Comprehensive assessments of socioeconomic and environmental aspects of RE and other energy technologies;
- Opportunities for meeting the needs of developing countries with sustainable RE services; and
- Policy, institutional and financial mechanisms to enable cost-effective deployment of RE in a wide variety of contexts.

Knowledge about RE and its climate change mitigation potential continues to advance. The existing scientific knowledge is significant and can facilitate the decision-making process. [1.1.8]

TS

Technical Summary

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1. Overview of Climate Change and Renewable Energy

1.1 Background

All societies require energy services to meet basic human needs (e.g., lighting, cooking, space comfort, mobility, communication) and to serve productive processes. For development to be sustainable, delivery of energy services needs to be secure and have low environmental impacts. Sustainable social and economic development requires assured and affordable access to the energy resources necessary to provide essential and sustainable energy services. This may mean the application of different strategies at different stages of economic development. To be environmentally benign, energy services must be provided with low environmental impacts and low greenhouse gas (GHG) emissions. However, the IPCC Fourth Assessment Report (AR4) reported that fossil fuels provided 85%[1] of the total primary energy in 2004, which is the same value as in 2008. Furthermore, the combustion of fossil fuels accounted for 56.6% of all anthropogenic GHG emissions (CO_2eq)[2] in 2004. [1.1.1, 9.2.1, 9.3.2, 9.6, 11.3]

Renewable energy (RE) sources play a role in providing energy services in a sustainable manner and, in particular, in mitigating climate change. This Special Report on *Renewable Energy Sources and Climate Change Mitigation* explores the current contribution and potential of RE sources to provide energy services for a sustainable social and economic development path. It includes assessments of available RE resources and technologies, costs and co-benefits, barriers to up-scaling and integration requirements, future scenarios and policy options. In particular, it provides information for policymakers, the private sector and civil society on:

- Identification of RE resources and available technologies and impacts of climate change on these resources [Chapters 2–7];
- Technology and market status, future developments and projected rates of deployment [Chapters 2–7,10];
- Options and constraints for integration into the energy supply system and other markets, including energy storage, modes of transmission, integration into existing systems and other options [Chapter 8];
- Linkages among RE growth, opportunities and sustainable development [Chapter 9];
- Impacts on secure energy supply [Chapter 9];
- Economic and environmental costs, benefits, risks and impacts of deployment [Chapters 9, 10];
- Mitigation potential of RE resources [Chapter 10];
- Scenarios that demonstrate how accelerated deployment might be achieved in a sustainable manner [Chapter 10];
- Capacity building, technology transfer and financing [Chapter 11]; and
- Policy options, outcomes and conditions for effectiveness [Chapter 11].

The report consists of 11 chapters. Chapter 1 sets the scene on RE and climate change; Chapters 2 through 7 provide information on six RE technologies while Chapters 8 through 11 deal with integrative issues (see Figure TS.1.1). The report communicates uncertainty where relevant.[3] This Technical Summary (TS) provides an overview of the report, summarizing the essential findings.

While the TS generally follows the structure of the full report, references to the various applicable chapters and sections are indicated with corresponding chapter and section numbers in square brackets. An explanation of terms, acronyms and chemical symbols used in the TS can be found in Annex I. Conventions and methodologies for determining costs, primary energy and other topics of analysis can be found in Annex II. Information on levelized costs of RE can be found in Annex III.

GHG emissions associated with the provision of energy services is a major cause of climate change. The AR4 concluded that "Most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic GHG (greenhouse gas) concentrations." Concentrations have continued to grow since the AR4 to over 390 ppm CO_2 or 39% above pre-industrial levels by the end of 2010. Since approximately 1850, global use of fossil fuels (coal, oil and gas) has increased to dominate energy supply, leading to a rapid growth in carbon dioxide (CO_2) emissions [Figure 1.6]. The amount of carbon in fossil fuel reserves and resources not yet burned [Figure 1.7] has the potential to add quantities of CO_2 to the atmosphere—if burned over coming centuries—that would exceed the range of any scenario considered in the AR4 [Figure 1.5] or in Chapter 10 of this report. [1.1.3, 1.1.4]

Despite substantial associated decarbonization, the overwhelming majority of the non-intervention emission projections exhibit considerably higher emissions in 2100 compared with those in 2000, implying rising GHG concentrations and, in turn, an increase in global mean temperatures. To avoid such adverse impacts of climate change on water resources, ecosystems, food security, human health and coastal settlements with potentially irreversible abrupt changes in the climate system,

1 The number from AR4 is 80% and has been converted from the physical content method for energy accounting to the direct equivalent method as the latter method is used in this report. Please refer to Section 1.1.9 and Annex II (Section A.II.4) for methodological details.

2 The contributions from other sources and/or gases are: CO_2 from deforestation, decay of biomass etc. (17.3%), CO_2 from other (2.8%), CH_4 (14.3%), N_2O (7.9%) and fluorinated gases (1.1%).

3 This report communicates uncertainty, for example, by showing the results of sensitivity analyses and by quantitatively presenting ranges in cost numbers as well as ranges in the scenario results. This report does not apply formal IPCC uncertainty terminology because at the time of the approval of this report, IPCC uncertainty guidance was in the process of being revised.

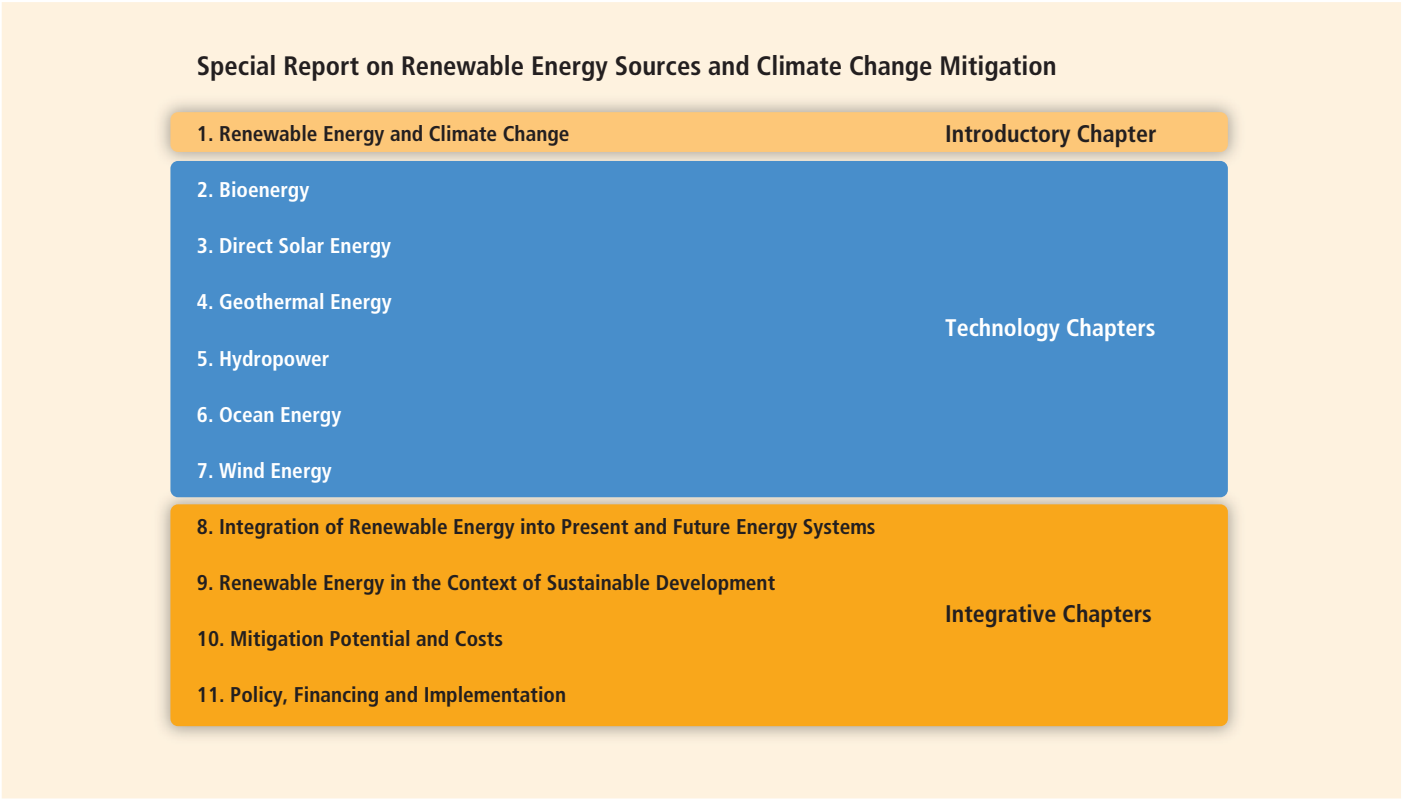


Figure TS.1.1 | Structure of the report. [Figure 1.1]

the Cancun Agreements call for limiting global average temperature rises to no more than 2°C above pre-industrial values, and agreed to consider limiting this rise to 1.5°C. In order to be confident of achieving an equilibrium temperature increase of only 2°C to 2.4°C, atmospheric GHG concentrations would need to be stabilized in the range of 445 to 490 ppm CO_2eq in the atmosphere. This in turn implies that global emissions of CO_2 will need to decrease by 50 to 85% below 2000 levels by 2050 and begin to decrease (instead of continuing their current increase) no later than 2015. [1.1.3]

To develop strategies for reducing CO_2 emissions, the Kaya identity can be used to decompose energy-related CO_2 emissions into four factors: 1) population, 2) gross domestic product (GDP) per capita, 3) energy intensity (i.e., total primary energy supply (TPES) per GDP) and 4) carbon intensity (i.e., CO_2 emissions per TPES). [1.1.4]

CO_2 emissions = Population x (GDP/population) x (TPES/GDP) x (CO_2/TPES)

The annual change in these four components is illustrated in Figure TS.1.2. [1.1.4]

While GDP per capita and population growth had the largest effect on emissions growth in earlier decades, decreasing energy intensity significantly slowed emissions growth in the period from 1971 to 2008. In the past, carbon intensity fell because of improvements in energy efficiency and switching from coal to natural gas and the expansion of nuclear energy in the 1970s and 1980s that was particularly driven by Annex I countries.[4] In recent years (2000 to 2007), increases in carbon intensity have been driven mainly by the expansion of coal use in both developed and developing countries, although coal and petroleum use have fallen slightly since 2007. In 2008 this trend was broken due to the financial crisis. Since the early 2000s, the energy supply has become more carbon intensive, thereby amplifying the increase resulting from growth in GDP per capita. [1.1.4]

On a global basis, it is estimated that RE accounted for 12.9% of the 492 EJ of total primary energy supply in 2008. The largest RE contributor was biomass (10.2%), with the majority (roughly 60%) of the biomass fuel used in traditional cooking and heating applications in developing countries but with rapidly increasing use of modern biomass as well.[5] Hydropower represented 2.3%, whereas other RE sources accounted for 0.4%. (Figure TS.1.3). In 2008, RE contributed approximately 19% of global electricity supply (16% hydropower, 3% other RE). [1.1.5]

Deployment of RE has been increasing rapidly in recent years. Under most conditions, increasing the share of RE in the energy mix will require policies to stimulate changes in the energy system. Government policy, the declining cost of many RE technologies, changes in the prices of fossil

4 See Glossary (Annex I) for a definition of Annex I countries.

5 Not accounted for here or in official databases is the estimated 20 to 40% of additional traditional biomass used in informal sectors. [2.1]

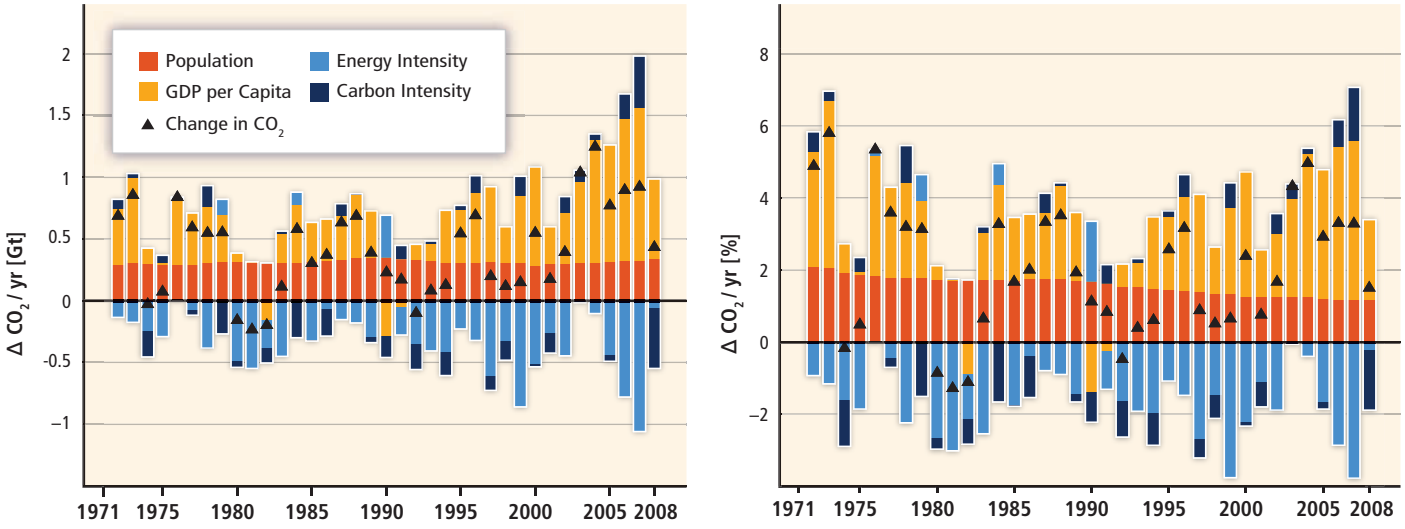


Figure TS.1.2 | Decomposition of (left) annual absolute change and (right) annual growth rate in global energy-related CO_2 emissions by the factors in the Kaya identity; population (red), GDP per capita (orange), energy intensity (light blue) and carbon intensity (dark blue) from 1971 to 2008. The colours show the changes that would occur due to each factor alone, holding the respective other factors constant. Total annual changes are indicated by a black triangle. [Figure 1.8]

fuels and other factors have supported the continuing increase in the use of RE. While the RE share is still relatively small, its growth has accelerated in recent years as shown in Figure TS.1.4. In 2009, despite global financial challenges, RE capacity continued to grow rapidly, including wind power (32%, 38 GW added), hydropower (3%, 31 GW added), grid-connected photovoltaics (53%, 7.5 GW added), geothermal power (4%, 0.4 GW added), and solar hot water/heating (21%, 31 GW_{th} added). Biofuels accounted for 2% of global road transport fuel demand in 2008 and nearly 3% in 2009. The annual production of ethanol increased to 1.6 EJ (76 billion litres) by the end of 2009 and biodiesel production increased to 0.6 EJ (17 billion litres). Of the approximate 300 GW of new electricity generating capacity added globally from 2008 to 2009, about 140 GW came from RE additions. Collectively, developing countries host 53% of global RE electricity generation capacity (including all sizes of hydropower), with China adding more RE power capacity than any other country in 2009. The USA and Brazil accounted for 54 and 35% of global bioethanol production in 2009, respectively, while China led in the use of solar hot water. At the end of 2009, the use of RE in hot water/heating

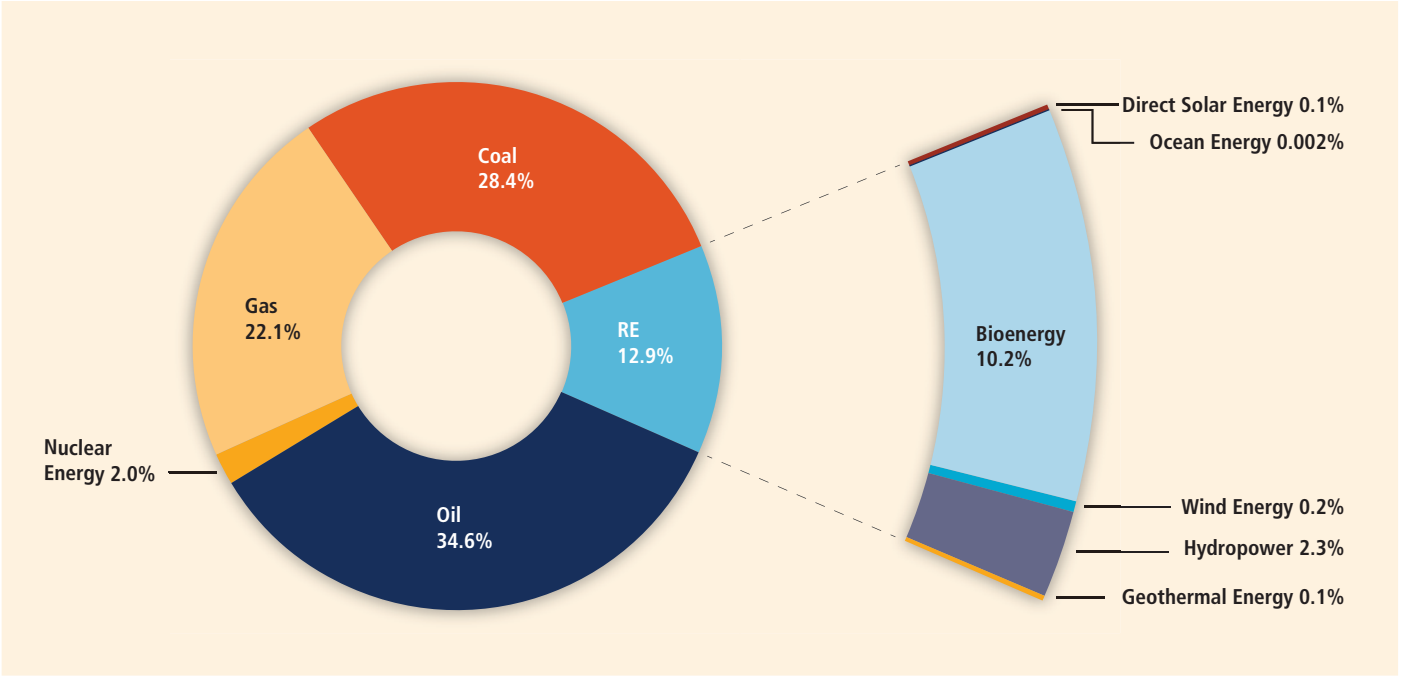


Figure TS.1.3 | Shares of energy sources in total global total primary energy supply in 2008 (492 EJ). Modern biomass contributes 38% of the total biomass share. [Figure 1.10]

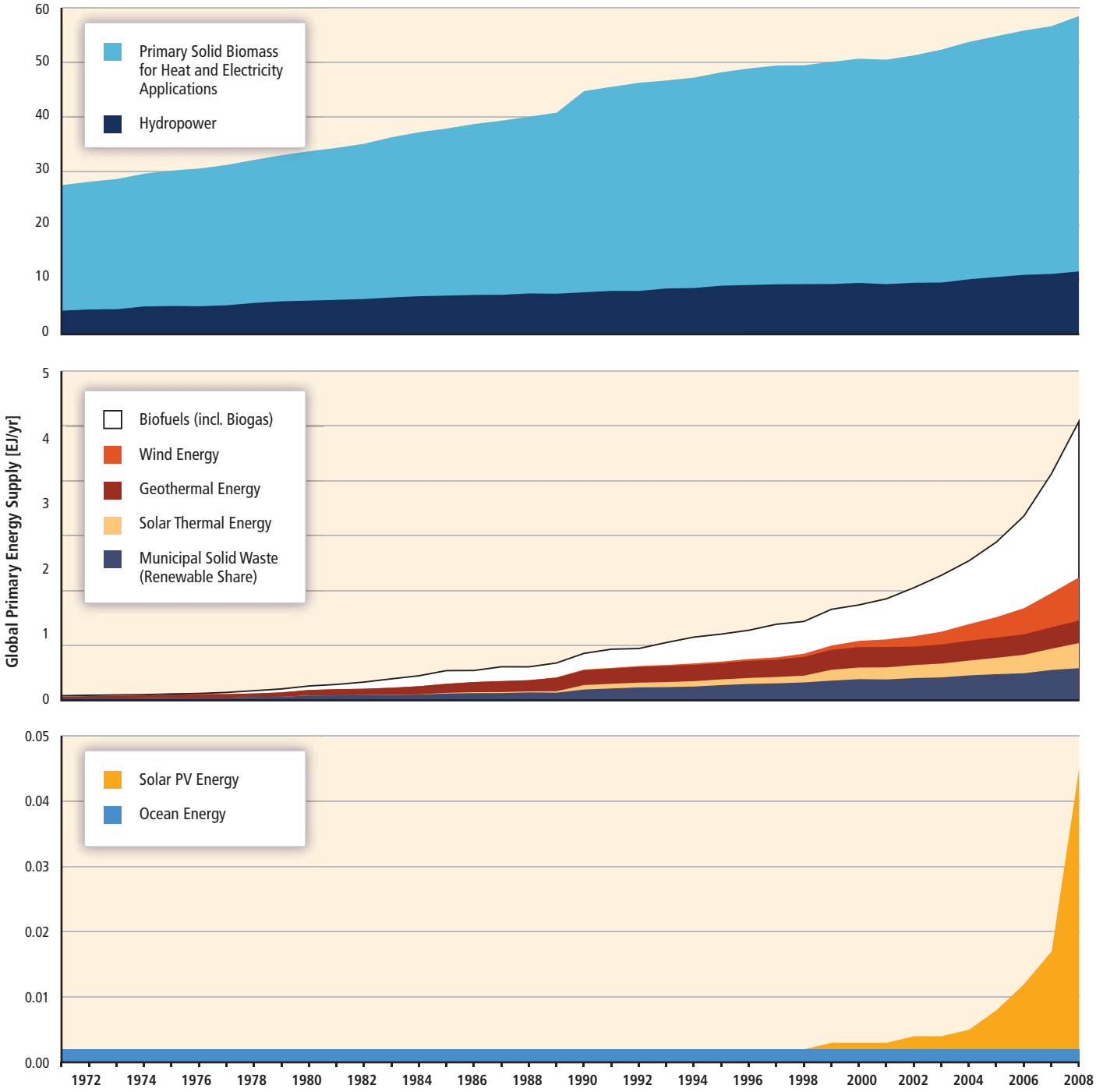


Figure TS.1.4 | Historical development of global primary energy supply from renewable energy from 1971 to 2008. [Figure 1.12]

Note: Technologies are referenced to separate vertical units for display purposes only. Underlying data for the figure has been converted to the 'direct equivalent' method of accounting for primary energy supply [1.1.9, Annex II.4], except that the energy content of biofuels is reported in secondary energy terms (the primary biomass used to produce the biofuel would be higher due to conversion losses [2.3, 2.4]).

markets included modern biomass (270 GW_{th}), solar energy (180 GW_{th}), and geothermal energy (60 GW_{th}). The use of RE (excluding traditional biomass) in meeting rural energy needs has also increased, including small-scale hydropower stations, various modern biomass options, and household or village photovoltaic (PV), wind or hybrid systems that combine multiple technologies. [1.1.5]

There are multiple means for lowering GHG emissions from the energy system while still providing desired energy services. The AR4 identified a number of ways to lower heat-trapping emissions from energy sources while still providing energy services: [1.1.6]

- Improve supply side efficiency of energy conversion, transmission and distribution, including combined heat and power.
- Improve demand side efficiency in the respective sectors and applications (e.g., buildings, industrial and agricultural processes, transportation, heating, cooling and lighting).
- Shift from high-GHG energy carriers such as coal and oil to lower-GHG energy carriers such as natural gas, nuclear fuels and RE sources.
- Utilize CO_2 capture and storage (CCS) to prevent post-combustion or industrial process CO_2 from entering the atmosphere. CCS has the potential for removing CO_2 from the atmosphere when biomass is processed, for example, through combustion or fermentation.
- Change behaviour to better manage energy use or to use fewer carbon- and energy-intensive goods and services.

The future share of RE applications will heavily depend on climate change mitigation goals, the level of requested energy services and resulting energy needs as well as their relative merit within the portfolio of zero- or low-carbon technologies (Figure TS.1.5). A comprehensive evaluation of any portfolio of mitigation options would involve an evaluation of their respective mitigation potential as well as all associated risks, costs and their contribution to sustainable development. [1.1.6]

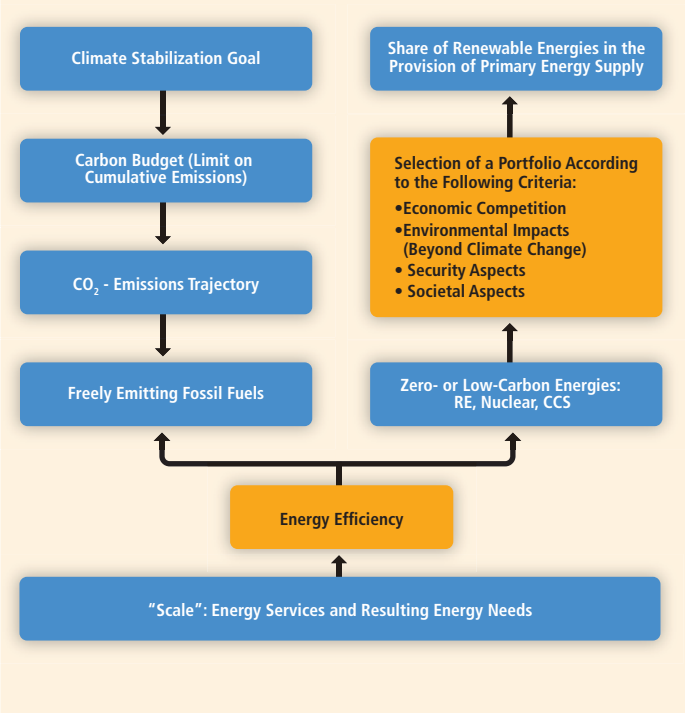


Figure TS.1.5 | The role of renewable energies within the portfolio of zero- or low-carbon mitigation options (qualitative description). [Figure 1.14]

Setting a climate protection goal in terms of the admissible change in global mean temperature broadly defines a corresponding GHG concentration limit with an associated CO_2 budget and subsequent time-dependent emission trajectory, which then defines the admissible amount of freely emitting fossil fuels. The complementary contribution of zero- or low-carbon energies to the primary energy supply is influenced by the 'scale' of the requested energy services. [1.1.6]

As many low-cost options to improve overall energy efficiency are already part of the non-intervention scenarios, the *additional* opportunities to decrease energy intensity in order to mitigate climate change are limited. In order to achieve ambitious climate protection goals, energy efficiency improvements alone do not suffice, requiring additional zero- or low-carbon technologies. The contribution RE will provide within the portfolio of these low-carbon technologies heavily depends on the economic competition between these technologies, a comparison of the relative environmental burden (beyond climate change) associated with them, as well as security and societal aspects (Figure TS.1.5). [1.1.6]

The body of scientific knowledge on RE and on the possible contribution of RE towards meeting GHG mitigation goals, as compiled and assessed in this report, is substantial. Nonetheless, due in part to the site-specific nature of RE, the diversity of RE technologies, the multiple end-use energy service needs that those technologies might serve, the range of markets and regulations governing integration, and the complexity of energy system transitions, knowledge about RE and its climate mitigation potential continues to advance. Additional knowledge remains to be gained in a number of broad areas related to RE and its possible role in GHG emissions reductions: [1.1.8]

- Future cost and timing of RE deployment;
- Realizable technical potential for RE at all geographical scales;
- Technical and institutional challenges and costs of integrating diverse RE technologies into energy systems and markets;
- Comprehensive assessment of socioeconomic and environmental aspects of RE and other energy technologies;
- Opportunities for meeting the needs of developing countries with sustainable RE services; and
- Policy, institutional and financial mechanisms to enable cost-effective deployment of RE in a wide variety of contexts.

Though much is already known in each of these areas, as compiled in this report, additional research and experience would further reduce uncertainties and thus facilitate decision making related to the use of RE in the mitigation of climate change. [1.1.6]

1.2 Summary of renewable energy resources and potential

RE is any form of energy from solar, geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. RE is obtained from the continuing or repetitive flows of energy occurring in the natural environment and includes resources such as biomass, solar energy, geothermal heat, hydropower, tide and waves, ocean thermal energy and wind energy. However, it is possible to utilize biomass at a greater rate than it can grow or to draw heat from a geothermal field at a faster rate than heat flows can replenish it. On the other hand, the rate of utilization of direct solar energy has no bearing on the rate at which it reaches the Earth. Fossil fuels (coal, oil, natural gas) do not fall under this definition, as they are not replenished within a time frame that is short relative to their rate of utilization. [1.2.1]

There is a multi-step process whereby primary energy is converted into an energy carrier, and then into an energy service. RE technologies are diverse and can serve the full range of energy service needs. Various types of RE can supply electricity, thermal energy and mechanical energy, as well as produce fuels that are able to satisfy multiple energy service needs. Figure TS.1.6 illustrates the multi-step conversion processes. [1.2.1]

Since it is energy services and not energy that people need, the process should be driven in an efficient manner that requires less primary energy consumption with low-carbon technologies that minimize CO_2 emissions. Thermal conversion processes to produce electricity (including biomass and geothermal) suffer losses of approximately 40 to 90%, and losses of around 80% occur when supplying the mechanical energy needed for transport based on internal combustion engines. These conversion losses raise the share of primary energy from fossil fuels, and the primary energy required from fossil fuels to produce electricity and mechanical energy from heat. Direct energy conversions from solar PV, hydro, ocean and wind energy to electricity do not suffer thermodynamic power cycle (heat to work) losses although they do experience other conversion inefficiencies in extracting energy from natural energy flows that may also be relatively large and irreducible (chapters 2-7). [1.2.1]

Some RE technologies can be deployed at the point of use (decentralized) in rural and urban environments, whereas others are primarily employed within large (centralized) energy networks. Though many

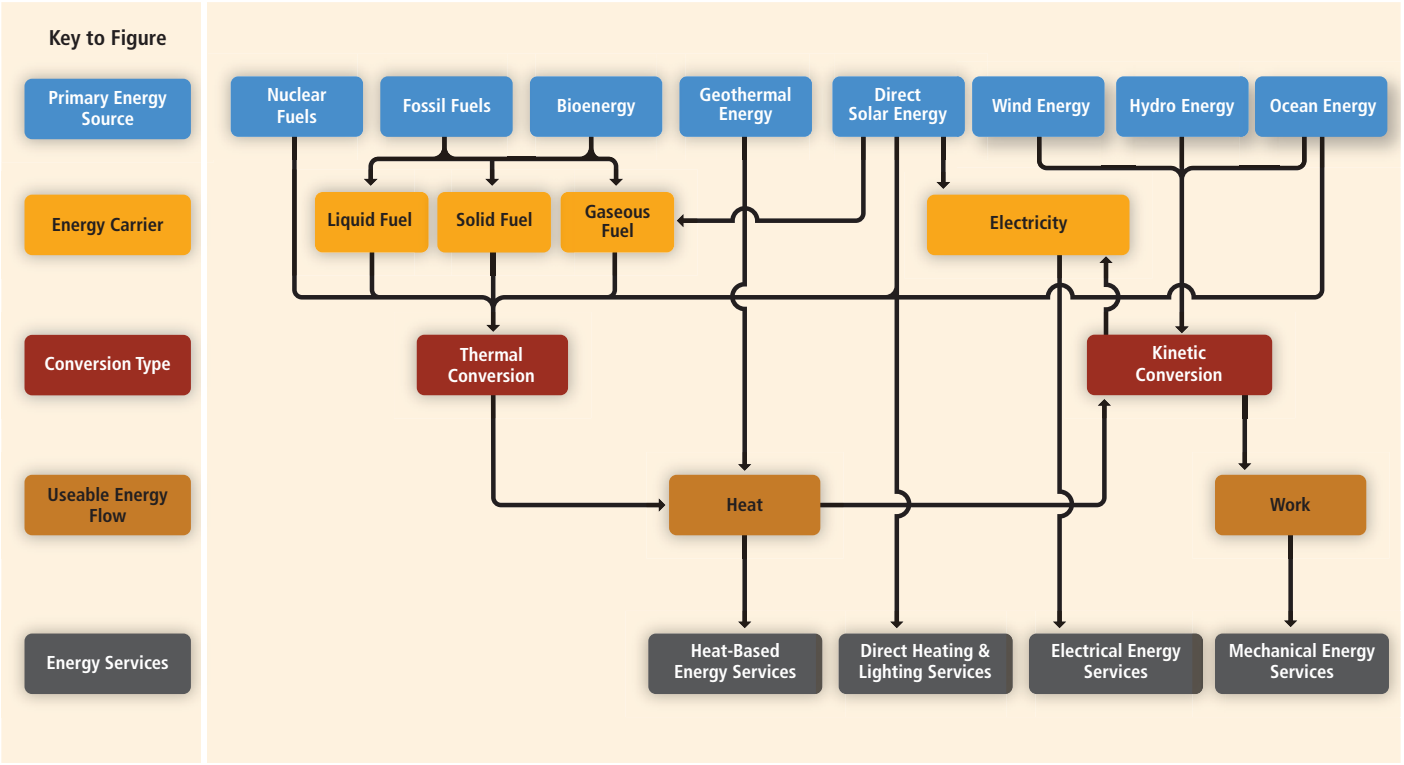


Figure TS.1.6 | Illustrative paths of energy from source to service. All connected lines indicate possible energy pathways. The energy services delivered to the users can be provided with differing amounts of end-use energy. This in turn can be provided with more or less primary energy from different sources, and with differing emissions of CO_2 and other environmental impacts. [Figure 1.16]

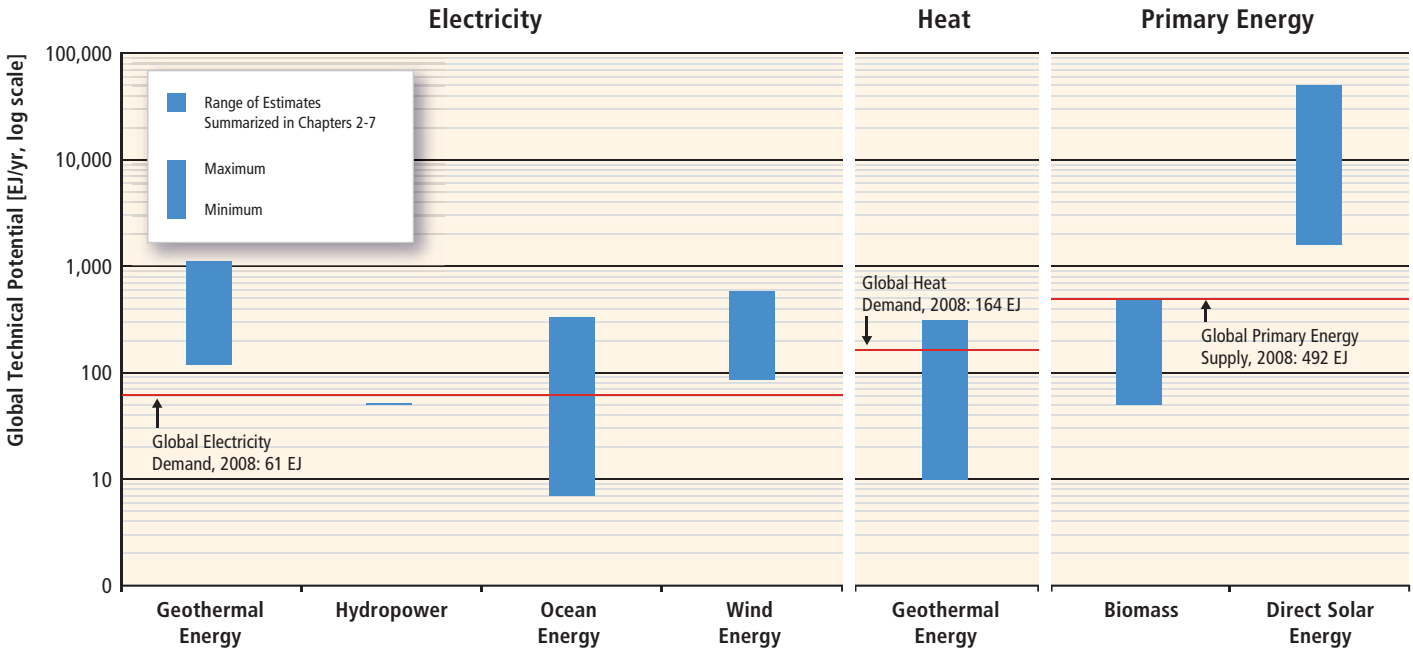
RE technologies are technically mature and are being deployed at significant scale, others are in an earlier phase of technical maturity and commercial deployment. [1.2.1]

The theoretical potential for RE exceeds current and projected global energy demand by far, but the challenge is to capture and utilize a sizable share of that potential to provide the desired energy services in a cost-effective and environmentally sound manner. [1.2.2]

The global technical potential of RE sources will also not limit continued market growth. A wide range of estimates are provided in the literature but studies have consistently found that the total global technical potential for RE is substantially higher than both current and projected future global energy demand. The technical potential for solar energy is the highest among the RE sources, but substantial technical potential exists for all forms of RE. The absolute size of the global technical potential for RE as a whole is unlikely to constrain RE deployment. [1.2.3]

Figure TS.1.7 shows that the technical potential[6] exceeds by a considerable margin the global electricity and heat demand, as well as the global primary energy supply, in 2008. While the figure provides a perspective for the reader to understand the relative sizes of the RE resources in the context of current energy demand and supply, note that the technical potentials are highly uncertain. Table A.1.1 in the Annex to Chapter 1 includes more detailed notes and explanations. [1.2.3]

RE can be integrated into all types of electricity systems from large, interconnected continental-scale grids down to small autonomous buildings. Whether for electricity, heating, cooling, gaseous fuels or liquid fuels, RE integration is contextual, site specific and complex. Partially dispatchable wind and solar energy can be more difficult to integrate than fully dispatchable hydropower, bioenergy and geothermal energy. As the penetration of partially dispatchable RE electricity increases, maintaining system reliability becomes more challenging and costly. A portfolio of solutions to minimize the risks and costs of RE integration can include the development of complementary flexible generation, strengthening and extending network infrastructure and interconnections, electricity demand that can respond in relation to supply availability, energy storage technologies (including reservoir-based hydropower), and modified institutional arrangements



Range of Estimates of Global Technical Potentials

Max (in EJ/yr)	1109	52	331	580	312	500	49837
Min (in EJ/yr)	118	50	7	85	10	50	1575

Figure TS.1.7 | Ranges of global technical potentials of RE sources derived from studies presented in Chapters 2 through 7. Biomass and solar are shown as primary energy due to their multiple uses. Note that the figure is presented in logarithmic scale due to the wide range of assessed data. [Figure 1.17]

Notes: Technical potentials reported here represent total worldwide potentials for annual RE supply and do not deduct any potential that is already being utilized. Note that RE electricity sources could also be used for heating applications, whereas biomass and solar resources are reported only in primary energy terms but could be used to meet various energy service needs. Ranges are based on various methods and apply to different future years; consequently, the resulting ranges are not strictly comparable across technologies. For the data behind the figure and additional notes that apply, see Table A.1.1 (as well as the underlying chapters).

6 See Annex I for a complete definition of technical potential.

including regulatory and market mechanisms. As the penetration level of RE increases, there is need for a mixture of inexpensive and effective communications systems and technologies, as well as smart meters. [1.2.4]

Energy services are the tasks performed using energy. A specific energy service can be provided in many ways and may therefore be characterized by high or low energy efficiency, implying the release of relatively smaller or larger amounts of CO_2 (under a given energy mix). Reducing energy needs at the energy services delivery stage through energy efficiency is an important means of reducing primary energy demand. This is particularly important for RE sources since they usually have lower power densities than fossil or nuclear fuels. Efficiency measures are often the lowest-cost option to reducing end-use energy demand. This report provides some specific definitions for different dimensions of efficiency. [1.2.5]

Energy savings resulting from efficiency measures are not always fully realized in practice. There may be a rebound effect in which some fraction of the measure is offset because the lower total cost of energy (due to less energy use) to perform a specific energy service may lead to utilization of more energy services. It is estimated that the rebound effect is probably limited by saturation effects to between 10 and 30% for home heating and vehicle use in Organisation for Economic Co-operation and Development (OECD) countries, and is very small for more efficient appliances and water heating. An efficiency measure that is successful in lowering economy-wide energy demand, however, lowers the price of energy as well, leading in turn to a decrease in economy-wide energy costs and additional cost savings (lower energy prices and less energy use). It is expected that the rebound effect may be greater in developing countries and among poor consumers. For climate change, the main concern with any rebound effect is its influence on CO_2 emissions. [1.2.5]

Carbon leakage may also reduce the effectiveness of carbon reduction policies. If carbon reduction policies are not applied uniformly across sectors and political jurisdictions, then it may be possible for carbon emitting activities to move to a sector or country without such policies. Recent research suggests, however, that estimates of carbon leakage are too high. [1.2.5]

1.3 Meeting energy service needs and current status

Global renewable energy flows from primary energy through carriers to end uses and losses in 2008 are shown in Figure TS.1.8. [1.3.1]

Globally in 2008, around 56% of RE was used to supply heat in private households and in the public and services sector. Essentially, this refers to wood and charcoal, widely used in developing countries for cooking. On the other hand, only a small amount of RE is used in the transport sector. Electricity production accounts for 24% of the end-use consumption. Biofuels contributed 2% of global road transport fuel supply in 2008, and traditional biomass (17%), modern biomass (8%), solar thermal and geothermal energy (2%) together fuelled 27% of the total global demand for heat in 2008. [1.3.1]

While the resource is obviously large and could theoretically supply all energy needs long into the future, the levelized cost of energy for many RE technologies is currently higher than existing energy prices, though in various settings RE is already economically competitive. Ranges of recent levelized costs of energy for selected commercially available RE technologies are wide, depending on a number of factors, including, but not limited to, technology characteristics and size, regional variations in cost and performance and differing discount rates (Figure TS.1.9). [1.3.2, 2.3, 2.7, 3.8, 4.8, 5.8, 6.7, 7.8, 10.5, Annex III]

The cost of most RE technologies has declined and additional expected technical advances would result in further cost reductions. Such cost reductions as well as monetizing the external cost of energy supply would improve the relative competitiveness of RE. The same applies if market prices increase due to other reasons. [1.3.2, 2.6, 2.7, 3.7, 3.8, 4.6, 4.7, 5.3, 5.7, 5.8, 6.6, 6.7, 7.7, 7.8, 10.5]

The contribution of RE to primary energy supply varies substantially by country and region. The geographic distribution of RE manufacturing, use and export is now being diversified from the developed world to other developing regions, notably Asia including China. In terms of installed renewable power capacity, China now leads the world followed by the USA, Germany, Spain and India. RE is more evenly distributed than fossil fuels and there are countries or regions rich in specific RE resources. [1.3.3]

1.4 Opportunities, barriers, and issues

The major global energy challenges are securing energy supply to meet growing demand, providing everybody with access to energy services and curbing energy's contribution to climate change. For developing countries, especially the poorest, energy is needed to stimulate production, income generation and social development, and to reduce the serious health problems caused by the use of fuel wood, charcoal, dung and agricultural waste. For industrialized countries, the primary reasons to encourage RE include emission reductions to mitigate climate change, secure energy supply concerns and employment creation. RE can open opportunities for addressing these multiple environmental, social and economic development dimensions, including adaptation to climate change. [1.4, 1.4.1]

Some form of renewable resource is available everywhere in the world, for example, solar radiation, wind, falling water, waves, tides and stored ocean heat or heat from the Earth. Furthermore, technologies exist that can harness these forms of energy. While the opportunities [1.4.1] seem great, there are barriers [1.4.2] and issues [1.4.3] that slow the introduction of RE into modern economies. [1.4]

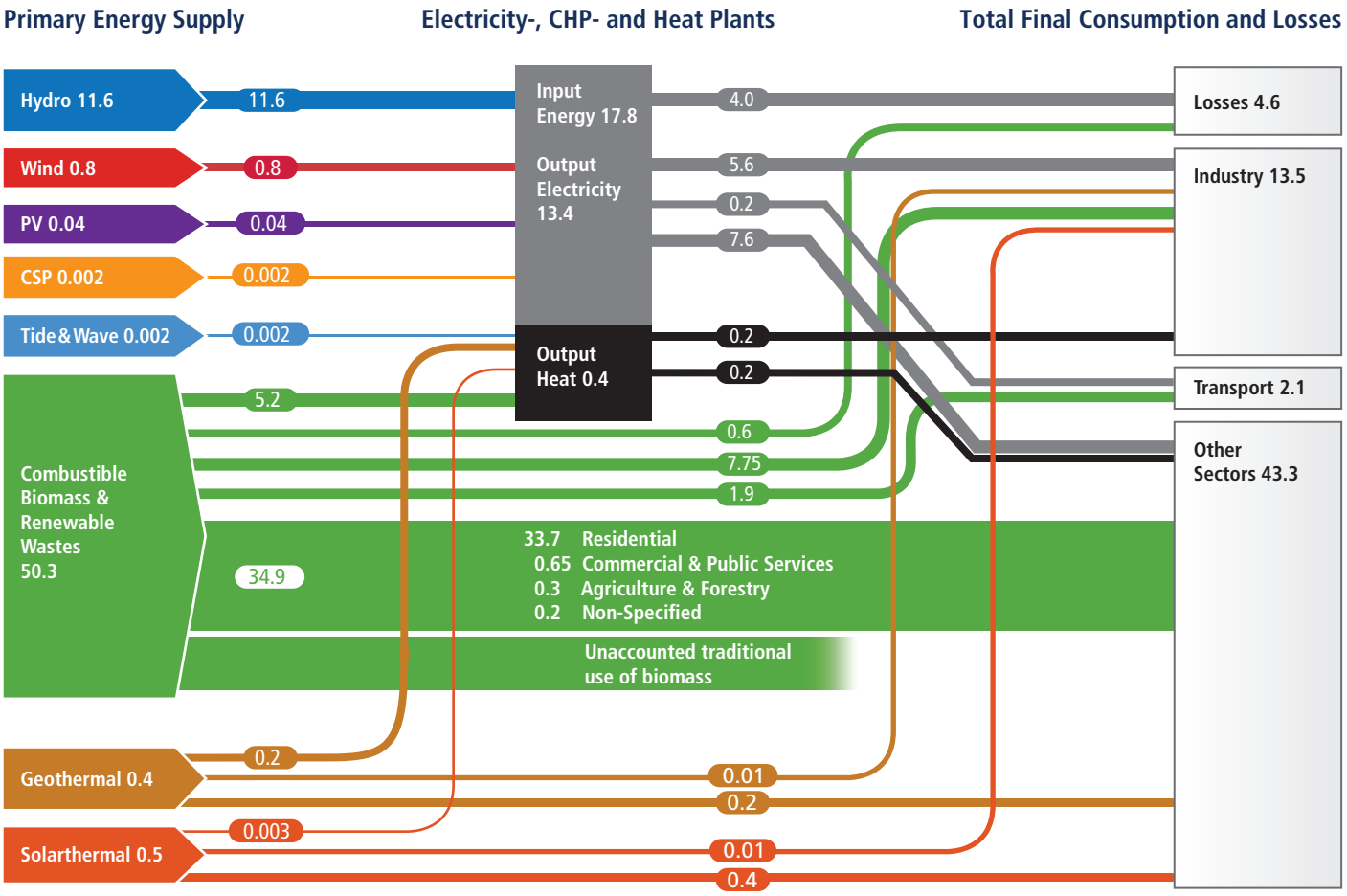


Figure TS.1.8 | Global energy flows (EJ in 2008) from primary RE through carriers to end-uses and losses (based on International Energy Agency (IEA) data). 'Other sectors' include agriculture, commercial and residential buildings, public services and non-specified other sectors. 'Transport sector' includes road transport, international aviation and international marine bunkers. [Figure 1.18]

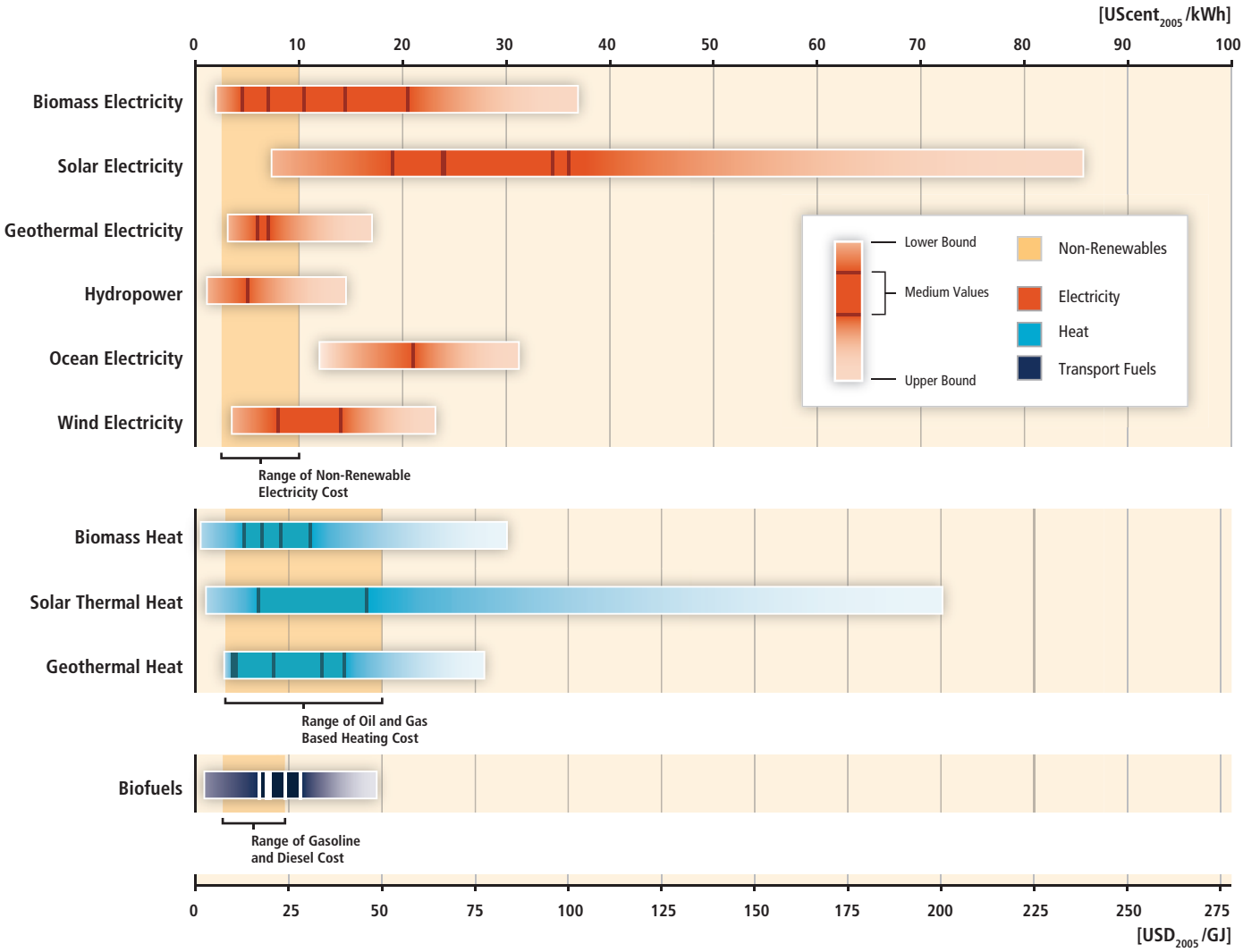
Opportunities can be defined as circumstances for action with the attribute of a chance character. In the policy context that could be the anticipation of additional benefits that may go along with the deployment of RE but that are not intentionally targeted. These include four major opportunity areas: social and economic development; energy access; energy security; and climate change mitigation and the reduction of environmental and health impacts. [1.4.1, 9.2–9.4]

Globally, per capita incomes as well as broader indicators such as the Human Development Index (HDI) are positively correlated with per capita energy use, and economic growth can be identified as the most relevant factor behind increasing energy consumption in the last decades. Economic development has been associated with a shift from direct combustion of fuels to higher quality electricity. [1.4.1, 9.3.1]

Particularly for developing countries, the link between social and economic development and the need for modern energy services is evident. Access to clean and reliable energy constitutes an important prerequisite for fundamental determinants of human development, contributing, inter alia, to economic activity, income generation, poverty alleviation, health, education and gender equality. Due to their decentralized nature, RE technologies can play an important role in fostering rural development. The creation of (new) employment opportunities is seen as a positive long-term effect of RE in both developed and developing countries. [1.4.1, 9.3.1.4, 11.3.4]

Access to modern energy services can be enhanced by RE. In 2008, 1.4 billion people around the world lacked electricity, some 85% of them in rural areas, and the number of people relying on the traditional use of biomass for cooking is estimated to be 2.7 billion. In particular, reliance on RE in rural applications, use of locally produced bioenergy to produce electricity, and access to clean cooking facilities will contribute to attainment of universal access to modern energy services. The transition to modern energy access is referred to as moving up the energy ladder and implies a progression from traditional to more modern devices/fuels that are more environmentally benign and have fewer negative health impacts. This transition is influenced by income level. [1.4.1, 9.3.2]

Energy security concerns that may be characterized as availability and distribution of resources, as well as variability and reliability of energy supply, may also be enhanced by the deployment of RE. As RE technologies help to diversify the portfolio of energy sources and to reduce the economy's



Notes: Medium values are shown for the following subcategories, sorted in the order as they appear in the respective ranges (from left to right):

Electricity	Heat	Transport Fuels
Biomass: 1. Cofiring 2. Small scale combined heat and power, CHP (Gasification internal combustion engine) 3. Direct dedicated stoker & CHP 4. Small scale CHP (steam turbine) 5. Small scale CHP (organic Rankine cycle)	**Biomass Heat:** 1. Municipal solid waste based CHP 2. Anaerobic digestion based CHP 3. Steam turbine CHP 4. Domestic pellet heating system	**Biofuels:** 1. Corn ethanol 2. Soy biodiesel 3. Wheat ethanol 4. Sugarcane ethanol 5. Palm oil biodiesel
Solar Electricity: 1. Concentrating solar power 2. Utility-scale PV (1-axis and fixed tilt) 3. Commercial rooftop PV 4. Residential rooftop PV	**Solar Thermal Heat:** 1. Domestic hot water systems in China 2. Water and space heating	
Geothermal Electricity: 1. Condensing flash plant 2. Binary cycle plant	**Geothermal Heat:** 1. Greenhouses 2. Uncovered aquaculture ponds 3. District heating 4. Geothermal heat pumps 5. Geothermal building heating	
Hydropower: 1. All types		
Ocean Electricity: 1. Tidal barrage		
Wind Electricity: 1. Onshore 2. Offshore		

The lower range of the levelized cost of energy for each RE technology is based on a combination of the most favourable input-values, whereas the upper range is based on a combination of the least favourable input values. Reference ranges in the figure background for non-renewable electricity options are indicative of the levelized cost of centralized non-renewable electricity generation. Reference ranges for heat are indicative of recent costs for oil and gas based heat supply options. Reference ranges for transport fuels are based on recent crude oil spot prices of USD 40 to 130/barrel and corresponding diesel and gasoline costs, excluding taxes.

Figure TS.1.9 | (Preceding page) Range in recent levelized cost of energy for selected commercially available RE technologies in comparison to recent non-renewable energy costs. Technology subcategories and discount rates were aggregated for this figure. For related figures with less or no such aggregation, see [1.3.2, 10.5, Annex III]. Additional information concerning the cost of non-renewable energy supply options is given in [10.5]. [Figure 10.28]

vulnerability to price volatility and redirect foreign exchange flows away from energy imports, they reduce social inequities in energy supply. Current energy supplies are dominated by fossil fuels (petroleum and natural gas) whose prices have been volatile with significant implications for social, economic and environmental sustainability in the past decades, especially for developing countries and countries with high shares of imported fuels. [1.4.1, 9.2.2, 9.3.3, 9.4.3]

Climate change mitigation is one of the key driving forces behind a growing demand for RE technologies. In addition to reducing GHG emissions, RE technologies can also offer benefits with respect to air pollution and health compared to fossil fuels. However, to evaluate the overall burden from the energy system on the environment and society, and to identify potential trade-offs and synergies, environmental impacts apart from GHG emissions and categories have to be taken into account as well. The resource may also be affected by climate change. Lifecycle assessments facilitate a quantitative comparison of 'cradle to grave' emissions across different energy technologies. Figure TS.1.10 illustrates the lifecycle structure for CO_2 emission analysis, and qualitatively indicates the relative GHG implications for RE, nuclear power and fossil fuels. [1.4.1, 9.2.2, 9.3.4, 11.3.1]

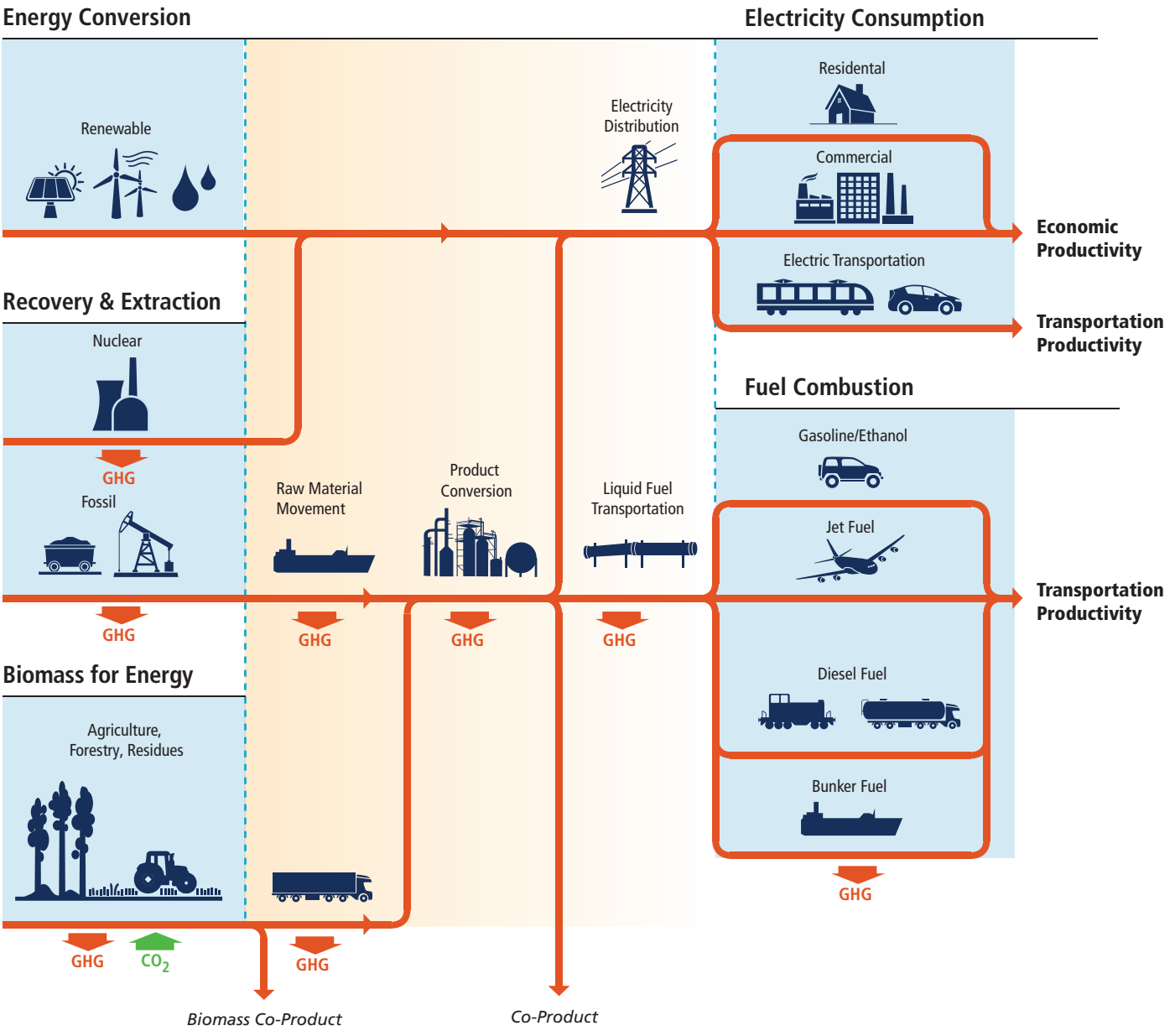


Figure TS.1.10 | Illustrative system for energy production and use illustrating the role of RE along with other production options. A systemic approach is needed to conduct lifecycle assessments. [Figure 1.22]

Traditional biomass use results in health impacts from the high concentrations of particulate matter and carbon monoxide, among other pollutants. In this context, non-combustion-based RE power generation technologies have the potential to significantly reduce local and regional air pollution and lower associated health impacts compared to fossil-based power generation. Improving traditional biomass use can reduce negative sustainable development (SD) impacts, including local and indoor air pollution, GHG emissions, deforestation and forest degradation. [1.4.1, 2.5.4, 9.3.4, 9.3.4, 9.4.2]

Impacts on water resources from energy systems strongly depend on technology choice and local conditions. Electricity production with wind and solar PV, for example, requires very little water compared to thermal conversion technologies, and has no impacts on water or air quality. Limited water availability for cooling thermal power plants decreases their efficiency, which can affect plants operating on coal, biomass, gas, nuclear and concentrating solar power. There have been significant power reductions from nuclear and coal plants during drought conditions in the USA and France in recent years. Surface-mined coal in particular produces major alterations of land; coal mines can create acid mine drainage and the storage of coal ash can contaminate surface and ground waters. Oil production and transportation have led to significant land and water spills. Most renewable technologies produce lower conventional air and water pollutants than fossil fuels, but may require large amounts of land as, for example, reservoir-based hydropower, wind and biofuels. Since a degree of climate change is now inevitable, adaptation to climate change is also an essential component of sustainable development. [1.4.1, 9.3.4]

Barriers are defined in AR4 as "any obstacle to reaching a goal, adaptation or mitigation potential that can be overcome or attenuated by a policy programme or measure". The various barriers to RE use can be categorized as market failures and economic barriers, information and awareness barriers, socio-cultural barriers and institutional and policy barriers. Policies and financing mechanisms to overcome those barriers are extensively assessed in Chapter 11. When a barrier is particularly pertinent to a specific technology, it is examined in the appropriate 'technology' chapters of this report [Chapters 2–7]. A summary of barriers and potential policy instruments to overcome these barriers is shown in Table 1.5 of Chapter 1. Market failures are often due to external effects. These arise from a human activity, when agents responsible for the activity do not take full account of the activity's impact on others. Another market failure is rent appropriation by monopolistic entities. In the case of RE deployment, these market failures may appear as underinvestment in invention and innovation in RE technologies, un-priced environmental impacts and risks of energy use as well as the occurrence of monopoly (one seller) or monopsony (one buyer) powers in energy markets. Other economic barriers include up-front investment cost and financial risks, the latter sometimes due to immaturity of the technology. [1.4.2, 1.5, 11.4]

Informational and awareness barriers include deficient data about natural resources, often due to site-specificity (e.g., local wind regimes), lack of skilled human resources (capacity) especially in rural areas of developing countries as well as the lack of public and institutional awareness. Socio-cultural barriers are intrinsically linked to societal and personal values and norms that affect the perception and acceptance of RE and may be slow to change. Institutional and policy barriers include existing industry, infrastructure and energy market regulation. Despite liberalization of energy markets in several countries in the 1990s, current industry structures are still highly concentrated and regulations governing energy businesses in many countries are still designed around monopoly or near-monopoly providers. Technical regulations and standards have evolved under the assumption that energy systems are large and centralized, and of high power density and/or high voltage. Intellectual property rights, tariffs in international trade and lack of allocation of government financial support may constitute further barriers. [1.4.2]

Issues are not readily amenable to policies and programmes. An issue is that the resource may be too small to be useful at a particular location or for a particular purpose. Some renewable resources such as wind and solar energy are variable and may not always be available for dispatch when needed. Furthermore, the energy density of many renewable sources is relatively low, so that their power levels may be insufficient on their own for some purposes such as very large-scale industrial facilities. [1.4.3]

1.5 Role of policy, research and development, deployment and implementation strategies

An increasing number and variety of RE policies—motivated by a variety of factors—have driven escalated growth in RE technologies in recent years. For policymakers wishing to support the development and deployment of RE technologies for climate change mitigation goals, it is critical to consider the potential of RE to reduce emissions from a lifecycle perspective, as addressed in each technology chapter of this report. Various policies have been designed to address every stage of the development chain involving research and development (R&D), testing, deployment, commercialization, market preparation, market penetration, maintenance and monitoring, as well as integration into the existing system. [1.4.1, 1.4.2, 9.3.4, 11.1.1, 11.2, 11.4, 11.5]

Two key market failures are typically addressed: 1) the external cost of GHG emissions are not priced at an appropriate level; and 2) deployment of low-carbon technologies such as RE create benefits to society beyond those captured by the innovator, leading to under-investment in such efforts. [1.4, 1.5, 11.1, 11.4]

Policy- and decision-makers approach the market in a variety of ways. No globally-agreed list of RE policy options or groupings exists. For

the purpose of simplification, R&D and deployment policies have been organized within the following categories in this report: [1.5.1, 11.5]

- **Fiscal incentive:** actors (individuals, households, companies) are granted a reduction of their contribution to the public treasury via income or other taxes;
- **Public finance:** public support for which a financial return is expected (loans, equity) or financial liability is incurred (guarantee); and
- **Regulation:** rule to guide or control conduct of those to whom it applies.

R&D, innovation, diffusion and deployment of new low-carbon technologies create benefits to society beyond those captured by the innovator, resulting in under-investment in such efforts. Thus, government R&D can play an important role in advancing RE technologies. Public R&D investments are most effective when complemented by other policy instruments, particularly RE deployment policies that simultaneously enhance demand for new RE technologies. [1.5.1, 11.5.2]

Some policy elements have been shown to be more effective and efficient in rapidly increasing RE deployment, but there is no one-size-fits-all policy. Experience shows that different policies or combinations of policies can be more effective and efficient depending on factors such as the level of technological maturity, affordable capital, ease of integration into the existing system and the local and national RE resource base:

- Several studies have concluded that some feed-in tariffs have been effective and efficient at promoting RE electricity, mainly due to the combination of long-term fixed price or premium payments, network connections, and guaranteed purchase of all RE electricity generated. Quota policies can be effective and efficient if designed to reduce risk; for example, with long-term contracts.
- An increasing number of governments are adopting fiscal incentives for RE heating and cooling. Obligations to use RE heat are gaining attention for their potential to encourage growth independent of public financial support.
- In the transportation sector, RE fuel mandates or blending requirements are key drivers in the development of most modern biofuel industries. Other policies include direct government payments or tax reductions. Policies have influenced the development of an international biofuel and pellet trade.

One important challenge will be finding a way for RE and carbon-pricing policies to interact such that they take advantage of synergies rather than tradeoffs. In the long-term, support for technological learning in RE can help reduce costs of mitigation, and putting a price on carbon can increase the competitiveness of RE. [1.5.1, 11.1, 11.4, 11.5.7]

RE technologies can play a greater role if they are implemented in conjunction with 'enabling' policies. A favourable, or 'enabling', environment for RE can be created by addressing the possible interactions of a given policy with other RE policies as well as with other non-RE policies and the existence of an 'enabling' environment can increase the efficiency and effectiveness of policies to promote RE. Since all forms of RE capture and production involve spatial considerations, policies need to consider land use, employment, transportation, agricultural, water, food security and trade concerns, existing infrastructure and other sectoral specifics. Government policies that complement each other are more likely to be successful. [1.5.2, 11.6]

Advancing RE technologies in the electric power sector, for example, will require policies to address their integration into transmission and distribution systems both technically [Chapter 8] and institutionally [Chapter 11]. The grid must be able to handle both traditional, often more central, supply as well as modern RE supply, which is often variable and distributed. [1.5.2, 11.6.5]

In the transport sector, infrastructure needs for biofuels, recharging hydrogen, battery or hybrid electric vehicles that are 'fuelled' by the electric grid or from off-grid renewable electrical production need to be addressed.

If decision makers intend to increase the share of RE and, at the same time, to meet ambitious climate mitigation targets, then long-standing commitments and flexibility to learn from experience will be critical. To achieve international GHG concentration stabilization levels that incorporate high shares of RE, a structural shift in today's energy systems will be required over the next few decades. The available time span is restricted to a few decades and RE must develop and integrate into a system constructed in the context of an existing energy structure that is very different from what might be required under higher-penetration RE futures. [1.5.3, 11.7]

A structural shift towards a world energy system that is mainly based on RE might begin with a prominent role for energy efficiency in combination with RE. Additional policies are required that extend beyond R&D to support technology deployment; the creation of an enabling environment that includes education and awareness raising; and the systematic development of integrative policies with broader sectors, including agriculture, transportation, water management and urban planning. The appropriate and reliable mix of instruments is even more important where energy infrastructure is not yet developed and energy demand is expected to increase significantly in the future. [1.2.5, 1.5.3, 11.7, 11.6, 11.7]

2. Bioenergy

2.1 Introduction to biomass and bioenergy

Bioenergy is embedded in complex ways in global biomass systems for food, fodder and fibre production and for forest products as well as in wastes and residue management. Perhaps most importantly, bioenergy plays an intimate and critical role in the daily livelihoods of billions of people in developing countries. Figure TS.2.1 shows the types of biomass used for bioenergy in developing and developed countries. Expanding bioenergy production significantly will require sophisticated land and water use management; global feedstock productivity increases for food, fodder, fibre, forest products and energy; substantial conversion technology improvements; and a refined understanding of the complex social, energy and environmental interactions associated with bioenergy production and use.

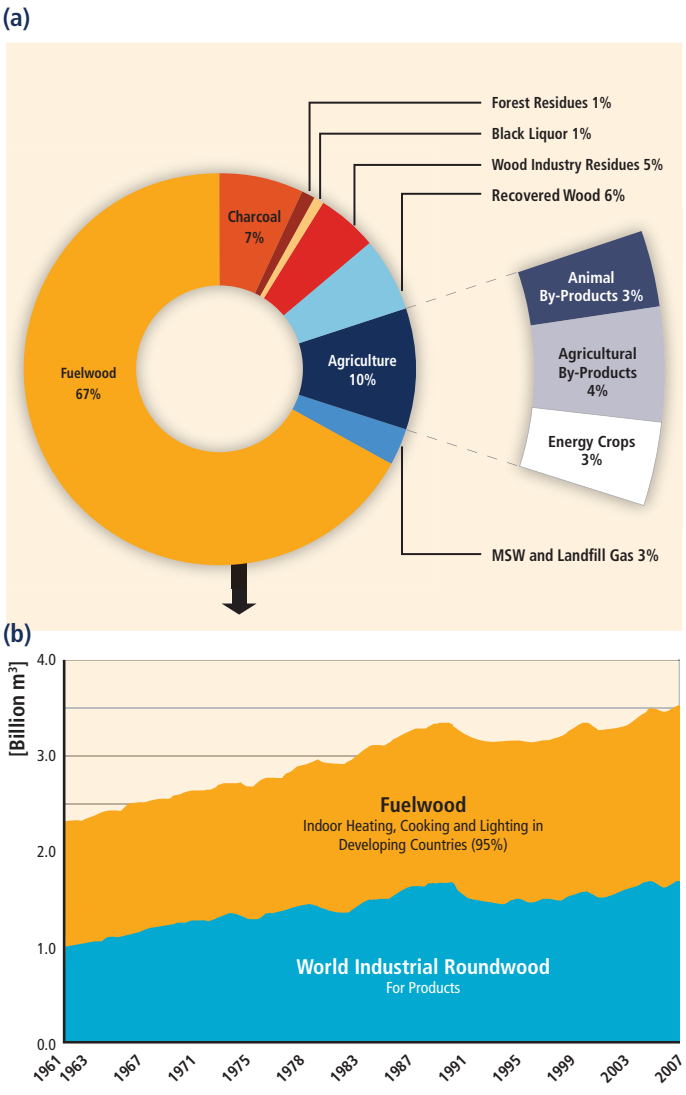


Figure TS.2.1 | (a) Shares of global primary biomass sources for energy; and (b) fuelwood used in developing countries parallels world industrial roundwood[1] production levels. [Figure 2.1]

Note: 1. Roundwood products are saw logs and veneer logs for the forest products industry and wood chips that are used for making pulpwood used in paper, newsprint and Kraft paper. In 2009, reflecting the downturn in the economy, there was a decline to 3.25 (total) and 1.25 (industrial) billion m^3.

In 2008, biomass provided about 10% (50.3 EJ/yr) of the global primary energy supply (see Table TS.2.1). Major biomass uses fall into two broad categories:

- Low-efficiency traditional biomass[7] such as wood, straws, dung and other manures are used for cooking, lighting and space heating, generally by the poorer populations in developing countries. This biomass is mostly combusted, creating serious negative impacts on health and living conditions. Increasingly, charcoal is becoming secondary energy carrier in rural areas with opportunities to create productive chains. As an indicator of the magnitude of traditional biomass use, Figure TS.2.1(b) illustrates that the global primary energy supply from traditional biomass parallels the world's industrial wood production. [2.5.4, 2.3, 2.3.2.2, 2.4.2, 2.5.7]

- High-efficiency modern bioenergy uses more convenient solids, liquids and gases as secondary energy carriers to generate heat, electricity, combined heat and power (CHP), and transport fuels for various sectors. Liquid biofuels include ethanol and biodiesel for global road transport and some industrial uses. Biomass derived gases, primarily methane, from anaerobic digestion of agricultural residues and municipal solid waste (MSW) treatment are used to generate electricity, heat or both. The most important contribution to these energy services is based on solids, such as chips, pellets, recovered wood previously used and others. Heating includes space and hot water heating such as in district heating systems. The estimated total primary biomass supply for modern bioenergy is 11.3 EJ/yr and the secondary energy delivered to end-use consumers is roughly 6.6 EJ/yr. [2.3.2, 2.4, 2.4.6, 2.6.2]

Additionally, the industry sector, such as the pulp and paper, forestry, and food industries, consumes approximately 7.7 EJ of biomass annually, primarily as a source for industrial process steam. [2.7.2, 8.3.4]

2.2 Bioenergy resource potential

The inherent complexity of biomass resources makes the assessment of their combined technical potential controversial and difficult to characterize. Estimates in the literature range from zero technical potential (no biomass available for energy production) to a maximum theoretical potential of

7 Traditional biomass is defined as biomass consumption in the residential sector in developing countries and refers to the often unsustainable use of wood, charcoal, agricultural residues and animal dung for cooking and heating. All other biomass use is defined as modern biomass; this report further differentiates between highly efficient modern bioenergy and industrial bioenergy applications with varying degrees of efficiency. [Annex I] The renewability and sustainability of biomass use is primarily discussed in Sections 2.5.4 and 2.5.5, respectively (see also Section 1.2.1 and Annex I).

Table TS.2.1 | Examples of traditional and select modern biomass energy flows in 2008; see Table 2.1 for notes on specific flows and accounting challenges. [Table 2.1]

Type	Approximate Primary Energy (EJ/yr)	Approximate Average Efficiency (%)	Approximate Secondary Energy (EJ/yr)
Traditional Biomass			
Accounted for in IEA energy balance statistics	30.7	10–20	3–6
Estimated for informal sectors (e.g., charcoal) [2.1]	6–12		0.6–2.4
Total Traditional Biomass	37–43		3.6–8.4
Modern Bioenergy			
Electricity and CHP from biomass, MSW, and biogas	4.0	32	1.3
Heat in residential, public/commercial buildings from solid biomass and biogas	4.2	80	3.4
Road Transport Fuels (ethanol and biodiesel)	3.1	60	1.9
Total Modern Bioenergy	11.3	58	6.6

about 1,500 EJ from global modelling efforts. Figure TS.2.2 presents a summary of technical potentials found in major studies, including data from the scenario analysis of Chapter 10. To put biomass technical potential for energy in perspective, global biomass used for energy currently amounts to approximately 50 EJ/yr and all harvested biomass used for food, fodder and fibre, when expressed in a caloric equivalent, contains about 219 EJ/yr (2000 data); nearly the entire current global biomass harvest would be required to achieve a 150 EJ/yr deployment level of bioenergy by 2050. [2.2.1]

An assessment of technical potential based on an analysis of the literature available in 2007 and additional modelling studies arrived at the conclusion that the upper bound of the technical potential in 2050 could amount to about 500 EJ, shown in the stacked bar of Figure TS.2.2. The study assumes policy frameworks that secure good governance of land use and major improvements in agricultural management and takes into account water limitations, biodiversity protection, soil degradation and competition with food. Residues originating from forestry, agriculture and organic wastes (including the organic fraction of MSW, dung, process residues, etc.) are estimated to amount to 40 to 170 EJ/yr, with a mean estimate of around 100 EJ/yr. This part of the technical potential is relatively certain, but competing applications may push net availability for energy applications to the lower end of the range. Surplus forestry products other than from forestry residues have an additional technical potential

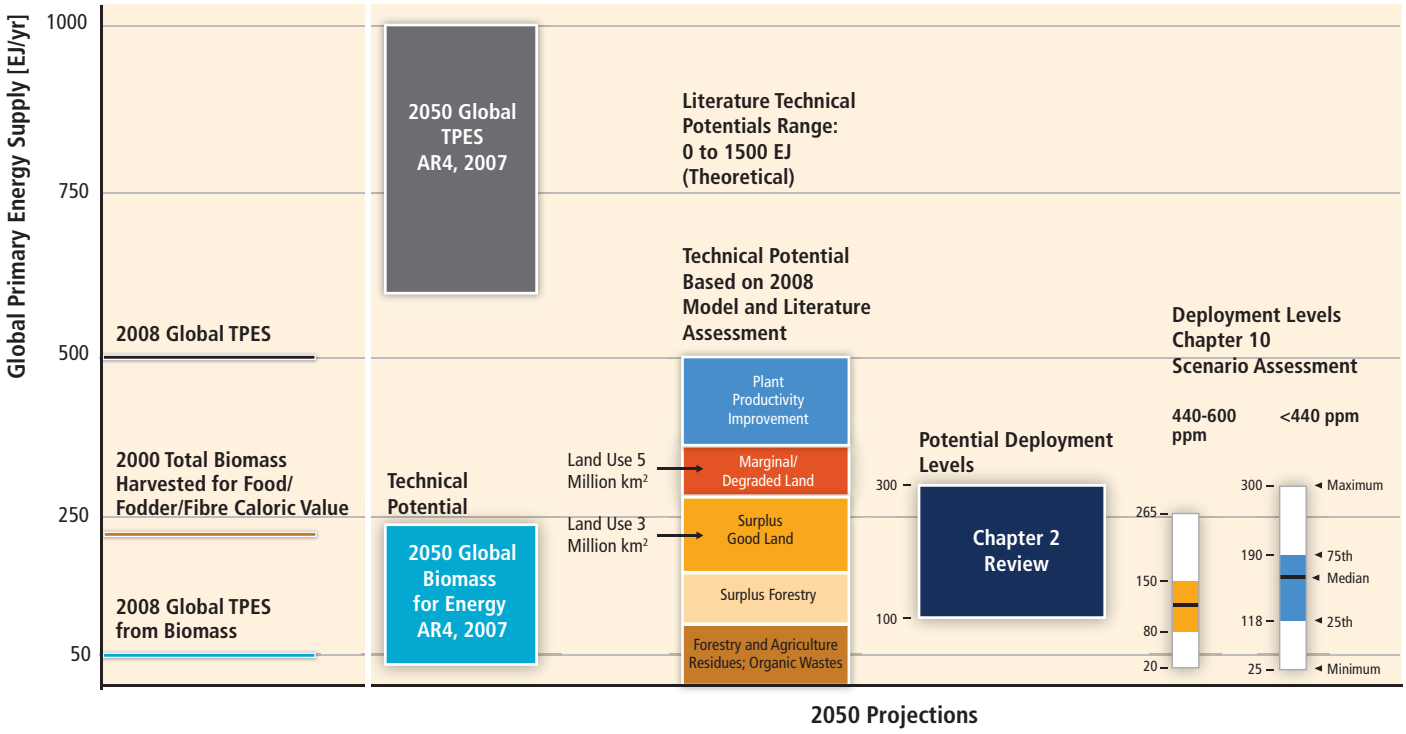


Figure TS.2.2 | A summary of major 2050 projections of global terrestrial biomass technical potential for energy and possible deployment levels compared to 2008 global total primary energy and biomass supply as well as the equivalent energy of world total biomass harvest. [Figure 2.25]

of about 60 to 100 EJ/yr. A lower estimate for energy crop production on possible surplus, good quality agricultural and pasture lands is 120 EJ/yr. The potential contribution of water-scarce, marginal and degraded lands could amount to up to an additional 70 EJ/yr. This would comprise a large area where water scarcity imposes limitations and soil degradation is more severe. Assuming strong learning in agricultural technology for improvements in agricultural and livestock management would add 140 EJ/yr. The three categories added together lead to a technical potential from this analysis of up to about 500 EJ/yr (Figure TS 2.2).

Developing this technical potential would require major policy efforts, therefore, actual deployment would likely be lower and the biomass resource base will be largely constrained to a share of the biomass residues and organic wastes, some cultivation of bioenergy crops on marginal and degraded lands, and some regions where biomass is a cheaper energy supply option compared to the main reference options (e.g., sugarcane-based ethanol production). [2.2.2, 2.2.5, 2.8.3]

The expert review conclusions based on available scientific literature are: [2.2.2–2.2.4]

- Important factors include (1) population and economic/technology development, food, fodder and fibre demand (including diets), and developments in agriculture and forestry; (2) climate change impacts on future land use including its adaptation capability; and (3) the extent of land degradation, water scarcity and biodiversity and nature conservation requirements.

- Residue flows in agriculture and forestry and unused (or extensively used thus becoming marginal/degraded) agricultural land are important sources for expansion of biomass production for energy, both in the near- and longer term. Biodiversity-induced limitations and the need to ensure maintenance of healthy ecosystems and avoidance of soil degradation set limits on residue extraction in agriculture and forestry.

- The cultivation of suitable plants (e.g., perennial crops or woody species) can allow for higher technical potentials by making it possible to produce bioenergy on lands less suited for conventional food crops—also when considering that the cultivation of conventional crops on such lands can lead to soil carbon emissions.

- Multi-functional land use systems with bioenergy production integrated into agriculture and forestry systems could contribute to biodiversity conservation and help restore/maintain soil productivity and healthy ecosystems.

- Regions experiencing water scarcity may have limited production. The possibility that conversion of lands to biomass plantations reduces downstream water availability needs to be considered. The use of suitable drought-tolerant energy crops can help adaptation in water-scarce situations. Assessments of biomass resource potentials need to more carefully consider constraints and opportunities in relation to water availability and competing uses.

Following the restrictions outlined above, the expert review concludes that potential deployment levels of biomass for energy by 2050 could be in the range of 100 to 300 EJ. However, there are large uncertainties in this potential, such as market and policy conditions, and there is strong dependence on the rate of improvements in the agricultural sector for food, fodder and fibre production and forest products. One example from the literature suggests that bioenergy can expand from around 100 EJ/yr in 2020 to 130 EJ/yr in 2030, and could reach 184 EJ/yr in 2050. [2.2.1, 2.2.2, 2.2.5]

To reach the upper range of the expert review deployment level of 300 EJ/yr (shown in Figure TS.2.2) would require major policy efforts, especially targeting improvements and efficiency increases in the agricultural sector and good governance, such as zoning, of land use.

2.3 Bioenergy technology and applications

Commercial bioenergy technology applications include heat production—with scales ranging from home cooking with stoves to large district heating systems; power generation from biomass via combustion, CHP, or co-firing of biomass and fossil fuels; and first-generation liquid biofuels from oil crops (biodiesel) and sugar and starch crops (ethanol) as shown in the solid lines of Figure TS.2.3. The figure also illustrates developing feedstocks (e.g., aquatic biomass), conversion routes and products.[8] [2.3, 2.6, 2.7, 2.8]

Section 2.3 addresses key issues related to biomass production and the logistics of supplying feedstocks to the users (individuals for traditional and modern biomass, firms that use and produce secondary energy products or, increasingly, an informal sector of production and distribution of charcoal). The conversion technologies that transform biomass to convenient secondary energy carriers use thermochemical, chemical or biochemical processes, and are summarized in Sections 2.3.1–2.3.3 and 2.6.1–2.6.3. Chapter 8 addresses energy product integration with the existing and evolving energy systems. [2.3.1–2.3.3, 2.6.1–2.6.3]

2.4 Global and regional status of markets and industry deployment

A review of biomass markets and policy shows that bioenergy has seen rapid developments in recent years such as the use of modern biomass for liquid and gaseous energy carriers (an increase of 37% from 2006 to 2009). Projections from the IEA, among others, count on biomass delivering a substantial increase in the share of RE, driven in some cases by national targets. International trade in biomass and biofuels has

8 Biofuels produced via new processes are also called advanced or next-generation biofuels, e.g. lignocellulosic.

also become much more important over recent years, with roughly 6% (reaching levels of up to 9% in 2008) of biofuels (ethanol and biodiesel only) traded internationally and one-third of all pellet production for energy use in 2009. The latter facilitated both increased utilization of biomass in regions where supplies were constrained as well as mobilized resources from areas lacking demand. Nevertheless, many barriers remain in developing effective commodity trading of biomass and biofuels that, at the same time, meets sustainability criteria. [2.4.1, 2.4.4]

In many countries, the policy context for bioenergy and, in particular, biofuels, has changed rapidly and dramatically in recent years. The debate surrounding biomass in the food versus fuel competition, and growing concerns about other conflicts, have resulted in a strong push for the development and implementation of sustainability criteria and frameworks as well as changes in target levels and schedules for bioenergy and biofuels. Furthermore, support for advanced biorefinery and next-generation biofuel[9] options is driving bioenergy to be more sustainable. [2.4.5]

Persistent and stable policy support has been a key factor in building biomass production capacity and markets, requiring infrastructure and conversion capacity that gets more competitive over time. These conditions have led to the success of the Brazilian programme to the point that ethanol production costs are now lower than those for gasoline. Sugarcane fibre bagasse generates heat and electricity, with an energy portfolio mix that is substantially based on RE and that minimizes foreign oil imports. Sweden and Finland also have shown significant growth in renewable electricity and in management of integrated resources, which steadily resulted in innovations such as industrial symbiosis of collocated industries. The USA has been able to quickly ramp up production with alignment of national and sub-national policies for power in the 1980s to 1990s and for biofuels in the 1990s to the present, as

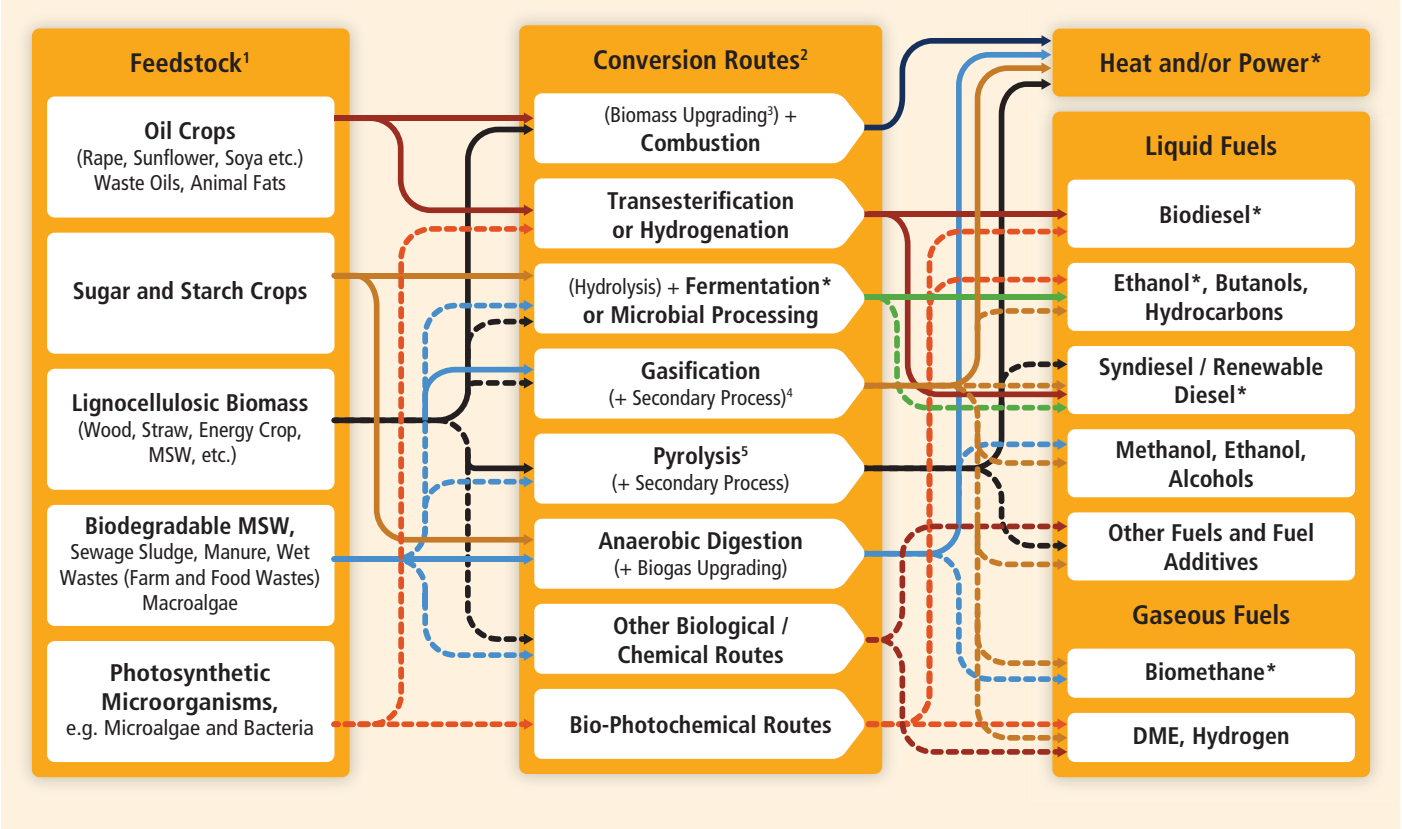


Figure TS.2.3 | Schematic view of the variety of commercial (solid lines) and developing bioenergy routes (dotted lines) from biomass feedstocks through thermochemical, chemical, biochemical and biological conversion routes to heat, power, CHP and liquid or gaseous fuels. Commercial products are marked with an asterisk. [Figure 2.2, 2.1.1]

Notes: 1. Parts of each feedstock could be used in other routes. 2. Each route can also make coproducts. 3. Biomass upgrading includes densification processes (such as pelletization, pyrolysis, torrefaction, etc.). 4. Anaerobic digestion processes to various gases which can be upgraded to biomethane, essentially methane, the major component of natural gas. 5. Could be other thermal processing routes such as hydrothermal, liquefaction, etc. Other chemical routes include aqueous phase reforming. DME=dimethyl ether.

9 Biofuels produced by new processes (e.g. from lignocellulosic biomass) are also called advanced biofuels.

petroleum prices and instability in key producing countries increased and to foster rural development and a secure energy supply. [2.4.5]

Countries differ in their priorities, approaches, technology choices and support schemes for further developing bioenergy. Market and policy complexities emerge when countries seek to balance specific priorities in agriculture and land use, energy policy and security, rural development and environmental protection while considering their unique stage of development, geographic access to resources, and availability and costs of resources. [2.4.5, 2.4.7]

One overall trend is that as policies surrounding bioenergy and biofuels become more holistic, sustainability becomes a stronger criterion at the starting point. This is true for the EU, the USA and China, but also for many developing countries such as Mozambique and Tanzania. This is a positive development, but by no means settled. The registered 70 initiatives worldwide by 2009 to develop and implement sustainability frameworks and certification systems for bioenergy and biofuels, as well as agriculture and forestry, can lead to a fragmentation of efforts. The need for harmonization and international and multilateral collaboration and dialogue are widely stressed. [2.4.6, 2.4.7]

2.5 Environmental and social impacts

Bioenergy production has complex interactions with other social and environmental systems. Concerns—ranging from health and poverty to biodiversity and water scarcity and quality—vary depending upon many factors including local conditions, technology and feedstock choices, sustainability criteria design, and the design and implementation of specific projects. Perhaps most important is the overall management and governance of land use when biomass is produced for energy purposes on top of meeting food and other demands from agricultural, livestock and fibre production. [2.5]

Direct land use change (dLUC) occurs when bioenergy feedstock production modifies an existing land use, resulting in a change in above- and below-ground carbon stocks. Indirect LUC (iLUC) occurs when a change in production level of an agricultural product (i.e., a reduction in food or feed production induced by agricultural land conversion to produce a bioenergy feedstock) leads to a market-mediated shift in land management activities (i.e., dLUC) outside the region of primary production expansion. iLUC is not directly observable and is complex to model and difficult to attribute to a single cause as multiple actors, industry, countries, policies and markets dynamically interact. [2.5.3, 9.3.4.1]

In cases where increases in land use due to biomass production for bioenergy are accompanied by improvements in agricultural management (e.g., intensification of perennial crop and livestock production in degraded lands), undesirable (i)LUC effects can be avoided. If left unmanaged, conflicts can emerge. The overall performance of bioenergy production systems is therefore interlinked with management of land and water resources use. Trade-offs between those dimensions exist and need to be managed through appropriate strategies and decision making (Figure TS.2.4). [2.5.8]

Most bioenergy systems can contribute to climate change mitigation if they replace traditional fossil fuel use and if the bioenergy production emissions are kept low. High nitrous oxide emissions from feedstock production and use of fossil fuels (especially coal) in the biomass conversion process can strongly impact the GHG savings. Options to lower GHG emissions include best practices in fertilizer management, process integration to minimize losses, utilization of surplus heat, and use of biomass or other low-carbon energy sources as process fuel. However, the displacement efficiency (GHG emissions relative to carbon in biomass) can be low when additional biomass feedstock is used for process energy in the conversion process - unless the displaced energy is generated from coal. If the biomass feedstock can produce both liquid fuel and electricity, the displacement efficiency can be high. [2.5.1–2.5.3]

There are different methods to evaluate the GHG emissions of key first- and second-generation biofuel options. Well-managed bioenergy projects can reduce GHG emissions significantly compared to fossil alternatives, especially for lignocellulosic biomass used in power generation and heat, and when that feedstock is commercially available. Advantages can be achieved by making appropriate use of agricultural residues and organic wastes, principally animal residues. Most current biofuel production systems have significant reductions in GHG emissions relative to the fossil fuels displaced, if no iLUC effects are considered. Figure TS.2.5 shows a snapshot of the ranges of lifecycle GHG emissions associated with various energy generation technologies from modern biomass compared to the respective fossil reference systems commonly used in these sectors. Commercial chains such as biomass direct power, anaerobic digestion biogas to power, and very efficient modern heating technologies are shown on the right side and provide significant GHG savings compared to the fossil fuels. More details of the GHG meta-analysis study comparing multiple biomass electricity generating technologies are available in Figure 2.11, which shows that the majority of lifecycle GHG emission estimates cluster between about 16 and 74 g CO_2eq/kWh.

The transport sector is addressed for today's and tomorrow's technologies. For light-duty vehicle applications, sugarcane today and lignocellulosic feedstocks in the medium term can provide significant emissions savings relative to gasoline. In the case of diesel, the range of GHG emissions depends on the feedstock carbon footprint. Biogas-derived biomethane also offers emission reductions (compared to natural gas) in the transport sector. [2.5.2, 9.3.4.1]

When land high in carbon (notably forests and especially drained peat soil forests) is converted to bioenergy production, upfront emissions may cause a time lag of decades to centuries before net emission savings are achieved. In contrast, the establishment of bioenergy plantations on marginal and degraded soils can lead to assimilation of CO_2 into soils

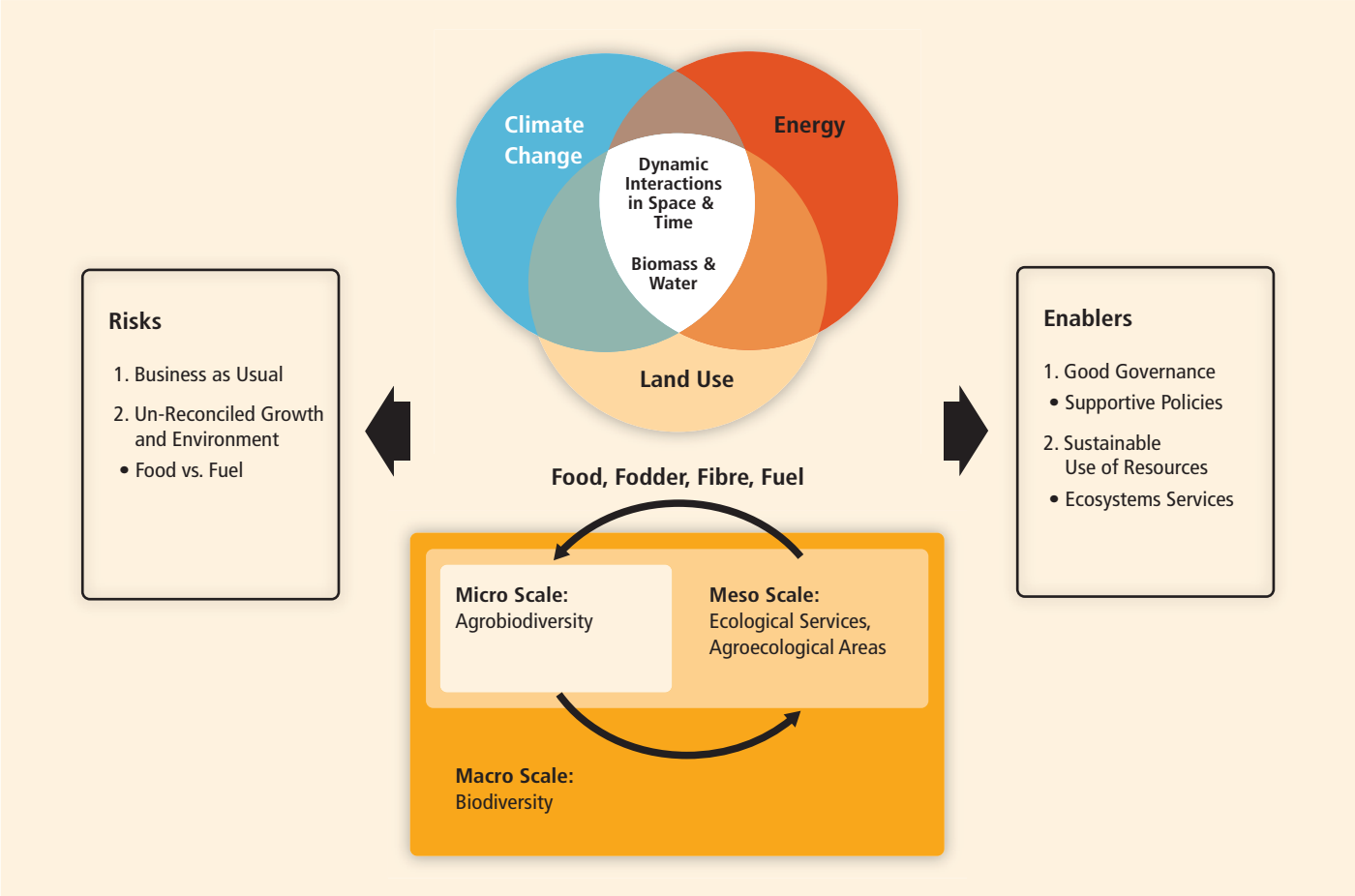


Figure TS.2.4 | The complex dynamic interactions among society, energy and the environment associated with bioenergy. Approaches of uncoordinated production of food and fuel that emerge in poor governance of land use are examples of business as usual practices. [Figure 2.15]

and aboveground biomass and when harvested for energy production it will replace fossil fuel use. Appropriate governance of land use (e.g., proper zoning) and choice of biomass production systems are crucial to achieve good performance. The use of post-consumer organic waste and by-products from the agricultural and forest industries does not cause LUC if these biomass sources were not utilized for alternative purposes. [2.5.3]

Lignocellulosic feedstocks for bioenergy can decrease the pressure on prime cropland. Stimulating increased productivity in all forms of land use reduces the LUC pressure. [2.2.4.2, 2.5.2]

The assessment of available iLUC literature indicates that initial models were lacking in geographic resolution leading to higher proportions of assignments of land use to deforestation. While a 2008 study claimed an iLUC factor of 0.8 (losing 0.8 ha of forest land for each hectare of land used for bioenergy) later (2010) studies that coupled macro-economic to biophysical models reported a reduction to 0.15 to 0.3. Major factors are the rate of improvement in agricultural and livestock management and the rate of deployment of bioenergy production. The results from increased model sophistication and improved data on the actual dynamics of land distribution in the major biofuel producing countries are leading to lower overall LUC impacts, but still with wide uncertainties. All studies acknowledge that land use management at large is a key. Research to improve LUC assessment methods and increase the availability and quality of information on current land use, bioenergy-derived products and other potential LUC drivers can facilitate evaluation and provide tools to mitigate the risk of bioenergy-induced LUC. [2.5.3, 9.3.4.1]

Air pollution effects of bioenergy depend on both the bioenergy technology (including pollution control technologies) and the displaced energy technology. Improved biomass cookstoves for traditional biomass use can provide large and cost-effective mitigation of GHG emissions with substantial co-benefits for the 2.7 billion people that rely on traditional biomass for cooking and heating in terms of health and quality of life. [2.5.4, 2.5.5]

Without proper management, increased biomass production could come with increased competition for water in critical areas, which is highly undesirable. Water is a critical issue that needs to be better analyzed at a regional level to understand the full impact of changes in vegetation and land use management. Recent studies indicate that considerable improvements can be made in water use efficiency in conventional

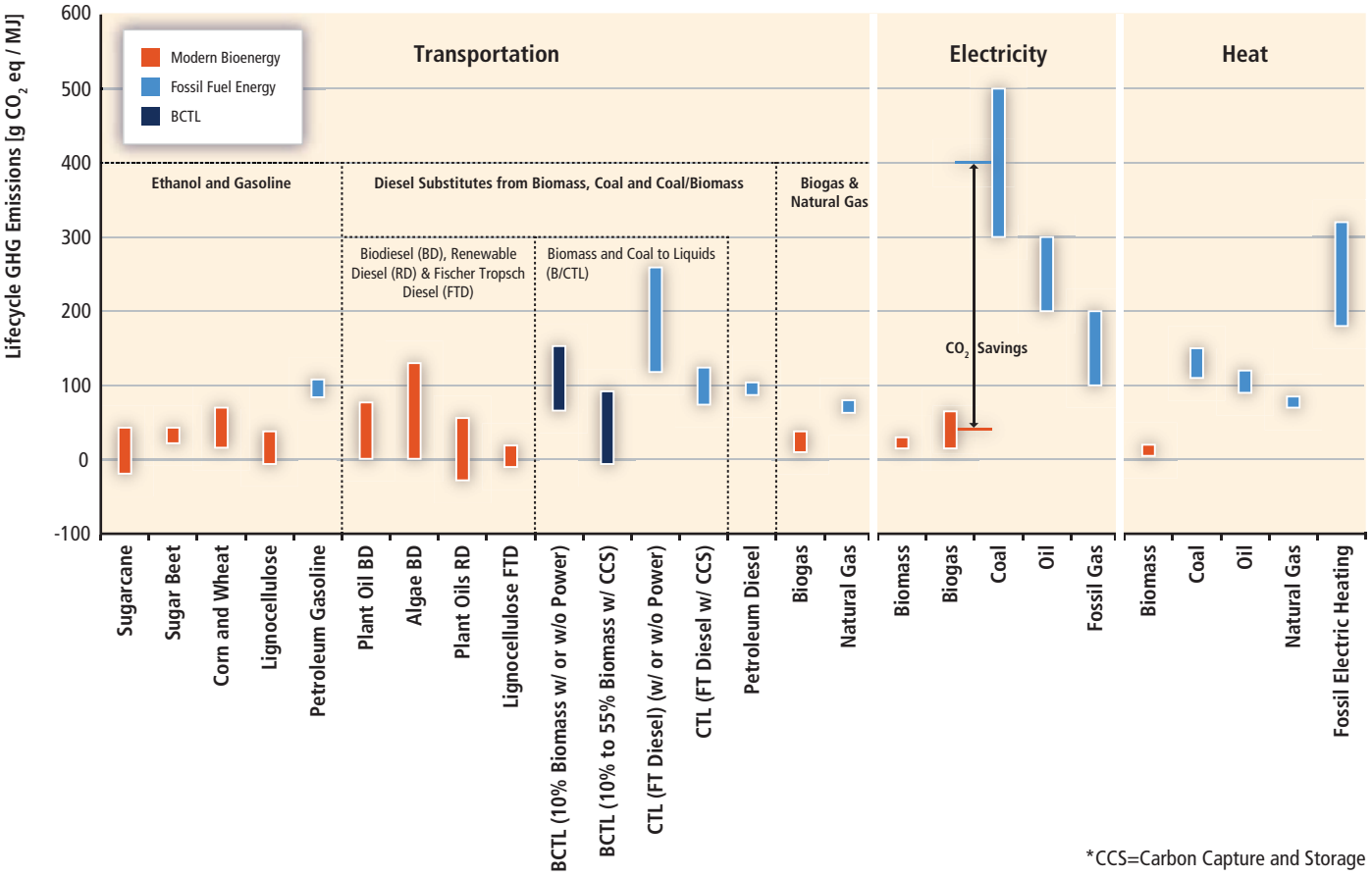


Figure TS.2.5 | Ranges of GHG emissions per unit energy output (MJ) from major modern bioenergy chains compared to current and selected advanced fossil fuel energy systems (land use-related net changes in carbon stocks and land management impacts are excluded). Commercial and developing (e.g., algae biofuels, Fischer-Tropsch) systems for biomass and fossil technologies are illustrated. When CCS technologies are developed, capture and sequestration of biomass carbon emissions can compensate fossil fuel-based energy production emissions. [Figure 2.10]

agriculture, bioenergy crops and, depending on location and climate, perennial cropping systems by improving water retention and lowering direct evaporation from soils. [2.5.5, 2.5.5.1]

Similar remarks can be made with respect to biodiversity, although more scientific uncertainty exists due to ongoing debates on methods of biodiversity impact assessment. Clearly, development of large-scale monocultures at the expense of natural areas is detrimental for biodiversity, as highlighted in the 2007 Convention on Biological Diversity. However, integrating different perennial grasses and woody crops into agricultural landscapes can also increase soil carbon and productivity, reduce shallow landslides and local 'flash floods', provide ecological corridors, reduce wind and water erosion and reduce sediment and nutrients transported into river systems. Forest biomass harvesting can improve conditions for replanting, improve productivity and growth of the remaining stand and reduce wildfire risk. [2.5.5.3]

Social impacts associated with large expansions in bioenergy production are very complex and difficult to quantify. The demand for biofuels represents one driver of demand growth in the agricultural and forestry sectors and therefore contributes to global food price increases. Even considering the benefit of increased prices to poor farmers, higher food prices adversely affect poverty levels, food security, and malnourishment of children. On the other hand, biofuels can also provide opportunities for developing countries to make progress in rural development and agricultural growth, especially when this growth is economically sustainable. In addition, expenditures on imported fossil fuels can be reduced. However, whether such benefits end up with rural farmers depends largely on the way production chains are organized and how land use is governed. [2.5.7.4–2.5.7.6, 9.3.4]

The development of sustainability frameworks and standards can reduce potential negative impacts associated with bioenergy production and lead to higher efficiency than today's systems. Bioenergy can contribute to climate change mitigation, a secure and diverse energy supply, and economic development in developed and developing countries alike, but the effects of bioenergy on environmental sustainability may be positive or negative depending upon local conditions, how criteria are defined, and how projects are designed and implemented, among many other factors. [2.4.5.2, 2.8.3, 2.5.8, 2.2.5, 9.3.4]

2.6 Prospects for technology improvement and integration

Further improvements in biomass feedstock production and conversion technologies are quite possible and necessary if bioenergy is to contribute to global energy supply to the degree reflected in the high end of deployment levels shown in Figure TS.2.2. Increasing land productivity, whether for food or energy purposes, is a crucial prerequisite for realizing large-scale future deployment of biomass for energy since it would make more land available for growing biomass and reduce the associated demand for land. In addition, multi-functional land and water use systems could develop with bioenergy and biorefineries integrated into agricultural and forestry systems, contributing to biodiversity conservation and helping to restore/maintain soil productivity and healthy ecosystems. [2.6.1]

Lignocellulosic feedstocks offer significant promise because they 1) do not compete directly with food production, 2) can be bred specifically for energy purposes, enabling higher production per unit land area and a large market for energy products, 3) can be harvested as residues from crop production and other systems that increase land use efficiency, and 4) allow the integration of waste management operations with a variety of other industries offering prospects for industrial symbiosis at the local level. Literature on and investment trends in conversion technologies indicate that the industry is poised to increase product diversification, as did the petroleum industry, with increased interest in the high energy density fuels for air transport, an application for which other non-carbon fuels have not been identified. [2.6.4]

A new generation of aquatic feedstocks that produce algal lipids for diesel, jet fuels, or higher value products from CO_2 and water with sunlight can provide strategies for lower land use impacts, as algae can grow in brackish waters, lands inappropriate for cultivation, and industrial waste water. Algal organisms can operate in the dark and metabolize sugars for fuels and chemicals. Many microbes could become microscopic factories to produce specific products, fuels and materials that decrease society's dependence on fossil energy sources. [2.6.1.2, 2.7.3]

Although significant technical progress has been made, the more complex processing required by solid lignocellulosic biomass and the integration of a number of new steps takes time and support to bring development through the 'Valley of Death' in demonstration plants, first-of-a-kind plants and early commercialization. Projected costs of biofuels from a wide range of sources and process variables are very sensitive to feedstock cost and range from USD_{2005} 10 to 30/GJ. The US National Academies project a 40% reduction in operating costs for biochemical routes by 2035 to USD_{2005} 12 to 15/GJ. [2.6.3, 2.6.4]

Biomass gasification currently provides about 1.4 GW_{th} in industrial applications, thermal applications and co-firing. Small-scale systems ranging from cooking stoves and anaerobic digestion systems to small gasifiers have been improving in efficiency over time. Many stakeholders have had a special interest in integrated gasification combined-cycle (IGCC) power plants that use bioenergy as a feedstock. These plants are projected to be more efficient than traditional steam turbine systems but have not yet reached full commercialization. However, they also have the potential to be integrated into CCS systems more effectively. In addition to providing power, syngas from gasification plants can be used to produce a wide range of fuels (methanol, ethanol, butanols and syndiesel) or can be used in a combined power and fuels approach. Technical and engineering challenges have so far prevented more rapid deployment of this technology option. Biomass to liquids conversion uses commercial technology developed for fossil fuels. Figure TS.2.5 illustrates projected emissions from coal to liquid fuels and the offsetting emissions that biomass could offer all the way to removal of GHG from the atmosphere when coupled with CCS technologies. Gaseous products (hydrogen, methane, synthetic natural gas) have lower estimated production costs and are in an early commercialization phase. [2.6.3, 2.6.4]

Pyrolysis and hydrothermal oils are low-cost transportable oils, used in heat or CHP applications and could become a feedstock for upgrading either in stand-alone facilities or coupled to a petrochemical refinery. [2.3.4, 2.6.3, 2.6.4, 2.7.1]

The production of biogas from a variety of waste streams and its upgrading to biomethane is already penetrating small markets for multiple applications, including transport in small networks in Sweden and for heat and power in Nordic and European countries. A key factor is the combination of waste streams, including agriculture residues. Improved upgrading and reducing costs is also needed. [2.6.3, 2.6.4]

Many bioenergy/biofuels routes enable CCS with significant opportunities for emissions reductions and sequestration. As CCS technologies are further developed and verified, coupling fermentation with concentrated CO_2 streams or IGCC offers opportunities to achieve carbon-neutral fuels, and in some cases negative net emissions. Achieving this goal will be facilitated by well-designed systems that span biomass selection, feedstock supply system, conversion to a secondary energy carrier and integration of this carrier into the existing and future energy systems. [2.6.3, 2.6.4, 9.3.4]

2.7 Current costs and trends

Biomass production, supply logistics, and conversion processes contribute to the cost of final products. [2.3, 2.6, 2.7]

The economics and yields of feedstocks vary widely across world regions and feedstock types with costs ranging from USD_{2005} 0.9 to 16/GJ (data from 2005 to 2007). Feedstock production for bioenergy competes with the forestry and food sectors, but integrated production systems such as agro-forestry or mixed cropping may provide synergies along with additional environmental services. Handling and transport of biomass from production sites to conversion plants may contribute 20 to up to 50% of the total costs of bioenergy production. Factors such as scale increase

and technological innovations increase competition and contribute to a decrease in economic and energy costs of supply chains by more than 50%. Densification via pelletization or briquetting is required for transportation distances over 50 km. [2.3.2, 2.6.2]

Several important bioenergy systems today, most notably sugarcane-based ethanol and heat and power generation from residues and waste biomass, can be deployed competitively. [Tables 2.6, 2.7]

Based on a standardized methodology outlined in Annex II, and the cost and performance data summarized in Annex III, the estimated production costs for commercial bioenergy systems at various scales and with some consideration of geographical regions are summarized in Figure TS.2.6. Values include production, supply logistics and conversion costs. [1.3.2, 2.7.2, 10.5.1, Annex II, Annex III]

Costs vary by world regions, feedstock types, feedstock supply costs, the scale of bioenergy production, and production time during the year, which is often seasonal. Examples of estimated commercial bioenergy levelized[10] cost ranges are roughly USD_{2005} 2 to 48/GJ for liquid and gaseous biofuels; roughly 3.5 to 25 US $cents_{2005}$/kWh (USD_{2005} 10 to 50/GJ) for electricity or CHP systems larger than about 2 MW (with feed stock costs of USD_{2005} 3/GJ feed and a heat value of USD_{2005} 5/GJ for steam or USD_{2005} 12/GJ for hot water); and roughly USD_{2005} 2 to 77/GJ for domestic or district heating systems with feedstock costs in the range of USD_{2005} 0 to 20/GJ (solid waste to wood pellets). These calculations refer to 2005 to 2008 data and are in expressed USD_{2005} at a 7% discount rate. The cost ranges for biofuels in Figure TS.2.6 cover the Americas, India, China and European countries. For heating systems, the costs are primarily European and the electricity and CHP costs come from primarily large user countries. [2.3.1–2.3.3, 2.7.2, Annex III]

In the medium term, the performance of existing bioenergy technologies can still be improved considerably, while new technologies offer the prospect of more efficient and competitive deployment of biomass for energy (and materials). Bioenergy systems, namely for ethanol and biopower production, show technological learning and related cost reductions with learning rates comparable to those of other RE technologies. This applies to cropping systems (following progress in agricultural management for sugarcane and maize), supply systems and logistics (as observed in Nordic countries and international logistics) and in conversion (ethanol production, power generation and biogas) as shown in Table TS.2.2.

Although not all bioenergy options discussed in Chapter 2 have been investigated in detail with respect to technological learning, several important bioenergy systems have reduced their cost and improved environmental performance. However, they usually still require government subsidies provided for economic development (e.g., poverty reduction and a secure energy supply) and other country-specific reasons. For traditional biomass, charcoal made from biomass is a major fuel in developing countries, and should benefit from the adoption of higher-efficiency kilns. [2.3, 2.6.1, 2.6.2, 2.6.3, 2.7.2, 10.4, 10.5]

The competitive production of bio-electricity (through methane or biofuels) depends on the integration with the end-use systems, performance of alternatives such as wind and solar energy, developing CCS technologies coupled with coal conversion, and nuclear energy. The implications of successful deployment of CCS in combination with biomass conversion could result in removal of GHGs from the atmosphere and attractive mitigation cost levels but have so far received limited attention. [2.6.3.3, 8.2.1, 8.2.3, 8.2.4, 8.3, 9.3.4]

Table TS.2.3 illustrates that costs for some key bioenergy technology are expected to decline over the near- to mid-term. With respect to lignocellulosic biofuels, recent analyses have indicated that the improvement potential is large enough for competition with oil at prices of USD_{2005} 60 to 80/barrel (USD_{2005} 0.38 to 0.44/litre). Currently available scenario analyses indicate that if shorter-term R&D and market support is strong, technological progress could allow for their commercialization around 2020 (depending on oil and carbon prices). Some scenarios also indicate that this would mean a major shift in the deployment of biomass for energy, since competitive production would decouple deployment from policy targets (mandates) and demand for biomass would move away from food crops to biomass residues, forest biomass and perennial cropping systems. The implications of such a (rapid) shift are so far poorly studied. [2.8.4, 2.4.3, 2.4.5]

Lignocellulosic ethanol development and demonstration continues in several countries. A key development step is the pretreatment to overcome the recalcitrance of the cell wall of woody, herbaceous or agricultural residues to make carbohydrate polymers accessible to hydrolysis (e.g., by enzymes) and fermentation of sugars to ethanol (or butanol) and lignin for process heat or electricity. Alternatively, multiple steps can be combined and bio-processed with multiple organisms simultaneously. A review of progress in the enzymatic area suggests that a 40% reduction in cost could be expected by 2030 from process improvements, which would bring down the estimated cost of production from USD_{2005} 18 to 22/GJ (pilot data) to USD 12 to 15/GJ, a competitive range. [2.6.3]

Biomass pyrolysis routes and hydrothermal concepts are also developing in conjunction with the oil industry and have demonstrated technically that upgrading of oils to blendstocks of gasoline or diesel and even jet fuel quality products is possible. [2.6.3]

Photosynthetic organisms such as algae biologically produce (using CO_2, water and sunlight) a variety of carbohydrates and lipids that can be used directly or for biofuels. These developments have significant long-term potential because algae photosynthetic efficiency is much higher

10 As in the electricity production in CHP systems in which calculations assumed a value for the co-produced heat, for biofuels systems, there are cases in which two co-products are obtained; for instance, sugarcane to sugar, ethanol, and electricity. Sugar co-product revenue could be about $US\$_{2005}$ 2.6/GJ and displace the ethanol cost by that amount.

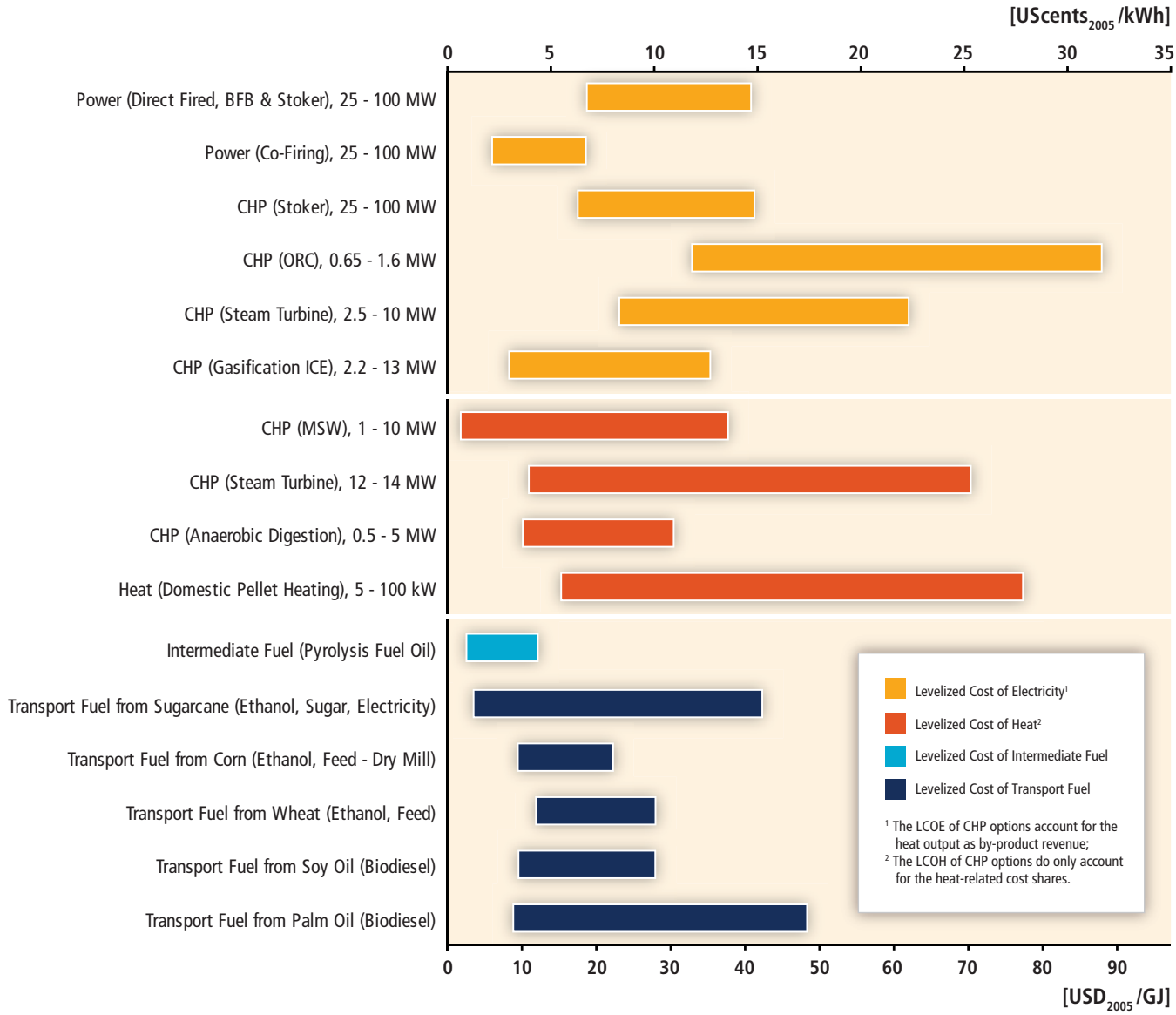


Figure TS.2.6 | Typical recent levelized cost of energy services from commercially available bioenergy systems at a 7% discount rate, calculated over a year of feedstock costs, which differ between technologies. These costs do not include interest, taxes, depreciation and amortization. [Figure 2.18] Levelized costs of electricity (LCOE), heat (LCOH), fuels (LCOF), intermediate fuel (LCOIF), BFB: Bubbling Fluidized Bed, ORC: Organic Rankine Cycle and ICE: Internal Combustion Engine. For biofuels, the range of LCOF represents production in a wide range of countries whereas LCOE and LCOH are given only for major user markets of the technologies for which data were available. Calculations are based on High Heating Value.

than that of oil crops. Potential bioenergy supplies from plants are very uncertain, but because their development can utilize brackish waters and heavily saline soils, their use is a strategy for low LUC impacts. [2.6.2, 3.3.5, 3.7.6]

Data availability is limited with respect to production of biomaterials, while cost estimates for chemicals from biomass are rare in peer-reviewed literature and future projections and learning rates even more so. This condition is linked, in part, to the fact that successful bio-based products are entering the market place either as partial components of otherwise fossil-derived products or as fully new synthetic polymers such as polylactides based on lactic acid derived from sugar fermentation. In addition to producing biomaterials to replace fossil fuels, analyses indicate that cascaded use of biomaterials and subsequent use of waste material for energy can offer more effective and larger mitigation impacts per hectare or tonne of biomass used. [2.6.3.5]

2.8 Potential deployment levels

Between 1990 and 2008, bioenergy use increased at an average annual growth rate of 1.5% for solid biomass, while the more modern biomass use for secondary carriers such as liquid and gaseous forms increased at 12.1 and 15.4% respectively. As a result, the share of biofuels in global road transport was 2% in 2008. The production of ethanol and biodiesel increased by 10 and 9%, respectively, in 2009, to 90 billion litres, such that biofuels contributed nearly 3% of global road transport in 2009, as oil demand decreased for the first time since 1980. Government

Table TS.2.2 | Experience curves for major components of bioenergy systems and final energy carriers expressed as reduction (%) in cost (or price) per doubling of cumulative production, the Learning Rate (LR); N: number of doublings of cumulative production; R2 is the correlation coefficient of the statistical data; O&M: Operations and Maintenance. [Table 2.17]

Learning system	LR (%)	Time frame	Region	N	R^2
Feedstock production					
Sugarcane (tonnes sugarcane)	32±1	1975–2005	Brazil	2.9	0.81
Corn (tonnes corn)	45±1.6	1975–2005	USA	1.6	0.87
Logistic chains					
Forest wood chips (Sweden)	15–12	1975–2003	Sweden/Finland	9	0.87–0.93
Investment and O&M costs					
CHP plants	19-25	1983–2002	Sweden	2.3	0.17–0.18
Biogas plants	12	1984–1998		6	0.69
Ethanol production from sugarcane	19±0.5	1975–2003	Brazil	4.6	0.80
Ethanol production from corn (only O&M costs)	13±0.15	1983–2005	USA	6.4	0.88
Final energy carriers					
Ethanol from sugarcane	7	1970–1985	Brazil		
	29	1985–2002		~6.1	N/A
Ethanol from sugarcane	20±0.5	1975–2003	Brazil	4.6	0.84
Ethanol from corn	18±0.2	1983–2005	USA	6.4	0.96
Electricity from biomass CHP	9-8	1990–2002	Sweden	~9	0.85–0.88
Electricity from biomass	15	Unknown	OECD	N/A	N/A
Biogas	0–15	1984–2001	Denmark	~10	0.97

Table TS.2.3 | Projected production cost ranges for developing technologies. [Table 2.18]

Selected Bioenergy Technologies	Energy Sector (Electricity, Thermal, Transport)[6]	2020-2030 Projected Production Costs (USD_{2005}/GJ)
Integrated gasification combined cycle [1]	Electricity and/or transport	12.8–19.1 (4.6–6.9 cents/kWh)
Oil plant-based renewable diesel and jet fuel	Transport and electricity	15–30
Lignocellulose sugar-based biofuels[2]	Transport	6–30
Lignocellulose syngas-based biofuels[3]		12–25
Lignocellulose pyrolysis-based biofuels[4]		14–24 (fuel blend components)
Gaseous biofuels[5]	Thermal and transport	6–12
Aquatic plant-derived fuels, chemicals	Transport	30–140

Notes: 1. Feed cost USD_{2005} 3.1/GJ, IGCC (future) 30 to 300 MW, 20-yr life, 10% discount rate. 2. Ethanol, butanols, microbial hydrocarbons and microbial hydrocarbons from sugar or starch crops or lignocellulose sugars. 3. Syndiesel, methanol and gasoline, etc.; syngas fermentation routes to ethanol. 4. Biomass pyrolysis and catalytic upgrading to gasoline and diesel blend components or to jet fuels. 5. Synfuel to synthetic natural gas, methane, dimethyl ether, hydrogen from biomass thermochemical and anaerobic digestion (larger scale). 6. Several applications can be coupled with CCS when these technologies, including CCS, are mature and thus could remove GHG from the atmosphere.

policies in various countries led to a five-fold increase in global biofuels production from 2000 to 2008. Biomass and renewable waste power generation was 259 TWh (0.93 EJ) in 2007 and 267 TWh (0.96 EJ) in 2008 representing 1% of the world's electricity and a doubling since 1990 (from 131 TWh (0.47 EJ)). [2.4]

The expected continued deployment of biomass for energy in the 2020 to 2050 time frame varies considerably between studies. A key message from the review of available insights is that large-scale biomass deployment strongly depends on sustainable development of the resource base, governance of land use, development of infrastructure and cost reduction of key technologies, for example, efficient and complete use of primary biomass for energy from the most promising first-generation feedstocks and new-generation lignocellulosic biomass. [2.4.3, 2.8]

The scenario results summarized in Figure TS.2.7 derive from a diversity of modelling teams and a wide range of assumptions including energy demand growth, cost and availability of competing low-carbon technologies, and cost and availability of RE technologies. Traditional biomass use is projected to decline in most scenarios while the use of liquid biofuels, biogas and electricity and hydrogen produced from biomass tends to increase. Results for biomass deployment for energy under these scenarios for 2020, 2030 and 2050 are presented for three GHG stabilization ranges based on the AR4: Categories III and IV (440-600 ppm CO_2), Categories I and II (<440 ppm CO_2) and Baselines (>600 ppm CO_2) all by 2100. [10.1–10.3]

Global biomass deployment for energy is projected to increase with more ambitious GHG concentration stabilization levels indicating its long-term role in reducing global GHG emissions. Median levels are 75

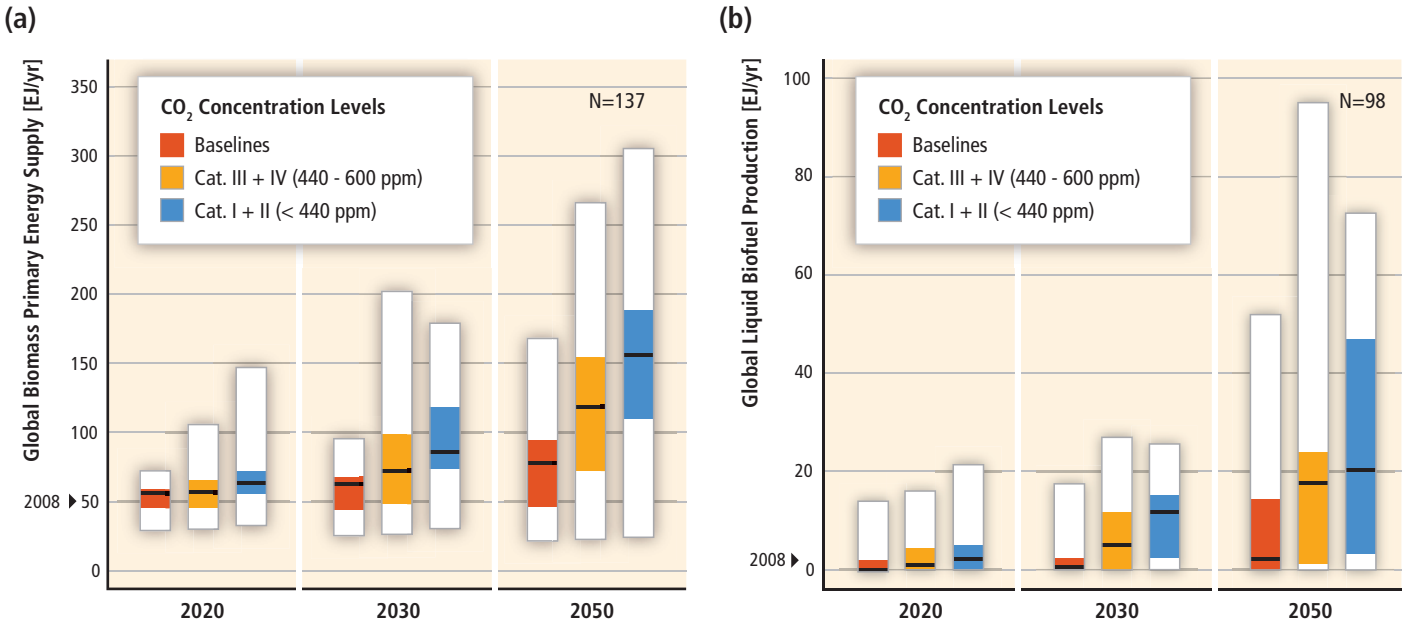


Figure TS.2.7 | (a) The global primary energy supply from biomass in long-term scenarios for electricity, heat and biofuels, all accounted for as primary energy; and (b) global biofuels production in long-term scenarios reported in secondary energy terms. For comparison, the historical levels in 2008 are indicated in the small black arrows on the left axis. [Figure 2.23]

to 85 EJ and 120 to 155 EJ for the two mitigation scenarios in 2030 and 2050, respectively, almost two and three times the 2008 deployment level of 50 EJ. These deployment levels are similar to the expert review mid-range levels for 2050. Global biofuels production shown in Figure TS.2.7(b) for 2020 and 2030 are at fairly low levels, but most models lack a detailed description of different conversion pathways and related learning potential. [2.7.3] For the <440 ppm mitigation scenario, biofuels production reaches six (2030) and ten (2050) times the 2008 actual value of 2 EJ. [2.2.5, 2.8.2, 2.5.8, 2.8.3]

The sector-level penetration of bioenergy is best explained using a single model with detailed transport sector representation such as the 2010 IEA World Energy Outlook (WEO) that also models both traditional and modern biomass applications and takes into account anticipated industrial and government investments and goals. This model projects very significant increases in modern bioenergy and a decrease in traditional biomass use. These projections are in qualitative agreement with the results from Chapter 10. In 2030, for the WEO 450-ppm mitigation scenario, the IEA projects that 11% of global transport fuels will be provided by biofuels with second-generation biofuels contributing 60% of the projected 12 EJ and half of this amount is projected to be supplied owing to continuation of current policies. Biomass and renewable wastes would supply 5% of the world's electricity generation or 1,380 TWh/yr (5 EJ/yr) of which 555 TWh/yr (2 EJ/yr) are a result of the stringent climate mitigation strategy. Biomass industrial heating applications for process steam and space and hot water heating for buildings (3.3 EJ in 2008) would each double in absolute terms from 2008 levels. However, the total heating demand is projected to decrease because of assumed traditional biomass decline. Heating is seen as a key area for continued modern bioenergy growth. Biofuels are projected to mitigate 17% of road and 3% of air transport emissions by 2030. [2.8.3]

2.8.1 Conclusions regarding deployment: Key messages about bioenergy

The long-term scenarios reviewed in Chapter 10 show increases in bioenergy supply with increasingly ambitious GHG concentration stabilization levels, indicating that bioenergy could play a significant long-term role in reducing global GHG emissions. [2.8.3]

Bioenergy is currently the largest RE source and is likely to remain one of the largest RE sources for the first half of this century. There is considerable growth potential, but it requires active development. [2.8.3]

- Assessments in the recent literature show that the technical potential of biomass for energy may be as large as 500 EJ/yr by 2050. However, large uncertainty exists about important factors such as market and policy conditions that affect this potential. [2.8.3]

- The expert assessment in Chapter 2 suggests potential deployment levels by 2050 in the range of 100 to 300 EJ/yr. Realizing this potential represents a major challenge but would make a substantial contribution to the world's primary energy demand in 2050—roughly equal to the equivalent heat content of today's worldwide biomass extraction in agriculture and forestry. [2.8.3]

- Bioenergy has significant potential to mitigate GHGs if resources are sustainably developed and efficient technologies are applied.

Certain current systems and key future options, including perennial crops, forest products and biomass residues and wastes, and advanced conversion technologies, can deliver significant GHG mitigation performance—an 80 to 90% reduction compared to the fossil energy baseline. However, land conversion and forest management that lead to a large loss of carbon stocks and iLUC effects can lessen, and in some cases more than neutralize, the net positive GHG mitigation impacts. [2.8.3]

- In order to achieve the high potential deployment levels of biomas for energy, increases in competing food and fibre demand must be moderate, land must be properly managed and agricultural and forestry yields must increase substantially. Expansion of bioenergy in the absence of monitoring and good governance of land use carries the risk of significant conflicts with respect to food supplies, water resources and biodiversity, as well as a risk of low GHG benefits. Conversely, implementation that follows effective sustainability frameworks could mitigate such conflicts and allow realization of positive outcomes, for example, in rural development, land amelioration and climate change mitigation, including opportunities to combine adaptation measures. [2.8.3]

- The impacts and performance of biomass production and use are region- and site-specific. Therefore, as part of good governance of land use and rural development, bioenergy policies need to consider regional conditions and priorities along with the agricultural (crops and livestock) and forestry sectors. Biomass resource potentials are influenced by and interact with climate change impacts but the specific impacts are still poorly understood; there will be strong regional differences in this respect. Bioenergy and new (perennial) cropping systems also offer opportunities to combine adaptation measures (e.g., soil protection, water retention and modernization of agriculture) with production of biomass resources. [2.8.3]

- Several important bioenergy options (i.e., sugarcane ethanol production in Brazil, select waste-to-energy systems, efficient biomass cookstoves, biomass-based CHP) are competitive today and can provide important synergies with longer-term options. Lignocellulosic biofuels to replace gasoline, diesel and jet fuels, advanced bioelectricity options, and biorefinery concepts can offer competitive deployment of bioenergy for the 2020 to 2030 timeframe. Combining biomass conversion with CCS raises the possibility of achieving GHG removal from the atmosphere in the long term—a necessity for substantial GHG emission reductions. Advanced biomaterials are promising as well for economics of bioenergy production and mitigation, though the potential is less well understood as is the potential role of aquatic biomass (algae), which is highly uncertain. [2.8.3]

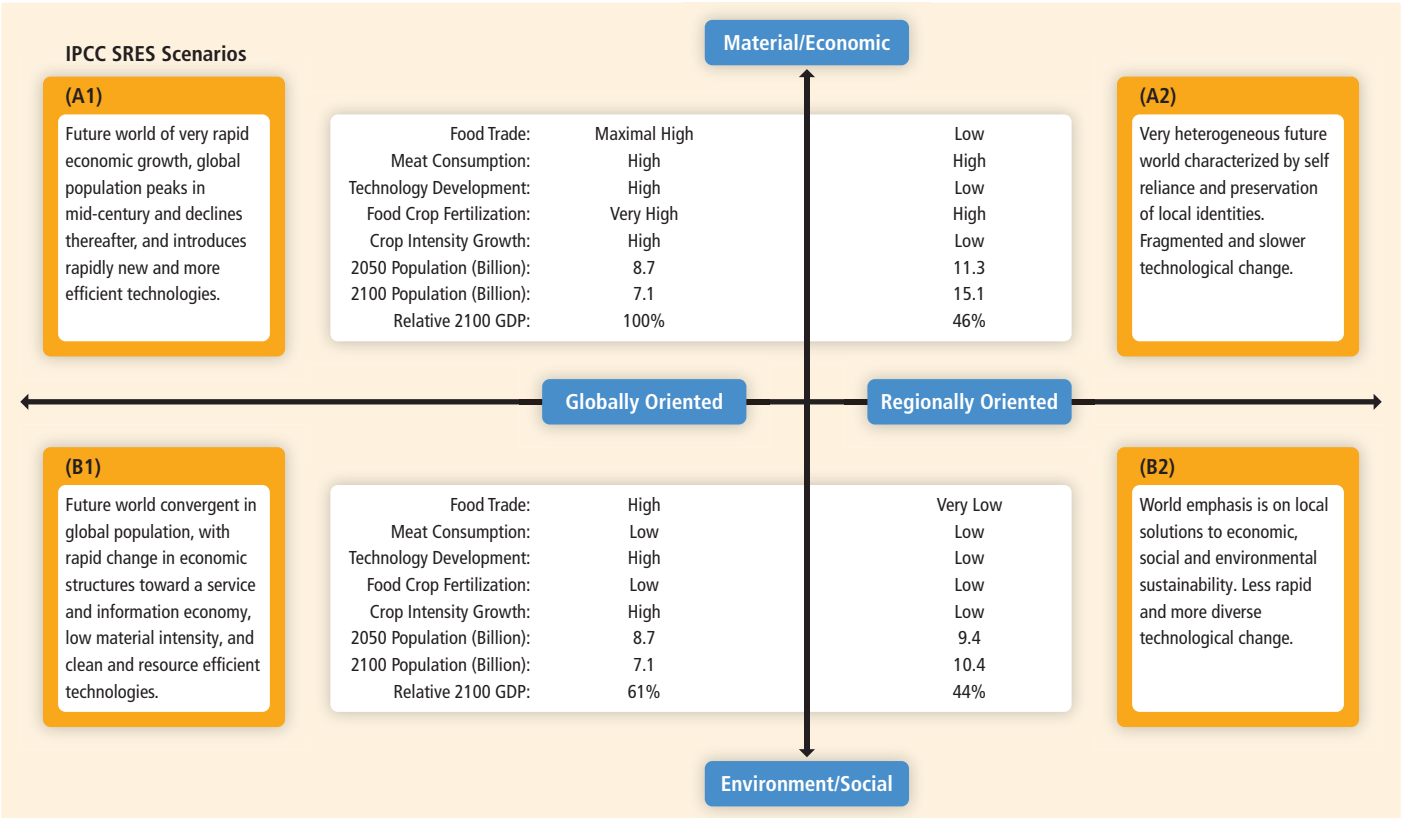


Figure TS.2.8 | Storylines for the key SRES scenario variables used to model biomass and bioenergy, the basis for the 2050 sketches adapted to this report and used to derive the stacked bar showing the biomass technical potential in Figure TS.2.2. [Figure 2.26]

- Rapidly changing policy contexts, recent market-based activities, the increasing support for advanced biorefineries and lignocellulosic biofuel options, and in particular the development of sustainability criteria and frameworks, all have the potential to drive bioenergy systems and their deployment in sustainable directions. Achieving this goal will require sustained investments that reduce costs of key technologies, improved biomass production and supply infrastructure, and implementation strategies that can gain public and political acceptance. [2.8.3]

In conclusion and for illustrating the interrelations between scenario variables (see Figure TS.2.8), key preconditions under which bioenergy production capacity is developed and what the resulting impacts may be, Figure TS.2.8 presents four different sketches for biomass deployment for energy at a global scale by 2050. The 100 to 300 EJ range that follows from the resource potential review delineates the lower and upper limit for deployment. The assumed storylines roughly follow the IPCC Special Report on Emissions Scenarios (SRES) definitions, applied to bioenergy and summarized in Figure TS.2.9 and which were also used

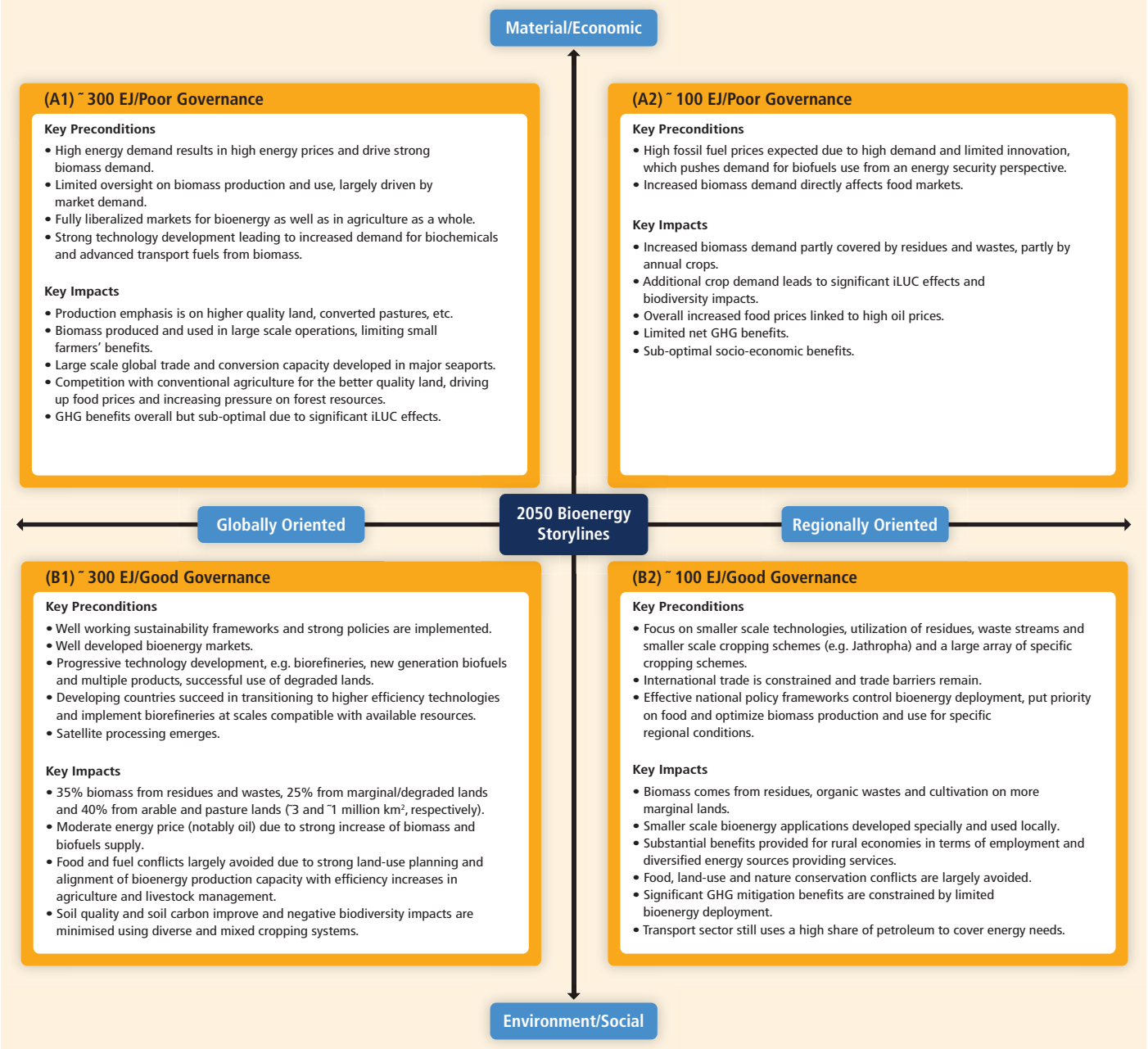


Figure TS.2.9 | Possible futures for 2050 biomass deployment for energy: Four illustrative contrasting sketches describing key preconditions and impacts following world conditions typical of the IPCC SRES storylines summarized in Figure TS.2.8. [Figure 2.27]

to derive the technical potential shown on the stacked bar of Figure TS.2.2. [2.8.3]

Biomass and its multiple energy products can be developed alongside food, fodder, fibre and forest products in both sustainable and unsustainable ways. As viewed through IPCC scenario storylines and sketches, high and low penetration levels can be reached with and without taking into account sustainable development and climate change mitigation pathways. Insights into bioenergy technology developments and integrated systems can be gleaned from these storylines. [2.8.3]

3. Direct Solar

3.1 Introduction

Direct solar energy technologies are diverse in nature. Responding to the various ways that humans use energy—such as heating, electricity, and fuels—they constitute a family of technologies. This summary focuses on four major types: 1) solar thermal, which includes both active and passive heating of buildings, domestic and commercial solar water heating, swimming pool heating and process heat for industry; 2) photovoltaic (PV) electricity generation via direct conversion of sunlight to electricity by photovoltaic cells; 3) concentrating solar power (CSP) electricity generation by optical concentration of solar energy to obtain high-temperature fluids or materials to drive heat engines and electrical generators; and 4) solar fuels production methods, which use solar energy to produce useful fuels. [3.1]

The term 'direct' solar energy refers to the energy base for those RE technologies that draw on the Sun's energy directly. Certain renewable technologies, such as wind and ocean thermal, use solar energy after it has been absorbed on the Earth and converted to other forms. (In the remainder of this section, the adjective 'direct' applied to solar energy will often be deleted as being understood.) [3.1]

3.2 Resource potential

Solar energy constitutes the thermal radiation emitted by the Sun's outer layer. Just outside Earth's atmosphere, this radiation, called solar irradiance, has a magnitude that averages 1,367 W/m^2 for a surface perpendicular to the Sun's rays. At ground level (generally specified as sea level with the sun directly overhead), this irradiance is attenuated by the atmosphere to about 1,000 W/m^2 in clear sky conditions within a few hours of noon—a condition called 'full sun'. Outside the atmosphere, the Sun's energy is carried in electromagnetic waves with wavelengths ranging from about 0.25 to 3 μm. Part of the solar irradiance is contributed by rays arriving directly from the sun without being scattered in the atmosphere. This 'beam' irradiance, which is capable of being concentrated by mirrors and lenses, is most available in low cloud-cover areas. The remaining irradiance is called the diffuse irradiance. The sum of the beam and diffuse irradiance is called global solar irradiation. [3.2]

The theoretical solar energy potential, which indicates the amount of irradiance at the Earth's surface (land and ocean) that is theoretically available for energy purposes, has been estimated at 3.9×10^6 EJ/yr. This number, clearly intended for illustrative purposes only, would require the full use of all available land and sea area at 100% conversion efficiency. A more useful metric is the technical potential; this requires assessing the fraction of land that is of practical use for conversion devices using a more realistic conversion efficiency. Estimates for solar energy's technical potential range from 1,575 to 49,837 EJ/yr, that is, roughly 3 to 100 times the world's primary energy consumption in 2008. [3.2, 3.2.2]

3.3 Technology and applications

Figure TS.3.1 illustrates the types of passive and active solar technologies currently in use to capture the Sun's energy to provide both residential energy services and direct electricity. In this summary, only technologies for active heating and electricity are treated in depth. [3.3.1–3.3.4]

Solar thermal: The key component in active solar thermal systems is the solar collector. A flat-plate solar collector consists of a blackened plate with attached conduits, through which passes a fluid to be heated. Flat-plate collectors may be classified as follows: unglazed, which are suitable for delivering heat at temperatures a few degrees above ambient temperature; glazed, which have a sheet of glass or other transparent material placed parallel to the plate and spaced a few centimetres above it, making it suitable for delivering heat at temperatures of about 30°C to 60°C; or evacuated, which are similar to glazed, but the space between the plate and the glass cover is evacuated, making this type of collector suitable for delivering heat at temperatures of about 50°C to 120°C. To withstand the vacuum, the plates of an evacuated collector are usually put inside glass tubes, which constitute both the collector's glazing and its container. In the evacuated type, a special black coating called a 'selective surface' is put on the plate to help prevent re-emission of the absorbed heat; such coatings are often used on the non-evacuated glazed type as well. Typical efficiencies of solar collectors used in their proper temperature range extend from about 40 to 70% at full sun. [3.3.2.1]

Flat-plate collectors are commonly used to heat water for domestic and commercial use, but they can also be used in active solar heating to provide comfort heat for buildings. Solar cooling can be obtained by using solar collectors to provide heat to drive an absorption refrigeration cycle. Other applications for solar-derived heat are industrial process heat, agricultural applications such as drying of crops, and for cooking. Water tanks are the most commonly used items to store heat during

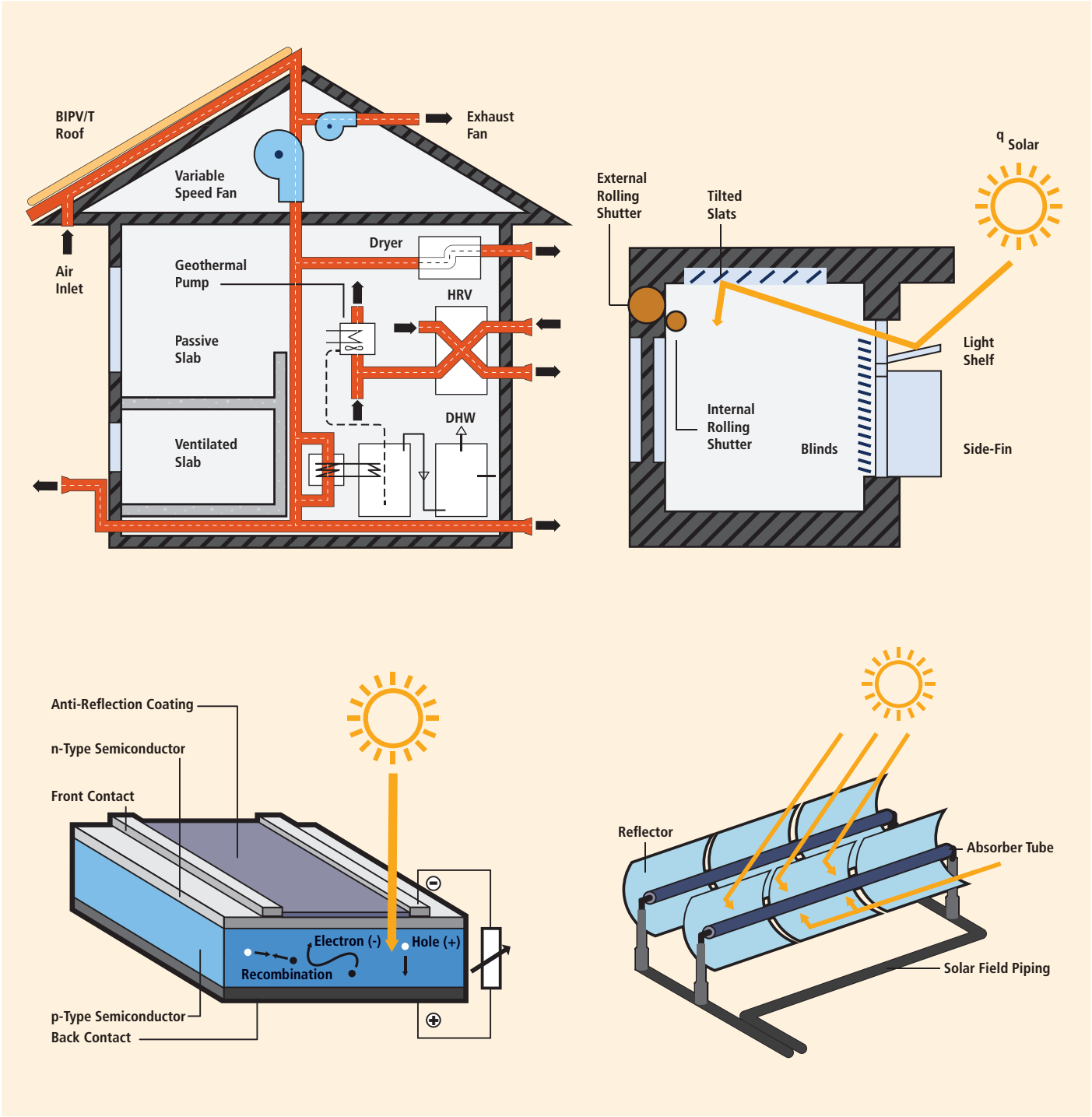


Figure TS.3.1 | Selected examples of (top) solar thermal, both passive and active integrated into a building; (bottom left) a photovoltaic device schematic for direct solar to electricity conversion; and (bottom right) one common type of concentrating solar power technology, a trough collector. [Derived from Figures 3.2, 3.5, 3.7]

the day/night period or short periods of cloudy weather. Supplemented by other energy sources, these systems typically provide 40 to 80% of the demand for heat energy of the target application. [3.3.2.2–3.3.2.4]

For passive solar heating, the building itself—particularly its windows—acts as the solar collector, and natural methods are used to distribute and store the heat. The basic elements of passive heating architecture are high-efficiency equatorial-facing windows and large internal thermal mass. The building must also be well insulated and incorporate methods such as shading devices to prevent it from overheating. Another feature of passive solar is 'daylighting', which incorporates special strategies to maximize the use of natural (solar) lighting in the building. Studies have shown that with current technology, using these strategies in new buildings in northern Europe or North America can reduce the building

heating demands by as much as 40%. For existing, rather than new, buildings retrofitted with passive heating concepts, reductions of as much as 20% are achievable. [3.3.1]

Photovoltaic electricity generation: A detailed description of how PV conversion works is available in many textbooks. In the simplest terms, a thin sheet of semiconductor material such as silicon is placed in the Sun. The sheet, known as a cell, consists of two distinct layers formed by introducing impurities into the silicon resulting in an n-type layer and a p-type layer that form a junction at the interface. Solar photons striking the cell generate electron-hole pairs that are separated spatially by an internal electric field at the junction. This creates negative charges on one side of the interface and positive charges are on the other side. This resulting charge separation creates a voltage. When the two sides of the illuminated cell are connected to a load, current flows from one side of the device via the load to the other side of the cell generating electricity. [3.3.3]

Various PV technologies have been developed in parallel. Commercially available PV technologies include wafer-based crystalline silicon PV, as well as the thin-film technologies of copper indium/gallium disulfide/(di) selenide (CIGS), cadmium telluride (CdTe), thin-film silicon (amorphous and microcrystalline silicon), and dye-sensitized solar cells. In addition, there are commercially available concentrating PV concepts, in which very high efficiency cells (such as gallium arsenide (GaAs)-based materials) are placed at the focus of concentrating mirrors or other collectors such as Fresnel lenses. Mono- and multi- crystalline (sometimes called "polycrystalline") silicon wafer PV (including ribbon technologies) are the dominant technologies on the PV market, with a 2009 market share of about 80%. Peak efficiencies achieved by various cell types include more than 40% for GaAs-based concentrator cells, about 25% for monocrystalline, 20% for multicrystalline and CIGS, 17% for CdTe, and about 10% for amorphous silicon. Typically, groups of cells are mounted side by side under a transparent sheet (usually glass) and connected in series to form a 'module' with dimensions of up to 1 m by 1 m. In considering efficiencies, it is important to distinguish between cell efficiencies (quoted above) and module efficiencies; the latter are typically 50 to 80% of the former. Manufacturers continue to improve performance and reduce costs with automation, faster cell processing, and low-cost, high-throughput manufacturing. The performance of modules is typically guaranteed by manufacturers for 20 to 30 years. [3.3.3.1, 3.3.3.2]

The application of PV for useful power involves more than just the cells and modules; the PV system, for example, will often include an inverter to convert the DC power from the cells to AC power to be compatible with common networks and devices. For off-grid applications, the system may include storage devices such as batteries. Work is ongoing to make these devices more reliable, reduce their cost, and extend their lifetime to be comparable with that of the modules. [3.3.3.4]

PV power systems are classified as two major types: off-grid and grid-connected. Grid-connected systems are themselves classified into two types: distributed and centralized. The distributed system is made up of a large number of small local power plants, some of which supply the electricity mainly to an on-site customer, and the remaining electricity feeds the grid. The centralized system, on the other hand, works as one large power plant. Off-grid systems are typically dedicated to a single or small group of customers and generally require an electrical storage element or back-up power. These systems have significant potential in non-electrified areas. [3.3.3.5]

Concentrating solar power electricity generation: CSP technologies produce electricity by concentrating the Sun's rays to heat a medium that is then used (either directly or indirectly) in a heat engine process (e.g., a steam turbine) to drive an electrical generator. CSP uses only the beam component of solar irradiation, and so its maximum benefit tends to be restricted to a limited geographical range. The concentrator brings the solar rays to a point (point focus) when used in central-receiver or dish systems and to a line (line focus) when used in trough or linear Fresnel systems. (These same systems can also be used to drive thermochemical processes for fuel production, as described below.) In trough concentrators, long rows of parabolic reflectors that track the movement of the Sun concentrate the solar irradiation on the order of 70 to 100 times onto a heat-collection element (HCE) mounted along the reflector's focal line. The HCE comprises a blackened inner pipe (with a selective surface) and a glass outer tube, with an evacuated space between the two. In current commercial designs, a heat transfer oil is circulated through the steel pipe where it is heated (to nearly 400°C), but systems using other heat transfer materials such as circulating molten salt or direct steam are currently being demonstrated. [3.3.4]

The second kind of line-focus system, the linear Fresnel system, uses long parallel mirror strips as the concentrator, again with a fixed linear receiver. One of the two point-focus systems, the central-receiver (also called the 'power tower'), uses an array of mirrors (heliostats) on the ground, each tracking the Sun on two axes so as to focus the Sun's rays at a point on top of a tall tower. The focal point is directed onto a receiver, which comprises either a fixed inverted cavity and/or tubes in which the heat transfer fluid circulates. It can reach higher temperatures (up to 1,000°C) than the line-focus types, which allows the heat engine to convert (at least theoretically) more of the collected heat to power. In the second type of point-focus system, the dish concentrator, a single paraboloidal reflector (as opposed to an array of reflectors) tracking the sun on two axes is used for concentration. The dish focuses the solar rays onto a receiver that is not fixed, but moves with the dish, being only about one dish diameter away. Temperatures on the receiver engine can reach as high as 900°C. In one popular realization of this concept, a Stirling engine driving an electrical generator is mounted at the focus. Stirling dish units are relatively small, typically producing 10 to 25 kW, but they can be aggregated in field configuration to realize a larger central station-like power output. [3.3.4]

The four different types of CSP plants have relative advantages and disadvantages. [3.3.4] All four have been built and demonstrated. An

important advantage of CSP technologies (except for dishes) is the ability to store thermal energy after it has been collected at the receiver and before going to the heat engine. Storage media considered include molten salt, pressurized air or steam accumulators (for short-term storage only), solid ceramic particles, high-temperature, phase-change materials, graphite, and high-temperature concrete. Commercial CSP plants are being built with thermal storage capacities reaching 15 hours, allowing CSP to offer dispatchable power. [3.3.4]

Solar fuel production: Solar fuel technologies convert solar energy into chemical fuels such as hydrogen, synthetic gas and liquids such as methanol and diesel. The three basic routes to solar fuels, which can work alone or in combination, are: (1) electrochemical; (2) photochemical/photo-biological; and (3) thermo-chemical. In the first route, hydrogen is produced by an electrolysis process driven by solar-derived electrical power that has been generated by a PV or CSP system. Electrolysis of water is an old and well-understood technology, typically achieving 70% conversion efficiency from electricity to hydrogen. In the second route, solar photons are used to drive photochemical or photo-biological reactions, the products of which are fuels: that is, they mimic what plants and organisms do. Alternatively, semiconductor material can be used as a solar light-absorbing anode in photoelectrochemical cells, which also generate hydrogen by water decomposition. In the third route, high-temperature solar-derived heat (such as that obtained at the receiver of a central-receiver CSP plant) is used to drive an endothermic chemical reaction that produces fuel. Here, the reactants can include combinations of water, CO_2, coal, biomass and natural gas. The products, which constitute the solar fuels, can be any (or combinations) of the following: hydrogen, syngas, methanol, dimethyl ether and synthesis oil. When a fossil fuel is used as the reactant, overall calorific values of the products will exceed those of the reactants, so that less fossil fuel needs to be burned for the same energy release. Solar fuel can also be synthesized from solar hydrogen and CO_2 to produce hydrocarbons compatible with existing energy infrastructures. [3.3.5]

3.4 Global and regional status of market and industry deployment

3.4.1 Installed capacity and generated energy

Solar thermal: Active solar heating and cooling technologies for residential and commercial buildings represent a mature market. This market, which is distributed to various degrees in most countries of the world, grew by 34.9% from 2007 to 2009 and continues to grow at a rate of about 16% per year. At the end of 2009, the global installed capacity of thermal power from these devices was estimated to be 180 GW_{th}. The global market for sales of active solar thermal systems reached an estimated 29.1 GW_{th} in 2008 and 31 GW_{th} in 2009. Glazed collectors comprise the majority of the world market. China accounted for 79% of the installation of glazed collectors in 2008, and the EU accounted for about 14.5%. In the USA and Canada, swimming pool heating is still the dominant application, with an installed capacity of 12.9 GW_{th} of unglazed plastic collectors. Notably in 2008, China led the world in installed capacity of flat-plate and evacuated-tube collectors with 88.7 GW_{th}. Europe had 20.9 GW_{th} and Japan 4.4 GW_{th}. In Europe, the market size more than tripled between 2002 and 2008. Despite these gains, solar thermal still accounts for only a relatively small portion of the demand for hot water in Europe. For example, in Germany, with the largest market, about 5% of one- and two-family homes are using solar thermal energy. One measure of the market penetration is the per capita annual usage of solar energy. The lead country in this regard is Cyprus, where the figure is 527 kW_{th} per 1,000 people. Note that there is no available information on passive solar regarding the status of its market and its deployment by industry. Consequently, the preceding numbers refer only to active solar. [3.4.1]

Photovoltaic electricity generation: In 2009, about 7.5 GW of PV systems were installed. That brought the cumulative installed PV capacity worldwide in 2009 to about 22 GW—a capacity able to generate up to 26 TWh (93,600 TJ) per year. More than 90% of this capacity is installed in three leading markets: the EU with 73% of the total, Japan with 12% and the USA with 8%. Roughly 95% of the PV installed capacity in the OECD countries is grid connected, the remainder being off-grid. Growth in the top eight PV markets through 2009 is illustrated in Figure TS.3.2. Spain and Germany have seen, by far, the largest amounts of solar installed in recent years. [3.4.1]

Concentrating solar power: CSP has reached a cumulative installed capacity of about 0.7 GW, with another 1.5 GW under construction. The capacity factors for a number of these CSP plants are expected to range from 25 to 75%; these can be higher than for PV because CSP plants contain the opportunity to add thermal storage where there is a commensurate need to overbuild the collector field to charge the thermal storage. The lower end of the capacity factor range is for no thermal storage and the upper end is for up to 15 hours of thermal storage. [3.8.4] The earliest commercial CSP plants were the Solar Electric Generating Systems in California

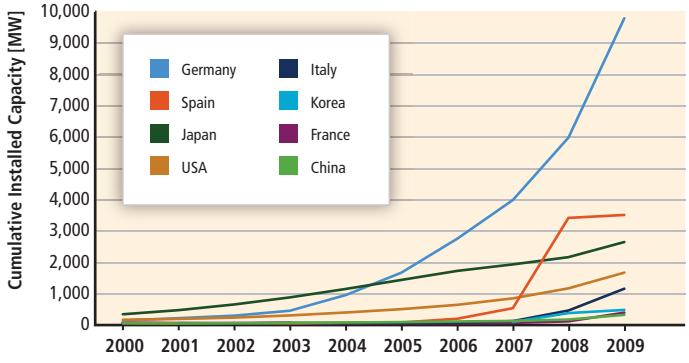


Figure TS.3.2 | Installed PV capacity for the years 2000 to 2009 in eight markets. [Figure 3.9]

capable of producing 354 MW of power; installed between 1985 and 1991, they are still operating today. The period from 1991 to the early 2000s was slow for CSP, but since about 2004, there has been strong growth in planned generation. The bulk of the current operating CSP generation consists of trough technology, but central-receiver technology comprises a growing share, and there is strong proposed commercial activity in dish-Stirling. In early 2010, most of the planned global capacity was in the USA and Spain, but recently other countries announced commercial plans. Figure TS.3.3 shows the current and planned deployment of CSP capacity through the year 2015. [3.3.4, 3.4.1]

Solar fuel production: Currently, solar fuel production is in the pilot-plant phase. Pilot plants in the power range of 300 to 500 kW have been built for the carbo-thermic reduction of zinc oxide, steam methane reforming, and steam gasification of petcoke. A 250-kW steam-reforming reactor is operating in Australia. [3.3.4, 3.4.1]

3.4.2 Industry capacity and supply chain

Solar thermal: In 2008, manufacturers produced approximately 41.5 million m^2 of solar collectors, a scale large enough to adapt to mass production, even though production is spread among a large number of companies around the world. Indeed, large-scale industrial production levels have been attained in most parts of the industry. In the manufacturing process, a number of readily available materials—including copper, aluminium, stainless steel, and thermal insulation—are being applied and combined through different joining technologies to produce the absorber plate. This box is topped by the cover glass, which is almost always low-iron glass, now readily available. Most production is in China, where it is aimed at internal consumption. Evacuated collectors, suitable for mass production techniques, are starting to dominate that market. Other important production sites are in Europe, Turkey, Brazil and India. Much of the export market comprises total solar water heating systems rather than solar collectors per se. The largest exporters of solar water heating systems are Australia, Greece, the USA and France. Australian exports constitute about 50% of its production. [3.4.2]

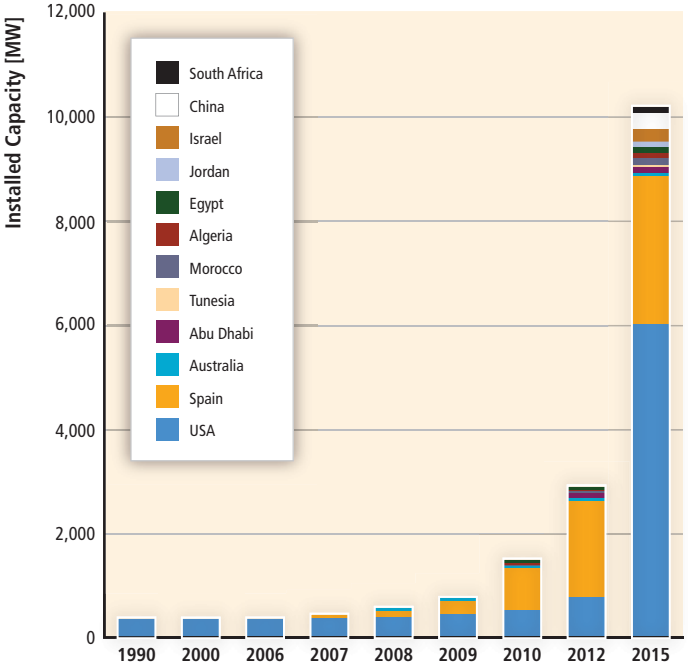


Figure TS.3.3 | Installed and planned concentrated solar power plants by country. [Figure 3.10]

For passive solar heating, part of the industry capacity and supply chain lies in people: namely, the engineers and architects who must systematically collaborate to produce a passively heated building. Close collaboration between the two disciplines has often been lacking in the past, but the dissemination of systematic design methodologies issued by different countries has improved the design capabilities. Windows and glazing are an important part of passively heated buildings, and the availability of a new generation of high-efficiency (low-emissivity, argon-filled) windows is having a major impact on solar energy's contribution to heating requirements in the buildings sector. These windows now constitute the bulk of new windows being installed in most northern-latitude countries. There do not appear to be any issues of industrial capacity or supply chains hindering the adoption of better windows. Another feature of passive design is adding internal mass to the building's structure. Concrete and bricks, the most commonly used storage materials, are readily available; phase-change materials (e.g., paraffin), considered to be the storage materials of the future, are not expected to have supply-chain issues. [3.4.2]

Photovoltaic electricity generation: The compound annual growth rate in PV manufacturing production from 2003 to 2009 exceeded 50%. In 2009, solar cell production reached about 11.5 GW per year (rated at peak capacity) split among several economies: China had about 51% of world production (including 14% from the Chinese province of Taiwan); Europe about 18%; Japan about 14%; and the USA about 5%. Worldwide, more than 300 factories produce solar cells and modules. In 2009, silicon-based solar cells and modules represented about 80% of the worldwide market. The remaining 20% mostly comprised cadmium telluride, amorphous silicon, and copper indium gallium diselenide. The total market is expected to increase significantly during the next few years, with thin-film module production gaining market share. Manufacturers are moving towards original design of manufacturing units and are also moving components of module production closer to the final market. Between 2004 and early 2008, the demand for crystalline silicon (or polysilicon) outstripped supply, which led to a price hike. With the new price, ample supplies have become available; the PV market is now driving its own supply of polysilicon. [3.4.2]

Concentrating solar power: In the past several years, the CSP industry has experienced a resurgence from a stagnant period to more than 2 GW being either commissioned or under construction. More than 10 different companies are now active in building or preparing for commercial-scale plants. They range from start-up companies to large organizations, including utilities, with international construction

management expertise. None of the supply chains for construction of plants are limited by the availability of raw material. Expanded capacity can be introduced with a lead time of about 18 months. [3.4.2]

Solar fuel production: Solar fuel technology is still at an emerging stage, and there is no supply chain in place at present for commercial applications. Solar fuels will comprise much of the same solar-field technology as is being deployed for other high-temperature CSP systems, in addition to downstream technologies similar to those in the petrochemical industry. [3.4.2]

3.4.3 Impact of policies

Direct solar energy technologies face a range of potential barriers to achieving wide-scale deployment. Solar technologies differ in levels of maturity, and although some applications are already competitive in localized markets, they generally face one common barrier: the need to reduce costs. Utility-scale CSP and PV systems face different barriers than distributed PV and solar heating and cooling technologies. Important barriers include: siting, permitting, and financing challenges to develop land with favourable solar resources for utility-scale projects; lack of access to transmission lines for large projects far from electric load centres; complex access laws, permitting procedures, and fees for smaller-scale projects; lack of consistent interconnection standards and time-varying utility rate structures that capture the value of distributed generated electricity; inconsistent standards and certifications and enforcement of these issues; and lack of regulatory structures that capture environmental and risk-mitigation benefits across technologies. Through appropriate policy designs, governments have shown that they can support solar technologies by funding R&D and by providing incentives to overcome economic barriers. Price-driven incentive frameworks, for example, were popularized after FIT policies boosted levels of PV deployment in Germany and Spain. Quota-driven frameworks such as renewable portfolio standards and government bidding are common in the USA and China, respectively. In addition to these regulatory frameworks, fiscal policies and financing mechanisms (e.g., tax credits, soft loans and grants) are often employed to support the manufacturing of solar goods and to increase consumer demand. Most successful solar policies are tailored to the barriers imposed by specific applications, and the most successful policies are those that send clear, long-term and consistent signals to the market. [3.4.3]

3.5 Integration into the broader energy system

Solar technologies have a number of attributes that allow their advantageous integration into a broader energy system. In this section, only the integration features unique to solar technologies are summarized. These include low-capacity energy demand, district heating and other thermal loads, PV generation characteristics and smoothing effects, and CSP generation characteristics and grid stabilization. [3.5.1–3.5.4]

For applications that have low power consumption, such as lighting or solar-derived hot water, solar technologies sometimes have a comparative advantage relative to non-renewable fuel technologies. In addition, solar technologies allow small decentralized applications as well as larger centralized ones. In some regions of the world, integration of solar energy into district heating and other thermal loads has proven to be an effective strategy, especially because highly insulated buildings can be heated effectively with relatively low-temperature energy carriers. In some locations, a district cooling and heating system can provide additional advantages compared to decentralized cooling, including cost advantages for economies of scale, diversity of cooling demand of different buildings, reducing noise and structural load, and equipment space savings. Also, by combining biomass and low-temperature solar thermal energy, system capacity factor and emissions profiles can be improved. [3.5.1, 3.5.2]

For PV power generation at a specific location, electricity varies systematically during a day and a year, but also randomly according to weather conditions. This variation can, in some instances, have a large impact on voltage and power flow in the local transmission and distribution system from the early penetration stage, and the supply-demand balance in total power system operation in the high-penetration stage. This effect can potentially constrain PV system integration. However, modelling and system simulations suggest that numerous PV systems in a broad area should have less-random and slower variations, which are sometimes referred to as the 'smoothing effect'. Studies are underway to evaluate and quantify actual smoothing effects at a large scale (1,000 sites at distances from 2 to 200 km) and at time scales of 1 minute or less. [3.5.3]

In a CSP plant, even without storage, the inherent thermal mass in the collector system and spinning mass in the turbine tend to significantly reduce the impact of rapid solar transients on electrical output, and thus, lead to a reduced impact on the grid. By including integrated thermal storage systems, capacity factors typical of base-load operation could be achieved in the future. In addition, integrating CSP plants with fossil fuel generators, especially with gas-fired integrated solar combined-cycle systems (with storage), can offer better fuel efficiency and extended operating hours and ultimately be more cost effective than operating separate CSP and/or combined-cycle plants. [3.5.4]

3.6 Environmental and social impacts

3.6.1 Environmental impacts

Apart from its benefits in GHG reduction, the use of solar energy can reduce the release of pollutants—such as particulates and noxious gases—from the older fossil fuel plants that it replaces. Solar thermal and PV technologies do not generate any type of solid, liquid or gaseous by-products when producing electricity. The family of solar energy technologies may create other types of air, water, land and ecosystem impacts, depending on how they are managed. The PV industry uses

some toxic, explosive gases as well as corrosive liquids in its production lines. The presence and amount of those materials depend strongly on the cell type. However, the intrinsic needs of the productive process of the PV industry force the use of quite rigorous control methods that minimize the emission of potentially hazardous elements during module production. For other solar energy technologies, air and water pollution impacts are generally expected to be relatively minor. Furthermore, some solar technologies in certain regions may require water usage for cleaning to maintain performance. [3.6.1]

Lifecycle assessment estimates of the GHGs associated with various types of PV modules and CSP technologies are provided in Figure TS.3.4. The majority of estimates for PV modules cluster between 30 and 80 g of CO_2eq/kWh. Lifecycle GHG emissions for CSP-generated electricity have recently been estimated to range from about 14 to 32 g of CO_2eq/kWh. These emission levels are about an order of magnitude lower than those of natural gas-fired power plants. [3.6.1, 9.3.4]

Land use is another form of environmental impact. For roof-mounted solar thermal and PV systems, this is not an issue, but it can be an issue for central-station PV as well as for CSP. Environmentally sensitive lands may pose a special challenge for CSP permitting. One difference for CSP vis-à-vis PV is that it needs a method to cool the working fluid, and such cooling often involves the use of scarce water. Using local air as the coolant (dry cooling) is a viable option, but this can decrease plant efficiency by 2 to 10%. [3.6.1]

3.6.2 Social impacts

The positive benefits of solar energy in the developing world provide arguments for its expanded use. About 1.4 billion people do not have access to electricity. Solar home systems and local PV-powered community grids can provide electricity to many areas for which connection to a main grid is cost prohibitive. The impact of electricity and solar energy technologies on the local population is shown through a long list of important benefits: the replacement of indoor-polluting kerosene lamps and inefficient cook stoves; increased indoor reading; reduced time gathering firewood for cooking (allowing the women and children who normally gather it to focus on other priorities); street lighting for security; improved health by providing refrigeration for vaccines and food products; and, finally, communications devices (e.g., televisions, radios). All of these provide a myriad of benefits that improve the lives of people. [3.6.2]

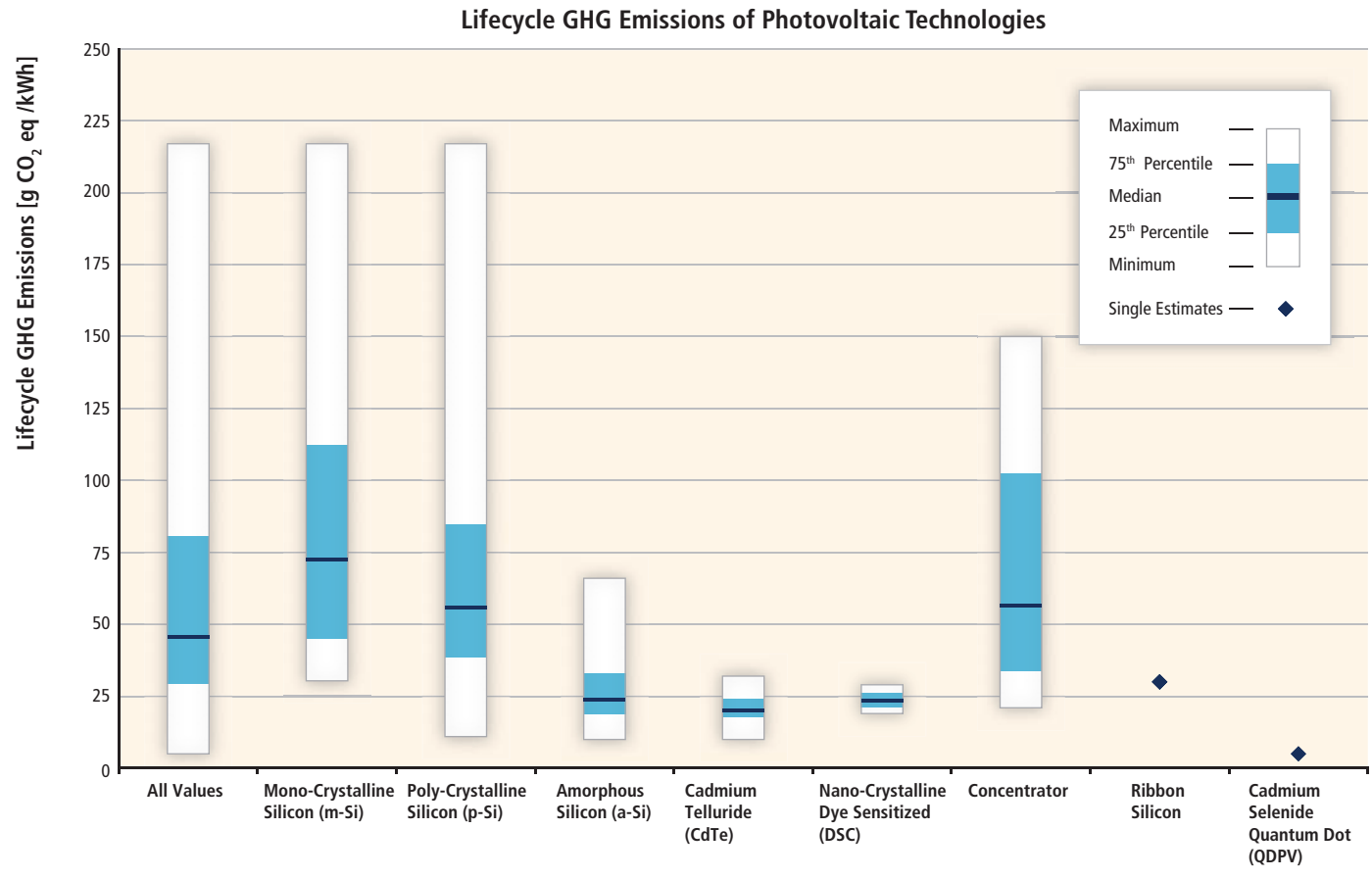
Job creation is an important social consideration associated with solar energy technology. Analysis indicates that solar PV has the highest job-generating potential among the family of solar technologies. Approximately 0.87 job-years per GWh are created through solar PV, followed by CSP with 0.23 job-years per GWh. When properly put forward, these job-related arguments can help accelerate social acceptance and increase public willingness to tolerate the perceived disadvantages of solar energy, such as visual impacts. [3.6.2]

3.7 Prospects for technology improvements and innovation

Solar thermal: If integrated at the earliest stages of planning, buildings of the future could have solar panels – including PV, thermal collector, and combined PV-thermal (hybrids) – making up almost all viewed components of the roof and façades. Such buildings could be established not just through the personal desires of individual builders/owners, but also as a result of public policy mandates, at least in some areas. For example, the vision of the European Solar Thermal Technology Platform is to establish the 'Active Solar Building' as a standard for new buildings by 2030, where an Active Solar Building, on average, covers all of its energy demand for water heating and space conditioning. [3.7.2]

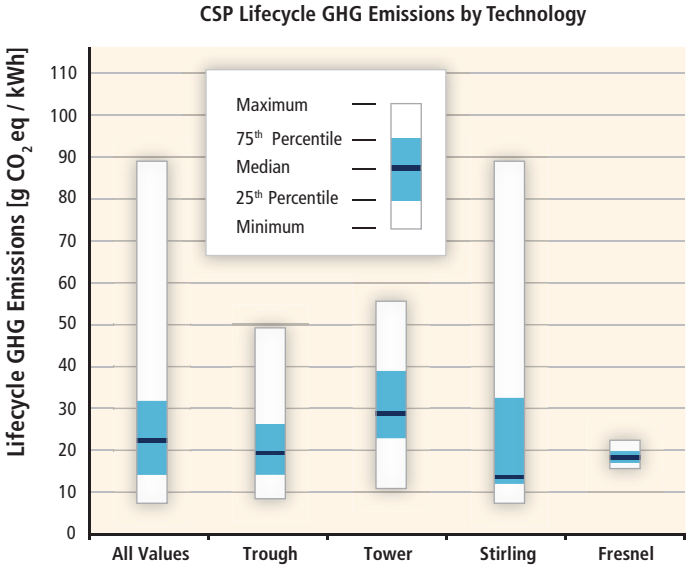
In highlighting the advances in passive solar, two climates can be distinguished between: those that are dominated by the demand for heating and those dominated by the demand for cooling. For the former, a wider-scale adoption of the following items can be foreseen: evacuated (as opposed to sealed) glazing, dynamic exterior night-time insulation, and translucent glazing systems that can automatically change solar/visible transmittance and that also offer improved insulation values. For the latter, there is the expectation for an increased use of cool roofs (i.e., light-coloured roofs that reflect solar energy); heat-dissipation techniques such as use of the ground and water as heat sinks; methods that improve the microclimate around the buildings; and solar control devices that allow penetration of the lighting, but not the thermal, component of solar energy. For both climates, improved thermal storage is expected to be embedded in building materials. Also anticipated are improved methods for distributing the absorbed solar heat around the building and/or to the outside air, perhaps using active methods such as fans. Finally, improved design tools are expected to facilitate these various improved methods. [3.7.1]

Photovoltaic electricity generation: Although now a relatively mature technology, PV is still experiencing rapid improvements in performance and cost, and a continuation of this steady progress is expected. The efforts required are being taken up in a framework of intergovernmental cooperation, complete with roadmaps. For the different PV technologies, four broad technological categories, each requiring specific R&D approaches, have been identified: 1) cell efficiency, stability, and lifetime; 2) module productivity and manufacturing; 3) environmental sustainability; and 4) applicability, all of which include standardization and harmonization. Looking to the future, PV technologies can by categorized in three major classes: current; emerging, which represent medium risk with a mid-term (10 to 20 year) time line; and the high-risk technologies aimed at 2030 and beyond, which have extraordinary potential but require technical breakthroughs. Examples of emerging cells are multiple-junction, polycrystalline thin films and crystalline silicon in the sub-100-µm thickness range. Examples of high-risk cells are organic solar cells, biomimetic devices and quantum dot designs that have the potential to substantially increase the maximum efficiency. Finally, there is important work to be done on the balance of systems (BOS), which comprises inverters, storage, charge controllers, system structures and the energy network. [3.7.3]



Estimates:	124	30	56	12	13	4	6	2*	1
References:	26	9	15	3	3	1	2	2	1

*same value



Estimates:	42	20	14	4	4
References:	13	7	5	3	1

Figure TS.3.4 | GHG emissions from the life cycles of (top) PV modules and (bottom) CSP technologies. See Annex II for details of literature search and citations of literature contributing to the estimates displayed. [Figures 3.14, 3.15]

CSP electricity generation: Although CSP is now a proven technology at the utility scale, technology advances are still taking place. As plants are built, both mass production and economies of scale are leading to cost reductions. There is scope for continuing improvement in solar-to-electricity efficiency, partly through higher collector temperatures. To increase temperature and efficiency, alternatives to the use of oil as the heat-transfer fluid—such as water (boiling in the receiver) or molten salts—are being developed, permitting higher operating temperatures. For central-receiver systems, the overall efficiencies can be higher because the operating temperatures are higher, and further improvements are expected to achieve peak efficiencies (solar to electricity) almost twice those of existing systems, up to 35%. Trough technology will benefit from continuing advances in solar-selective surfaces, and central receivers and dishes will benefit from improved receiver/absorber designs that afford high levels of solar irradiance at the focus. Capital cost reduction is expected to come from the benefits of mass production, economies of scale and learning from previous experience. [3.7.4]

Solar fuel production: Solar electrolysis using PV or CSP is available for niche applications, but it remains costly. Many paths are being pursued to develop a technology that will reduce the cost of solar fuels. These include solid-oxide electrolysis cells, the photoelectrochemical cell (which combines all the steps in solar electrolysis into a single unit), advanced thermo-chemical processes, and photochemical and photobiological processes—sometimes in combinations that integrate artificial photosynthesis in man-made biomimetic systems and photobiological hydrogen production in living organisms. [3.7.5]

Other potential future applications: Other methods under investigation for producing electricity using solar thermal technologies without an intermediate thermodynamic cycle include thermoelectric, thermionic, magnetohydrodynamic and alkali-metal methods. Space solar power, in which solar power collected in space is beamed via microwaves to receiving antennae on the ground, has also been proposed. [3.7.6]

3.8 Cost trends

Although the cost of solar energy varies widely by technology, application, location and other factors, costs have been reduced significantly during the past 30 years, and technical advances and supportive public policies continue to offer the potential for additional cost reductions. The degree of continued innovation will have a significant bearing on the level of solar deployment. [3.7.2–3.7.5, 3.8.2–3.8.5]

Solar thermal: The economics of solar heating applications depend on appropriate design of the system with regard to energy service needs, which often involves the use of auxiliary energy sources. In some regions, for example, in southern parts of China, solar water heating (SWH) systems are cost competitive with traditional options. SWH systems are generally more competitive in sunny regions, but this picture changes for space heating based on its usually higher overall heating load. In colder regions capital costs can be spread over a longer heating season, and solar thermal can then become more competitive. [3.8.2]

The investment costs for solar thermal heating systems vary widely depending on the complexity of the technology used as well as the market conditions in the country of operation. The costs for an installed system vary from as low as USD_{2005} 83/m² for SWH systems in China to more than USD_{2005} 1,200/m² for certain space-heating systems. The levelized cost of heat (LCOH) mirrors the wide variation in investment cost, and depends on an even larger number of variables, including the particular type of system, investment cost of the system, available solar irradiance in a particular location, conversion efficiency of the system, operating costs, utilization strategy of the system and the applied discount rate. Based on a standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOH for solar thermal systems over a large set and range of input parameters has been calculated to vary widely from USD_{2005} 9 to 200/GJ, but can be estimated for more specific settings with parametric analysis. Figure TS.3.5 shows the LCOH over a somewhat narrower set and range of input parameters. More specifically, the figure shows that for SWH systems with costs in the range of USD_{2005} 1,100 to 1,200/kW_{th} and conversion efficiencies of roughly 40%, LCOH is expected to range from slightly more than USD_{2005} 30/GJ to slightly less than USD_{2005} 50/GJ in regions comparable to Central and Southern European locations and up to almost USD_{2005} 90/GJ for regions with less solar irradiation. Not surprisingly, LCOH estimates are highly sensitive to all of the parameters shown in Figure TS.3.5, including investment costs and capacity factors. [3.8.2, Annex II, Annex III]

Over the last decade, for each 50% increase in installed capacity of solar water heaters, investment costs have fallen 20% in Europe. According to the IEA, further cost reductions in OECD countries will come from the use of cheaper materials, improved manufacturing processes, mass production, and the direct integration into buildings of collectors as multi-functional building components and modular, easy-to-install systems. Delivered energy costs in OECD countries are anticipated by the IEA to eventually decline by around 70 to 75%. [3.8.2]

PV electricity generation: PV prices have decreased by more than a factor of 10 during the last 30 years; however, the current levelized cost of electricity (LCOE) from solar PV is generally still higher than wholesale market prices for electricity. In some applications, PV systems are already competitive with other local alternatives (e.g., for electricity supply in certain rural areas in developing countries). [3.8.3, 8.2.5, 9.3.2]

The LCOE of PV highly depends on the cost of individual system components, with the highest cost share stemming from the PV module. The LCOE also includes BOS components, cost of labour for installation, operation and maintenance (O&M) cost, location and capacity factor, and the applied discount rate. [3.8.3]

The price for PV modules dropped from USD_{2005} 22/W in 1980 to less than USD_{2005} 1.50/W in 2010. The corresponding historical learning rate ranges from 11 to 26%, with a median learning rate of 20%. The price in USD/W for an entire system, including the module, BOS, and installation costs, has also decreased steadily, reaching numbers as low as USD_{2005} 2.72/W for some thin-film technologies by 2009. [3.8.3]

The LCOE for PV depends not only on the initial investment; it also takes into account operation costs and the lifetime of the system components, local solar irradiation levels and system performance. Based on the standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the recent LCOE for different types of PV systems has been calculated. It shows a wide variation from as low as USD_{2005} 0.074/kWh to as high as USD_{2005} 0.92/kWh, depending on a large set and range of input parameters. Narrowing the range of parameter variations, the LCOE in 2009 for utility-scale PV electricity generation in regions of high solar irradiance in Europe and the USA were in the range of about USD_{2005} 0.15/kWh to USD_{2005} 0.4/kWh at a

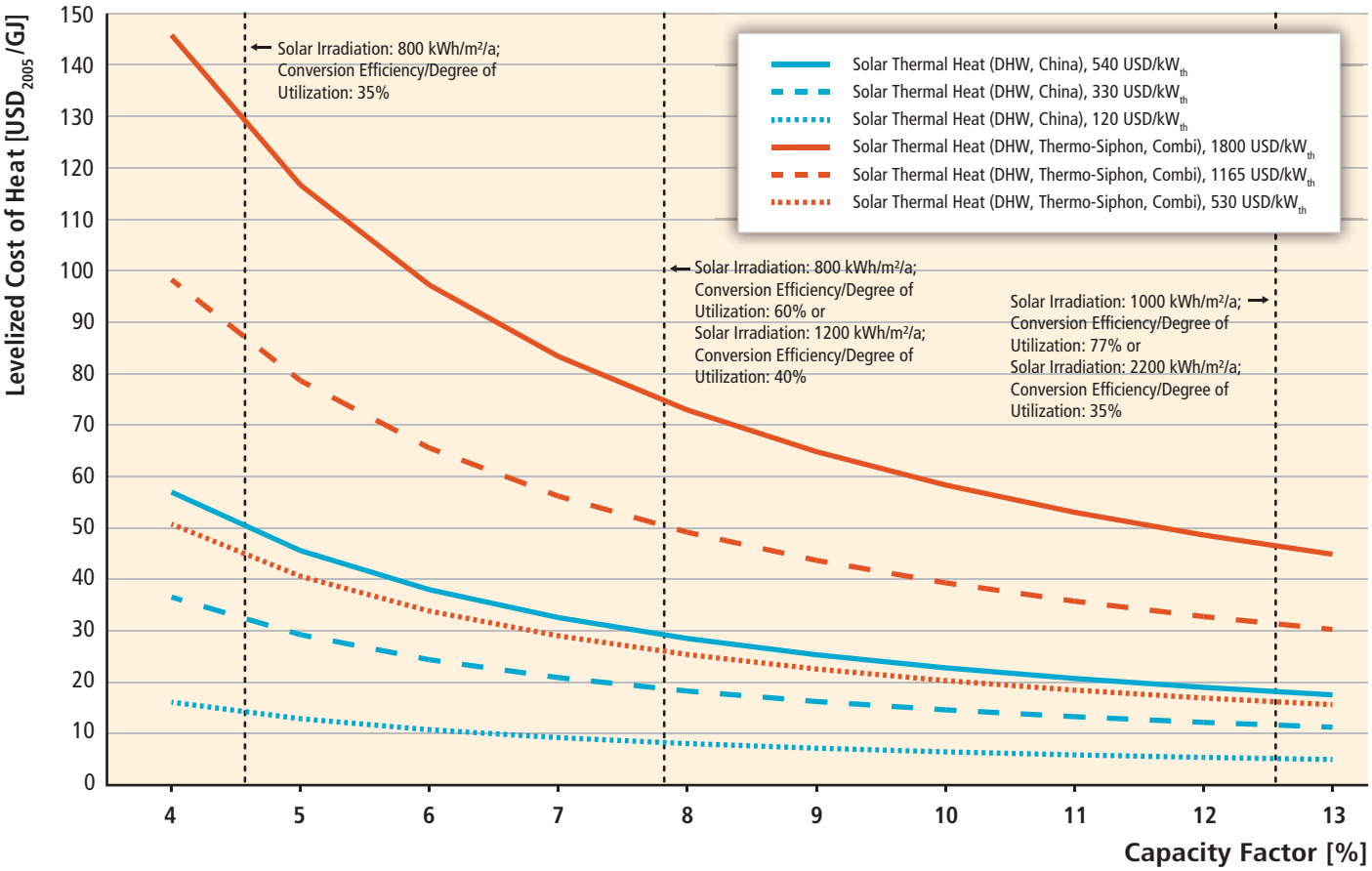


Figure TS.3.5 | Sensitivity of levelized cost of heat with respect to investment cost as a function of capacity factor. (Discount rate assumed to be 7%, annual operation and maintenance cost USD_{2005} 5.6 and14/kW, and lifetimes set at 12.5 and 20 years for domestic hot water (DHW) systems in China and various types of systems in OECD countries, respectively.) [Figure 3.16]

7% discount rate, but may be lower or higher depending on the available resource and on other framework conditions. Figure TS.3.6 shows a wide variation of LCOE for PV depending on the type of system, investment cost, discount rates and capacity factors. [1.3.2, 3.8.3, 10.5.1, Annex II, Annex III]

Costs of electricity generation or LCOE are projected by the IEA to reach the following in 2020: US $cent_{2005}$ 14.5/kWh to US $cent_{2005}$ 28.6/kWh for the residential sector and US $cent_{2005}$ 9.5/kWh to US $cent_{2005}$ 19/kWh for the utility sector under favourable conditions of 2,000 kWh/kW (equivalent to a 22.8% capacity factor) and less favourable conditions of 1,000 kWh/kW (equivalent to a 11.4% capacity factor), respectively. The goal of the US Department of Energy is even more ambitious, with an LCOE goal of US $cent_{2005}$ 5/kWh to US $cent_{2005}$ 10/kWh, depending on the end user, by 2015. [3.8.3]

CSP electricity generation: CSP electricity systems are a complex technology operating in a complex resource and financial environment; so many factors affect the LCOE. The publicized investment costs of CSP plants are often confused when compared to other renewable sources, because varying levels of integrated thermal storage increase the investment, but also improve the annual output and capacity factor of the plant. For large, state-of-the-art trough plants, current investment costs are estimated to be USD_{2005} 3.82/W (without storage) to USD_{2005} 7.65/W (with storage) depending on labour and land costs, technologies, the amount and distribution of beam irradiance and, above all, the amount of storage and the size of the solar field. Performance data for modern CSP plants are limited, particularly for plants equipped with thermal storage, because new plants only became operational from 2007 onward. Capacity factors for early plants without storage were up to 28%. For modern plants without storage, capacity factors of roughly 20 to 30% are envisioned; for plants with thermal storage, capacity factors of 30 to 75% may be achieved. Based on the standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOE for a solar trough plant with six hours of thermal storage in 2009 over a large set and range of input parameters has been calculated to range from slightly more than US $cent_{2005}$ 10/kWh to about US $cent_{2005}$ 30/kWh. Restricting the range of discount rates to 10% results in a somewhat narrower range of about US $cent_{2005}$ 20/kWh to US $cent_{2005}$ 30/kWh, which is roughly in line with the range of US $cent_{2005}$ 18 to US $cent_{2005}$ 27/kWh available in the literature. Particular cost

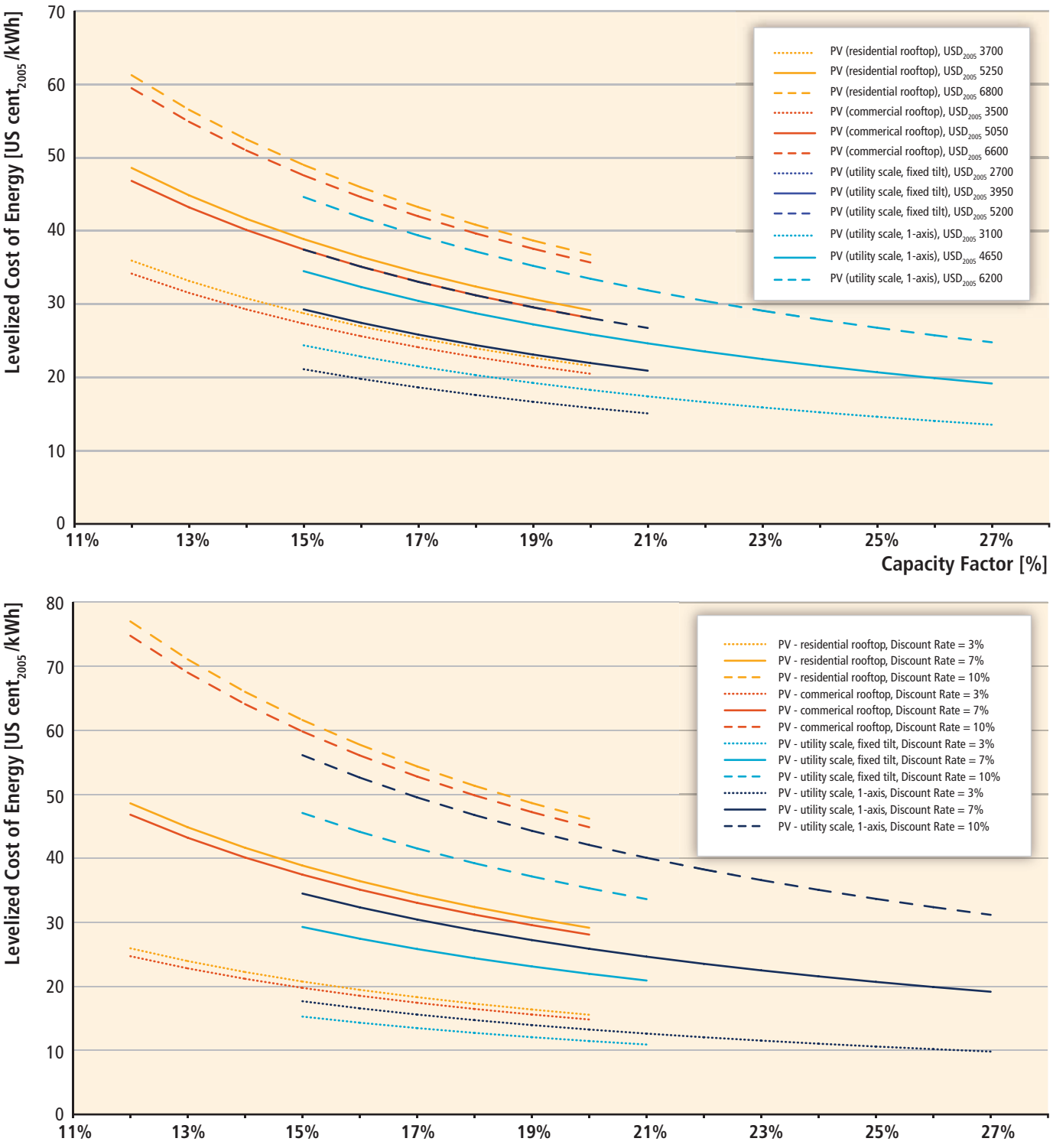


Figure TS.3.6 | Levelized cost of PV electricity generation, 2008–2009: (top) as a function of capacity factor and investment cost*,***; and (bottom) as a function of capacity factor and discount rate**,***. [Figure 3.19]

Notes: * Discount rate assumed to equal 7%. ** Investment cost for residential rooftop systems assumed at USD 5,500 US/kW, for commercial rooftop systems at USD 5,150, for utility-scale fixed tilt projects at USD 3,650/kW and for utility-scale one-axis projects at USD 4,050/kW. ***Annual O&M cost assumed at USD 41 to 64/kW, lifetime at 25 years.

and performance parameters, including the applied discount rate and capacity factor, affect the specific LCOE estimate, although the LCOE of different system configurations for otherwise identical conditions are expected to differ only marginally. [3.8.4]

The learning ratio for CSP, excluding the power block, has been estimated at 10 ± 5%. Specific LCOE goals for the USA are US cent$_{2005}$ 6/kWh to US cent$_{2005}$ 8/kWh with 6 hours storage by 2015 and US cent$_{2005}$ 50/kWh to US cent$_{2005}$ 60/kWh with 12 to 17 hours of storage by 2020. The EU is pursuing similar goals. [3.8.4]

3.9 Potential deployment

3.9.1 Near-term (2020) forecasts

Table TS.3.1 summarizes findings from the available studies on potential deployment up to 2020, as taken from the literature. Sources for the tabulated data are the following: European Renewable Energy Council (EREC) – Greenpeace (Energy [r]evolution, reference and advanced scenarios); and IEA (CSP and PV Technology Roadmaps). With regard to the solar thermal entries, note that passive solar contributions are not included in these data; although this technology reduces the demand for energy, it is not part of the supply chain considered in energy statistics. [3.9]

3.9.2 Long-term deployment in the context of carbon mitigation

Figure TS.3.7 presents the results of more than 150 long-term modelling scenarios described in Chapter 10. The potential deployment scenarios vary widely—from direct solar energy playing a marginal role in 2050 to it becoming one of the major sources of energy supply. Although direct solar energy today provides only a very small fraction of the world energy supply, it remains undisputed that this energy source has one of the largest potential futures.

Reducing cost is a key issue in making direct solar energy more commercially relevant and in position to claim a larger share of the worldwide energy market. This can only be achieved if solar technologies' costs are reduced as they move along their learning curves, which depend primarily on market volumes. In addition, continuous R&D efforts are required to ensure that the slopes of the learning curves do not flatten too early. The true costs of deploying solar energy are still unknown because the main deployment scenarios that exist today consider only a single technology. These scenarios do not take into account the co-benefits of a renewable/sustainable energy supply via a range of different RE sources and energy efficiency measures.

Potential deployment depends on the actual resources and availability of the respective technology. However, to a large extent, the regulatory and legal framework in place can foster or hinder the uptake of direct solar energy applications. Minimum building standards with respect to building orientation and insulation can reduce the energy demand of buildings significantly and can increase the share of RE supply without increasing the overall demand. Transparent, streamlined administrative procedures to install and connect solar power sources to existing grid infrastructures can further lower the cost related to direct solar energy.

4. Geothermal Energy

4.1 Introduction

Geothermal resources consist of thermal energy from the Earth's interior stored in both rock and trapped steam or liquid water, and are used to generate electric energy in a thermal power plant or in other domestic and agro-industrial applications requiring heat as well as in CHP applications. Climate change has no significant impacts on the effectiveness of geothermal energy. [4.1]

Geothermal energy is a renewable resource as the tapped heat from an active reservoir is continuously restored by natural heat production, conduction and convection from surrounding hotter regions, and the extracted geothermal fluids are replenished by natural recharge and by reinjection of the cooled fluids. [4.1]

Table TS.3.1 | Evolution of cumulative solar capacities. [Table 3.7]

		Low-Temperature Solar Heat (GW_{th})			Solar PV Electricity (GW)			CSP Electricity (GW)		
	Year	2009	2015	2020	2009	2015	2020	2009	2015	2020
Name of Scenario	**Current cumulative installed capacity**	**180**			**22**			**0.7**		
	EREC – Greenpeace (reference scenario)		180	230		44	80		5	12
	EREC – Greenpeace ([r]evolution scenario)		715	1,875		98	335		25	105
	EREC – Greenpeace (advanced scenario)		780	2,210		108	439		30	225
	IEA Roadmaps		N/A			95[1]	210		N/A	148

Note: 1. Extrapolated from average 2010 to 2020 growth rate.

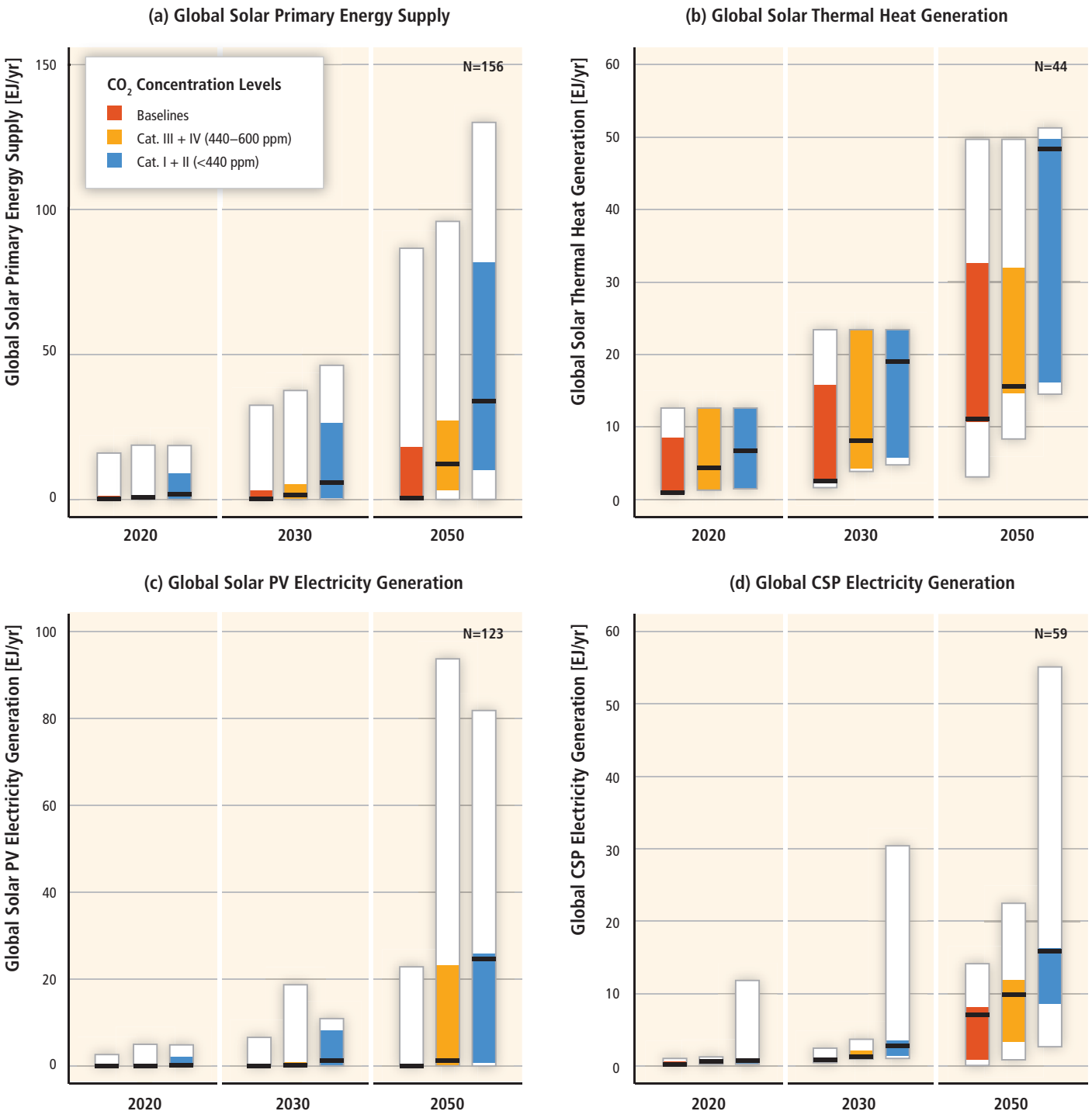


Figure TS.3.7 | Global solar supply and generation in long-term scenarios (median, 25th to 75th percentile range, and full range of scenario results; colour coding is based on categories of atmospheric CO_2 concentration level in 2100; the specific number of scenarios underlying the figure is indicated in the upper right-hand corner). (a) Global solar primary energy supply; (b) global solar thermal heat generation; (c) global solar PV electricity generation; and (d) global CSP electricity generation. [Figure 3.22]

4.2 Resource potential

The accessible stored heat from hot dry rocks in the Earth is estimated to range from 110 to 403 x 10^6 EJ down to 10 km depth, 56 to 140 x 10^6 EJ down to 5 km depth, and around 34 x 10^6 EJ down to 3 km depth. Using previous estimates for hydrothermal resources and calculations for enhanced (or engineered) geothermal systems derived from stored heat estimates at depth, geothermal technical potentials for electric generation range from 118 to 146 EJ/yr (at 3 km depth) to 318 to 1,109 EJ/yr (at 10 km depth), and for direct uses range from 10 to 312 EJ/yr (Figure TS.4.1). [4.2.1]

Technical potentials are presented on a regional basis in Table TS.4.1. The regional breakdown is based on the methodology applied by the Electric Power Research Institute to estimate theoretical geothermal

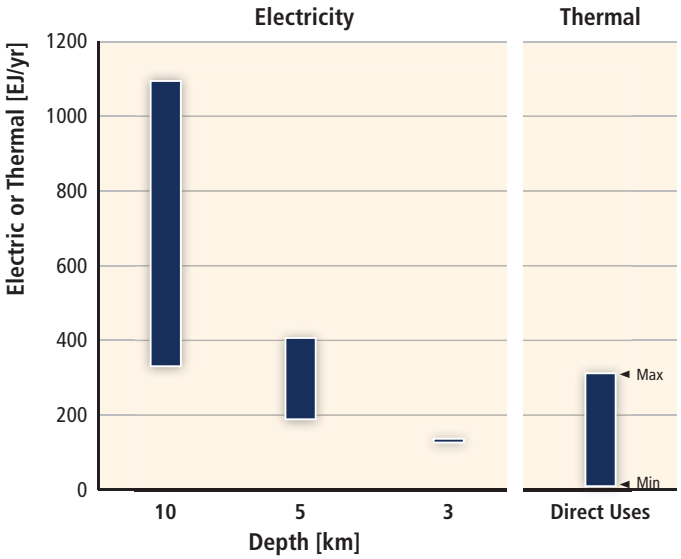


Figure TS.4.1 | Geothermal technical potentials for electricity and direct uses (heat). Direct uses usually do not require development to depths greater than about three km. [Figure 4.2]

potentials for each country, and then countries are grouped regionally. Thus, the present disaggregation of global technical potential is based on factors accounting for regional variations in the average geothermal gradient and the presence of either a diffuse geothermal anomaly or a high-temperature region associated with volcanism or plate boundaries. The separation into electric and thermal (direct uses) potentials is somewhat arbitrary in that most higher-temperature resources could be used for either, or both, in CHP applications depending on local market conditions. [4.2.2]

The heat extracted to achieve the technical potentials can be fully or partially replenished over the long term by the continental terrestrial heat flow of 315 EJ/yr at an average flux of 65 mW/m^2. [4.2.1]

4.3 Technology and applications

Geothermal energy is currently extracted using wells and other means that produce hot fluids from: (a) hydrothermal reservoirs with naturally high permeability, or (b) Enhanced or engineered geothermal systems (EGS) with artificial fluid pathways (Figure TS.4.2). Technology for electricity generation from hydrothermal reservoirs is mature and reliable, and has been operating for about 100 years. Technologies for direct heating using geothermal heat pumps (GHPs) for district heating and for other applications are also mature. Technologies for EGS are in the demonstration stage. [4.3]

Electric power from geothermal energy is especially suitable for supplying base-load power, but also can be dispatched and used to meet peak demand. Hence, geothermal electric power can complement variable electricity generation. [4.3]

Since geothermal resources are underground, exploration methods (including geological, geochemical and geophysical surveys) have been developed to locate and assess them. The objectives of geothermal exploration are to identify and rank prospective geothermal reservoirs prior to drilling. Today, geothermal wells are drilled over a range of depths up to 5 km using conventional rotary drilling methods similar to those for accessing oil and gas reservoirs. Advanced drilling technologies allow for high-temperature operation and provide directional capability. [4.3.1]

The basic types of geothermal power plants in use today are steam condensing turbines and binary cycle units. Condensing plants can be of the flash or dry-steam type (the latter do not require brine separation, resulting in simpler and cheaper plants) and are more common than binary units. They are installed in intermediate- and high-temperature resources (≥150°C) with capacities often between 20 and 110 MW_e.

Table TS.4.1 | Geothermal technical potentials on continents for the IEA regions. [Table 4.3]

REGION[1]	Electric technical potential (EJ/yr) at depths to:						Technical potentials (EJ/yr) for direct uses	
	3 km		5 km		10 km			
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
OECD North America	25.6	31.8	38.0	91.9	69.3	241.9	2.1	68.1
Latin America	15.5	19.3	23.0	55.7	42.0	146.5	1.3	41.3
OECD Europe	6.0	7.5	8.9	21.6	16.3	56.8	0.5	16.0
Africa	16.8	20.8	24.8	60.0	45.3	158.0	1.4	44.5
Transition Economies	19.5	24.3	29.0	70.0	52.8	184.4	1.6	51.9
Middle East	3.7	4.6	5.5	13.4	10.1	35.2	0.3	9.9
Developing Asia	22.9	28.5	34.2	82.4	62.1	216.9	1.8	61.0
OECD Pacific	7.3	9.1	10.8	26.2	19.7	68.9	0.6	19.4
Total	**117.5**	**145.9**	**174.3**	**421.0**	**317.5**	**1,108.6**	**9.5**	**312.2**

Note: 1. For regional definitions and country groupings see Annex II.

In binary cycle plants, the geothermal fluid passes through a heat exchanger heating another working fluid with a low boiling point, which vaporizes and drives a turbine. They allow for use of lower-temperature hydrothermal reservoirs and of EGS reservoirs (generally from 70°C to 170°C), and are often constructed as linked modular units of a few MW_e in capacity. Combined or hybrid plants comprise two or more of the above basic types to improve versatility, increase overall thermal efficiency, improve load-following capability, and efficiently cover a wide resource temperature range. Finally, cogeneration plants, or CHP plants, produce both electricity and hot water for direct use. [4.3.3]

EGS reservoirs require stimulation of subsurface regions where temperatures are high enough for effective utilization. A reservoir consisting of a fracture network is created or enhanced to provide well-connected fluid pathways between injection and production wells. Heat is extracted by circulating water through the reservoir in a closed loop and can be used for power generation and for industrial or residential heating (see Figure TS.4.2). [4.3.4]

Direct use provides heating and cooling for buildings including district heating, fish ponds, greenhouses, bathing, wellness and swimming pools, water purification/desalination and industrial and process heat for agricultural products and mineral drying. Although it can be debated whether GHPs are a 'true' application of geothermal energy, they can be utilized almost anywhere in the world for heating and cooling, and take advantage of the relatively constant ground or groundwater temperature in the range of 4°C to 30°C. [4.3.5]

4.4 Global and regional status of market and industry development

For nearly a century, geothermal resources have been used to generate electricity. In 2009, the global geothermal electric market had a wide range of participants with 10.7 GW_e of installed capacity. Over 67 TWh_e (0.24 EJ) of electricity were generated in 2008 in 24 countries (Figure TS.4.3), and provided more than 10% of total electricity demand in 6 of them. There were also 50.6 GW_{th} of direct geothermal applications operating in 78 countries, which generated 121.7 TWh_{th} (0.44 EJ) of heat in 2008. GHPs contributed 70% (35.2 GW_{th}) of this installed capacity for direct use. [4.4.1, 4.4.3]

The global average annual growth rate of installed geothermal electric capacity over the last five years (2005-2010) was 3.7%, and over the last 40 years (1970-2010), 7.0%. For geothermal direct uses rates were 12.7% (2005-2010), and 11% between 1975 and 2010. [4.4.1]

EGS is still in the demonstration phase, with one small plant in operation in France and one pilot project in Germany. In Australia considerable investment has been made in EGS exploration and development in recent years, and the USA has recently increased support for EGS research, development and demonstration as part of a revived national geothermal programme. [4.4.2]

(a)

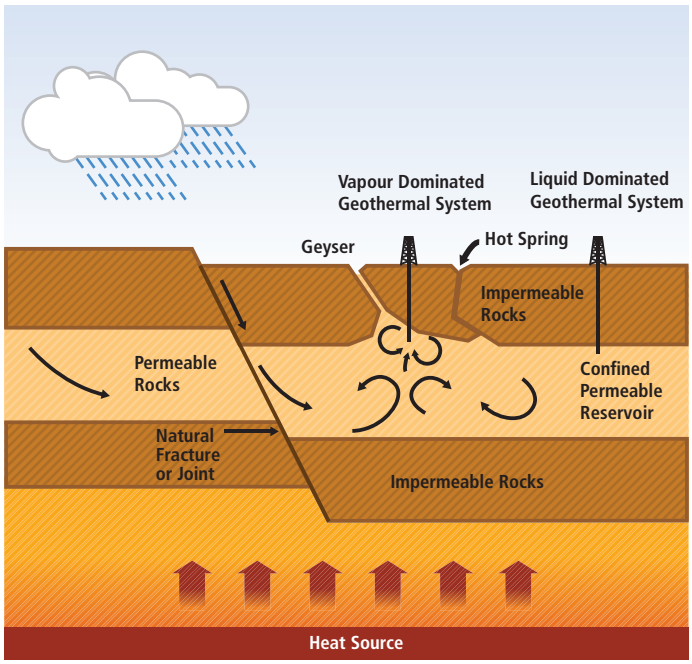


Figure TS.4.2a | Scheme showing convective (hydrothermal) resources. [Figure 4.1a]

In 2009, the main types (and relative percentages) of direct geothermal applications in annual energy use were: space heating of buildings (63%), bathing and balneology (25%), horticulture (greenhouses and soil heating) (5%), industrial process heat and agricultural drying (3%), aquaculture (fish farming) (3%) and snow melting (1%). [4.4.3]

For geothermal to reach its full capacity in climate change mitigation it is necessary to overcome technical and non-technical barriers. Policy measures specific to geothermal technology can help overcome these barriers. [4.4.4]

4.5 Environmental and social impacts

Environmental and social impacts related to geothermal energy do exist, and are typically site- and technology-specific. Usually, these impacts are manageable, and the negative environmental impacts are minor. The main GHG emission from geothermal operations is CO_2, although it is not created through combustion, but emitted from naturally occurring sources. A field survey of geothermal power plants operating in 2001 found a wide spread in the direct CO_2 emission rates, with values ranging from 4 to 740 g/kWh_e depending on technology design and composition of the geothermal fluid in the underground reservoir. Direct CO_2 emissions for direct use applications are negligible, while EGS power plants are likely to be designed as liquid-phase closed-loop circulation systems, with zero direct emissions. Lifecycle assessments anticipate that CO_2-equivalent emissions are less than 50 g/kWh_e for geothermal power plants; less than 80 g/kWh_e for projected EGS; and

(b)

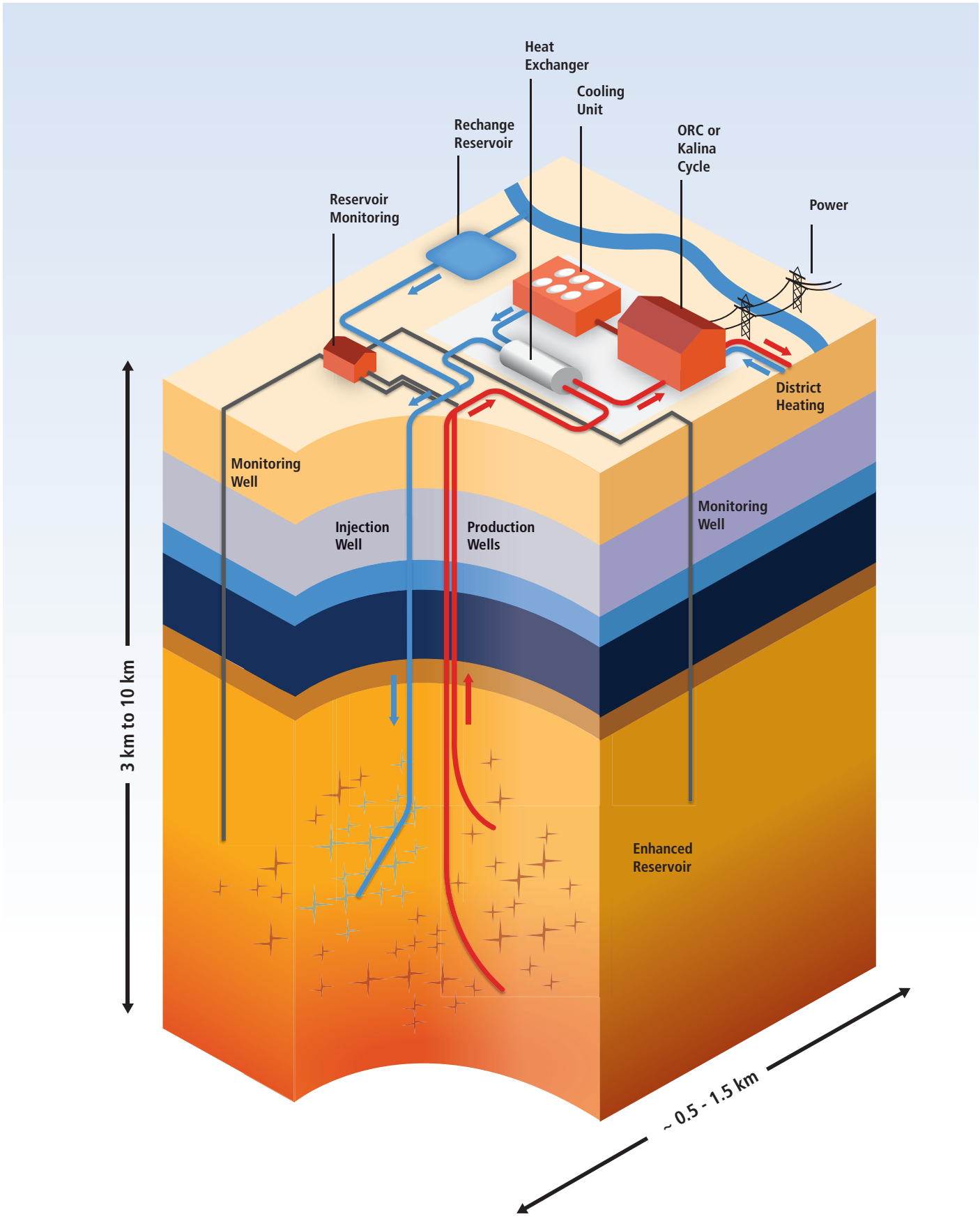


Figure TS.4.2b | Scheme showing conductive (EGS) resources. [Figure 4.1b]

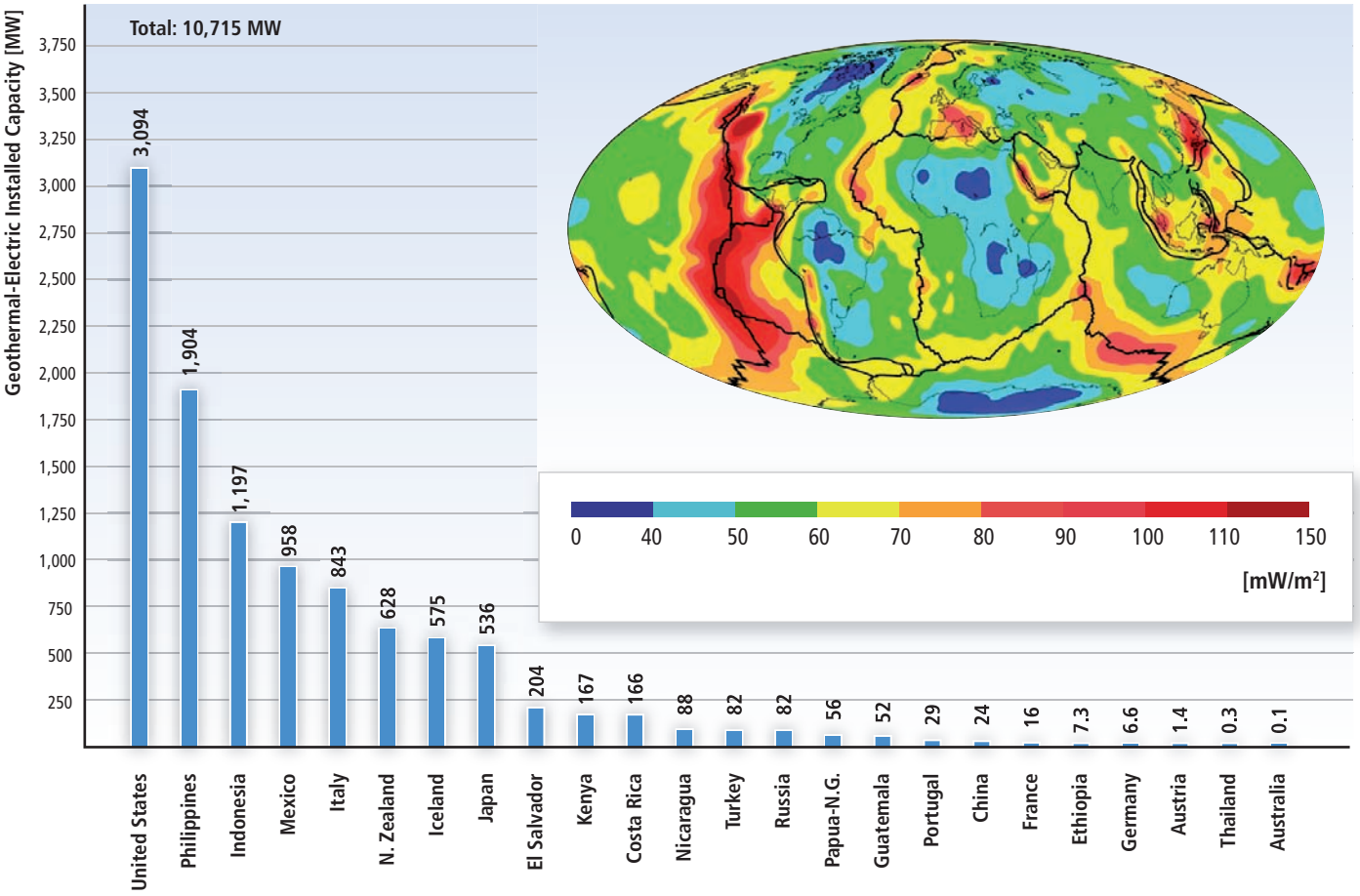


Figure TS.4.3 | Geothermal electric installed capacity by country in 2009. Figure shows worldwide average heat flow in mW/m² and tectonic plate boundaries. [Figure 4.5]

between 14 and 202 g/kWh$_{th}$ for district heating systems and GHPs. [4.5, 4.5.1, 4.5.2]

Environmental impacts associated with geothermal projects involve consideration of a range of local air, land and water use impacts during both construction and operational phases that are common to most energy projects as well as specific to geothermal energy. Geothermal systems involve natural phenomena, and typically discharge gases mixed with steam from surface features, and minerals dissolved in water from hot springs. Some gases may be dangerous, but are typically either treated or monitored during production. In the past, surface disposal of separated water was more common, but today happens only in exceptional circumstances. Geothermal brine is usually injected back into the reservoir to support reservoir pressures and to avoid adverse environmental effects. Surface disposal, if significantly in excess of natural hot-spring flow rates, and if not strongly diluted, can have adverse effects on the ecology of rivers, lakes or marine environments. [4.5.3.1]

Local hazards arising from natural phenomena, such as micro-earthquakes, hydrothermal steam eruptions and ground subsidence may be influenced by the operation of geothermal fields. During 100 years of development, no buildings or structures within a geothermal operation or local community have been significantly damaged by shallow earthquakes originating from either geothermal production or injection activities. Some EGS demonstration projects, particularly in populated areas of Europe, have raised social opposition. The process of high-pressure injection of cold water into hot rock generates small seismic events. Induced seismic events have not been large enough to lead to human injury or significant property damage, but proper management of this issue will be an important step to facilitating significant expansion of future EGS projects. [4.5.3.2]

Land use requirements range from 160 to 290 m²/GWh$_e$/yr excluding wells, and up to 900 m²/GWh/yr including wells. Specific geothermal impacts on land use include effects on outstanding natural features such as springs, geysers and fumaroles. Land use issues in many settings (e.g., Japan, the USA and New Zealand) can be a serious impediment to further expansion of geothermal development. [4.5.3.3]

Geothermal resources may also have significant environmental advantages compared to the energy use they otherwise offset. [4.5.1]

4.6 Prospects for technology improvement, innovation and integration

Geothermal resources can be integrated into all types of electrical power supply systems, from large, interconnected continental transmission grids to onsite use in small, isolated villages or autonomous buildings. Since geothermal energy typically provides base-load electric generation, integration of new power plants into existing power systems does not present a major challenge. For geothermal direct uses, no integration problems have been observed, and for heating and cooling, geothermal energy (including GHPs) is already widespread at the domestic, community and district scales. Section 8 of this summary addresses integration issues in greater depth. [4.6]

Several prospects for technology improvement and innovation can reduce the cost of producing geothermal energy and lead to higher energy recovery, longer field and plant lifetimes, and better reliability. Advanced geophysical surveys, injection optimization, scaling/corrosion inhibition, and better reservoir simulation modelling will help reduce the resource risks by better matching installed capacity to sustainable generation capacity. [4.6]

In exploration, R&D is required to locate hidden geothermal systems (e.g., with no surface manifestations) and for EGS prospects. Refinement and wider usage of rapid reconnaissance geothermal tools such as satellite- and airborne-based hyper-spectral, thermal infrared, high-resolution panchromatic and radar sensors could make exploration efforts more effective. [4.6.1]

Special research in drilling and well construction technology is needed to improve the rate of penetration when drilling hard rock and to develop advanced slim-hole technologies, with the general objectives of reducing the cost and increasing the useful life of geothermal production facilities. [4.6.1]

The efficiency of the different system components of geothermal power plants and direct uses can still be improved, and it is important to develop conversion systems that more efficiently utilize the energy in the produced geothermal fluid. Another possibility is the use of suitable oil and gas wells potentially capable of supplying geothermal energy for power generation. [4.6.2]

EGS projects are currently at a demonstration and experimental stage. EGS require innovative methods to hydraulically stimulate reservoir connectivity between injection and production wells to attain sustained, commercial production rates while reducing the risk of seismic hazard, and to improve numerical simulators and assessment methods to enable reliable predictions of chemical interaction between geo-fluids and geothermal reservoirs rocks. The possibility of using CO_2 as a working fluid in geothermal reservoirs, particularly in EGS, is also under investigation since it could provide a means for enhancing the effect of geothermal energy deployment, lowering CO_2 emissions beyond just generating electricity with a carbon-free renewable resource. [4.6.3]

Currently there are no technologies in use to tap submarine geothermal resources, but in theory electrical energy could be produced directly from a hydrothermal vent. [4.6.4]

4.7 Cost trends

Geothermal projects typically have high upfront investment costs, due to the need to drill wells and construct power plants, and relatively low operational costs. Though costs vary by project, the LCOE of power plants using hydrothermal resources are often competitive in today's electricity markets; the same is true for direct uses of geothermal heat. EGS plants remain in the demonstration phase, but estimates of EGS costs are higher than those for hydrothermal reservoirs. [4.7]

The investment costs of a typical geothermal electric project are: (a) exploration and resource confirmation (10 to 15% of the total); (b) drilling of production and injection wells (20 to 35% of the total); (c) surface facilities and infrastructure (10 to 20% of the total); and (d) power plant (40 to 81% of the total). Current investment costs vary worldwide between USD_{2005} 1,800 and 5,200/kW_e. [4.7.1]

Geothermal electric O&M costs, including make-up wells (i.e., new wells to replace failed wells and restore lost production or injection capacity), have been calculated to be USD_{2005} 152 to 187/kW_e/yr, but in some countries can be significantly lower (e.g., USD_{2005} 83 to 117/kW_e/yr in New Zealand). [4.7.2]

Power plant longevity and capacity factor are also important economic parameters. The worldwide capacity factor average in 2008 for existing geothermal power plants was 74.5%, with newer installations above 90%. [4.7.3]

Based on a standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOE for hydrothermal geothermal projects over a large set and range of input parameters has been calculated to range from US $cents_{2005}$ 3.1/kWh to US $cents_{2005}$ 17/kWh, depending on the particular type of technology and project-specific conditions. Using a narrower set and range of parameters, Figure TS.4.4 shows that, at a 7% discount rate, recently installed green-field hydrothermal projects operating at the global average capacity factor of 74.5% (and under other conditions specified in [4.7.4]) have LCOE in the range from US $cents_{2005}$ 4.9/kWh to US $cents_{2005}$ 7.2/kWh for condensing flash plants and, for binary cycle plants, from US $cents_{2005}$ 5.3/kWh to US $cents_{2005}$ 9.2/kWh. The LCOE is shown to vary substantially with capacity factor, investment cost and discount rate. No LCOE data exist for EGS, but some projections have been made using different models for several cases with diverse temperatures and depths, for example, US $cents_{2005}$ 10/kWh to US $cents_{2005}$ 17.5/kWh for relatively high-grade EGS resources. [1.3.2, 4.7.4, 10.5.1, Annex II, Annex III]

Estimates of possible cost reductions from design changes and technical advances rely solely on expert knowledge of the geothermal process

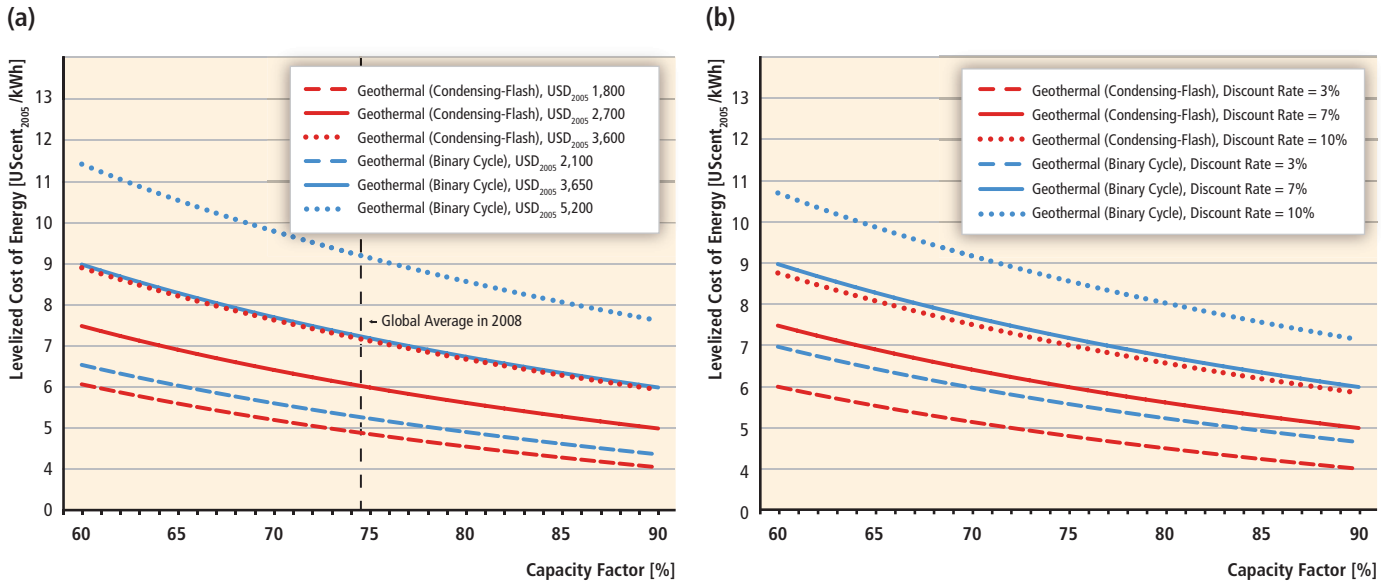


Figure TS.4.4 | Levelized cost of geothermal power, 2008: a) as a function of capacity factor and cost*,***; and b) as a function of capacity factor and discount rate**,***. [Figure 4.8]

Notes: * Discount rate assumed to equal 7%. ** Investment cost for condensing flash plants assumed at USD 2,700/kW and for binary-cycle plants at USD 3,650/kW. ***Annual O&M cost assumed to be USD 170/kW and lifetime 27.5 years.

value chain, as published learning curve studies are limited. Engineering improvements in design and stimulation of geothermal reservoirs, and improvements in materials, operation and maintenance are expected to have the greatest impact on LCOE in the near term, for example, leading to higher capacity factors and a lower contribution of drilling cost to overall investment costs. For green-field projects in 2020, the worldwide average projected LCOE is expected to range from US cents$_{2005}$ 4.5/kWh to US cents$_{2005}$ 6.6/kWh for condensing flash plants and from US cents$_{2005}$ 4.9/kWh to US cents$_{2005}$ 8.6/kWh for binary cycle plants ranges, given an average worldwide capacity factor of 80%, a 27.5-year lifetime and a discount rate of 7%. Therefore, a global average LCOE reduction of about 7% is expected for geothermal flash and binary plants by 2020. Future costs of EGS are expected to decline to lower levels as well. [4.7.5]

The LCOH for direct-use projects has a wide range, depending upon specific use, temperature and flow rate required, associated O&M and labour costs, and output of the produced product. In addition, costs for new construction are usually less than costs for retrofitting older structures. The cost figures given in Table TS.4.2 are based on a climate typical of the northern half of the USA or Europe. Heating loads would be higher for more northerly climates such as Iceland, Scandinavia and Russia. Most figures are based on cost in the USA, but would be similar in developed countries and lower in developing countries. [4.7.6]

Industrial applications are more difficult to quantify, as they vary widely depending upon the energy requirements and the product to be produced. These plants normally require higher temperatures and often compete with power plant use; however, they do have a high load factor of 0.40 to 0.70, which improves the economics. Industrial applications vary from large food, timber and mineral drying plants (USA and New Zealand) to pulp and paper plants (New Zealand). [4.7.6]

4.8 Potential deployment

Geothermal energy can contribute to near- and long-term carbon emissions reduction. In 2008, global geothermal energy use represented only about 0.1% of the global primary energy supply. However, by 2050, geothermal could meet roughly 3% of the global electricity demand and 5% of the global demand for heating and cooling. [4.8]

Taking into account the geothermal electric projects under construction or planned in the world, installed geothermal capacity is expected to reach 18.5 GW$_e$ by 2015. Practically all the new power plants expected to be on line by 2015 will be flash-condensing and binary utilizing hydrothermal resources, with a small contribution from EGS projects. Geothermal direct uses (heat applications including GHP) are expected to grow at the same historic annual rate (11% between 1975 and 2010) to reach 85.2 GW$_{th}$. By 2015, total electric generation could reach 121.6 TWh/yr (0.44 EJ/yr) while direct generation of heat could reach 224 TWh$_{th}$/yr (0.8 EJ/yr), with the regional breakdown presented in Table TS.4.3. [4.8.1]

The long-term potential deployment of geothermal energy based on a comprehensive assessment of numerous model-based scenarios is mentioned in Section 10 of this summary and spans a broad range. The scenario medians for three GHG concentration stabilization ranges, based

Table TS.4.2 | Investment costs and calculated levelized cost of heat (LCOH) for several direct geothermal applications. [Table 4.8]

Heat application	Investment cost (USD_{2005}/kW_{th})	LCOH (USD_{2005}/GJ) at discount rates of:		
		3%	7%	10%
Space heating (buildings)	1,600–3,940	20–50	24–65	28–77
Space heating (districts)	570–1,570	12–24	14–31	15–38
Greenhouses	500–1,000	7.7–13	8.6–14	9.3–16
Uncovered aquaculture ponds	50–100	8.5–11	8.6–12	8.6–12
GHP (residential and commercial)	940–3,750	14–42	17–56	19–68

Table TS.4.3 | Regional current and forecast installed capacity for geothermal power and direct uses (heat) and forecast generation of electricity and heat by 2015. [Table 4.9]

REGION[1]	Current capacity (2010)		Forecast capacity (2015)		Forecast generation (2015)	
	Direct (GW_{th})	Electric (GW_e)	Direct (GW_{th})	Electric (GW_e)	Direct (TW_{th})	Electric (TWh_e)
OECD North America	13.9	4.1	27.5	6.5	72.3	43.1
Latin America	0.8	0.5	1.1	1.1	2.9	7.2
OECD Europe	20.4	1.6	32.8	2.1	86.1	13.9
Africa	0.1	0.2	2.2	0.6	5.8	3.8
Transition Economies	1.1	0.1	1.6	0.2	4.3	1.3
Middle East	2.4	0	2.8	0	7.3	0
Developing Asia	9.2	3.2	14.0	6.1	36.7	40.4
OECD Pacific	2.8	1.2	3.3	1.8	8.7	11.9
TOTAL	**50.6**	**10.7**	**85.2**	**18.5**	**224.0**	**121.6**

Notes: 1. For regional definitions and country groupings see Annex II. Estimated average annual growth rate for 2010 to 2015 is 11.5% for power and 11% for direct uses. Average worldwide capacity factors of 75% (for electric) and 30% (for direct use) were assumed by 2015.

Table TS.4.4 | Potential geothermal deployments for electricity and direct uses in 2020 through 2050. [Table 4.10]

Year	Use	Capacity[1] (GW)	Generation (TWh/yr)	Generation (EJ/yr)	Total (EJ/yr)
2020	Electricity	25.9	181.8	0.65	2.01
	Direct	143.6	377.5	1.36	
2030	Electricity	51.0	380.0	1.37	5.23
	Direct	407.8	1,071.7	3.86	
2050	Electricity	150.0	1,182.8	4.26	11.83
	Direct	800.0	2,102.3	7.57	

Notes: 1. Installed capacities for 2020 and 2030 are extrapolated from 2015 estimates using a 7% annual growth rate for electricity and 11% for direct uses, and for 2050 are the middle value between projections cited in Chapter 4. Generation was estimated with average worldwide capacity factors of 80% (2020), 85% (2030) and 90% (2050) for electricity and of 30% for direct uses.

on the AR4 baselines (>600 ppm CO_2), 440 to 600 ppm (Categories III and IV) and <440 ppm (Categories I and II), range from 0.39 to 0.71 EJ/yr for 2020, 0.22 to 1.28 EJ/yr for 2030 and 1.16 to 3.85 EJ/yr for 2050.

Carbon policy is likely to be one of the main driving factors for future geothermal development, and under the most favourable GHG concentration stabilization policy (<440 ppm), geothermal deployment by 2020, 2030 and 2050 could be significantly higher than the median values noted above. By projecting the historic average annual growth rates of geothermal power plants (7%) and direct uses (11%) from the estimates for 2015, the installed geothermal capacity in 2020 and 2030 for electricity and direct uses could be as shown in Table TS.4.4.

By 2050, the geothermal-electric capacity would be as high as 150 GW_e (with half of that comprised of EGS plants), and up to an additional 800 GW_{th} of direct-use plants (Table TS.4.4). [4.8.2]

Even the highest estimates for the long-term contribution of geothermal energy to the global primary energy supply (52.5 EJ/yr by 2050) are within the technical potential ranges (118 to 1,109 EJ/yr for electricity and 10 to 312 EJ/yr for direct uses) and even within the upper range of hydrothermal resources (28.4 to 56.8 EJ/yr). Thus, technical potential is not likely to be a barrier to reaching more ambitious levels of geothermal deployment (electricity and direct uses), at least on a global basis. [4.8.2]

Evidence suggests that geothermal supply could meet the upper range of projections derived from a review of about 120 energy and GHG-reduction scenarios. With its natural thermal storage capacity, geothermal is especially suitable for supplying base-load power. Considering its technical potential and possible deployment, geothermal energy could meet roughly 3% of global electricity demand by 2050, and also has the potential to provide roughly 5% of the global demand for heating and cooling by 2050. [4.8.3]

5. Hydropower

5.1 Introduction

Hydropower is a renewable energy source where power is derived from the energy of water moving from higher to lower elevations. It is a proven, mature, predictable and cost-competitive technology. The mechanical power of falling water is an old tool used for various services from the time of the Greeks more than 2,000 years ago. The world's first hydroelectric station of 12.5 kW was commissioned on 30 September 1882 on Fox River at the Vulcan Street Plant in Appleton, Wisconsin, USA. Though the primary role of hydropower in global energy supply today is in providing centralized electricity generation, hydropower plants also operate in isolation and supply independent systems, often in rural and remote areas of the world. [5.1]

5.2 Resource potential

The annual global technical potential for hydropower generation is 14,576 TWh (52.47 EJ) with a corresponding estimated total capacity potential of 3,721 GW—four times the currently installed global hydropower capacity (Figure TS.5.1). Undeveloped capacity ranges from about 47% in Europe to 92% in Africa, indicating large and well-distributed opportunities for hydropower development worldwide (see Table TS.5.1). Asia and Latin America have the largest technical potentials and the largest undeveloped resources. Africa has highest portion of total potential that is still undeveloped. [5.2.1]

It is noteworthy that the total installed capacities of hydropower in North America, Latin America, Europe and Asia are of the same order of magnitude and, in Africa and Australasia/Oceania, an order of magnitude less; Africa due to underdevelopment and Australasia/Oceania because of size, climate and topography. The global average capacity factor for hydropower plants is 44%. Capacity factor can be indicative of how hydropower is employed in the energy mix (e.g., peaking versus base-load generation) or water availability, or can be an opportunity for increased generation through equipment upgrades and operational optimization. [5.2.1]

The resource potential for hydropower could change due to climate change. Based on a limited number of studies to date, the climate change impacts on existing global hydropower systems is expected to be slightly positive, even though individual countries and regions could have significant positive or negative changes in precipitation and runoff. Annual power production capacity in 2050 could increase by 2.7 TWh (9.72 PJ) in Asia under the SRES A1B scenario, and decrease by 0.8 TWh (2.88 PJ) in Europe. In other regions, changes are found to be even smaller. Globally, the changes caused by climate change in the existing hydropower production system are estimated to be less than 0.1%, although additional research is needed to lower the uncertainty of these projections. [5.2.2]

5.3 Technology and applications

Hydropower projects are usually designed to suit particular needs and specific site conditions, and are classified by project type, head (i.e., the vertical height of water above the turbine) or purpose (single- or multi-purpose). Size categories (installed capacity) are based on national definitions and differ worldwide due to varying policies. There is no immediate, direct link between installed capacity as a classification criterion and general properties common to all hydropower plants (HPPs) above or below that MW limit. All in all, classification according to size, while both common and administratively simple, is—to a degree—arbitrary: general concepts like 'small' or 'large' hydropower are not technically or scientifically rigorous indicators of impacts, economics or characteristics. It may be more useful to evaluate a hydropower project on its sustainability or economic performance thus setting out more realistic indicators. The cumulative relative environmental and social impacts of large versus small hydropower development remain unclear and context dependent. [5.3.1]

Hydropower plants come in three main project types: run-of-river (RoR), storage and pumped storage. RoR HPPs have small intake basins with no storage capacity. Power production therefore follows the hydrological cycle of the watershed. For RoR HPPs the generation varies as water availability changes and thus they may be operated as variable in small streams or as base-load power plants in large rivers. Large-scale RoR HPPs may have some limited ability to regulate water flow, and if they operate in cascades in unison with storage hydropower in upstream reaches, they may contribute to the overall regulating and balancing ability of a fleet of HPPs. A fourth category, in-stream (hydrokinetic) technology, is less mature and functions like RoR without any regulation. [5.3.2]

Hydropower projects with a reservoir (storage hydropower) deliver a broad range of energy services such as base load, peak, and energy storage, and act as a regulator for other sources. In addition they often deliver services that go beyond the energy sector, including flood control, water supply, navigation, tourism and irrigation. Pumped storage plants store water as a source for electricity generation. By reversing the

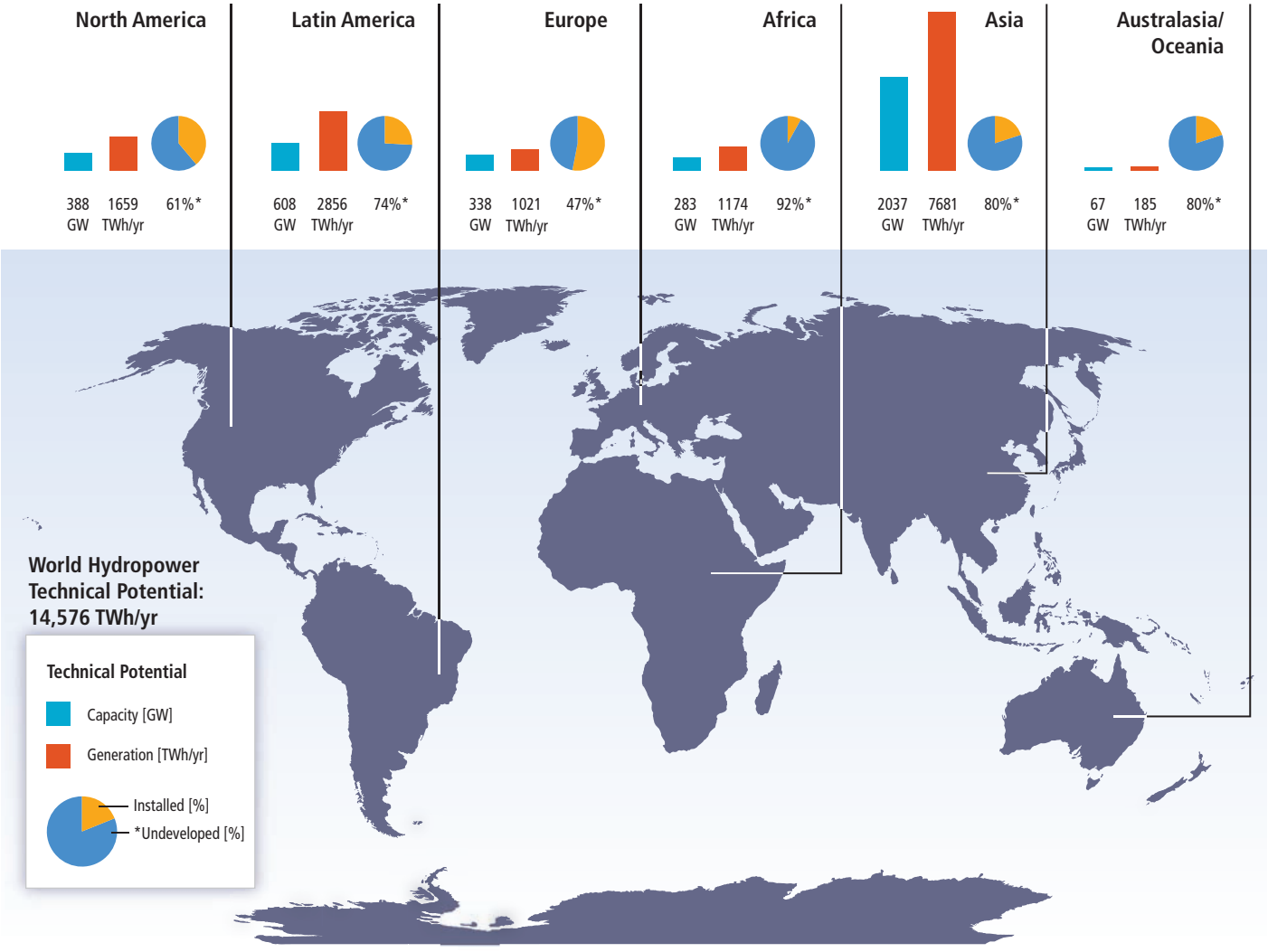


Figure TS.5.1 | Regional hydropower technical potential in terms of annual generation and installed capacity and the percentage of undeveloped technical potential in 2009. [Figure 5.2]

Table TS.5.1 | Regional hydro power technical potential in terms of annual generation and installed capacity (GW); and current generation, installed capacity, average capacity factors and resulting undeveloped potential as of 2009. [Table 5.1]

World region	Technical potential, annual generation TWh/yr (EJ/yr)	Technical potential, installed capacity (GW)	2009 Total generation TWh/yr (EJ/yr)	2009 Installed capacity (GW)	Undeveloped potential (%)	Average regional capacity factor (%)
North America	1,659 (5.971)	388	628 (2.261)	153	61	47
Latin America	2,856 (10.283)	608	732 (2.635)	156	74	54
Europe	1,021 (3.675)	338	542 (1.951)	179	47	35
Africa	1,174 (4.226)	283	98 (0.351)	23	92	47
Asia	7,681 (27.651)	2,037	1,514 (5.451)	402	80	43
Australasia/Oceania	185 (0.666)	67	37 (0.134)	13	80	32
World	**14,576 (52.470)**	**3,721**	**3,551 (12.783)**	**926**	**75**	**44**

flow of water, electrical energy can be produced on demand, with a very fast response time. Pumped storage is the largest-capacity form of grid energy storage now available. [5.3.2.2–5.3.2.3]

Sediment transport and reservoir sedimentation are problems that need to be understood as they have a number of negative effects on HPP performance: depletion of reservoir storage capacity over time; an increase in downstream degradation; increased flood risk upstream of reservoirs; generation losses due to reductions in turbine efficiency; increased frequency of repair and maintenance; and reductions in turbine lifetime and in regularity of power generation. The sedimentation problem may ultimately be controlled through land use policies and the

protection of vegetation coverage. Hydropower has the best conversion efficiency of all known energy sources (about 90% efficiency, water to wire) and a very high energy payback ratio. [5.3.3]

Normally the life of a hydroelectric power plant is 40 to 80 years. Electrical and mechanical components and control equipment wear out early compared to civil structures, typically in 30 to 40 years, after which they require renovation. Upgrading/up-rating of HPPs calls for a systematic approach as there are a number of factors (hydraulic, mechanical, electrical and economic) that play a vital role in deciding the course of action. From a techno-economic viewpoint, up-rating should be considered along with renovation and modernization measures. Hydropower generating equipment with improved performance can be retrofitted, often to accommodate market demands for more flexible, peaking modes of operation. Most of the 926 GW of hydropower equipment in operation today (2010) will need to be modernized by 2030 to 2040. Refurbishment of existing hydropower plants often results in enhanced hydropower capacity, both where turbine capacity is being renovated/up-rated or where existing civil infrastructure (like barrages, weirs, dams, canal tunnels, etc.) is being reworked to add new hydropower facilities. [5.3.4]

5.4 Global and regional status of market and industry development

Hydropower is a mature, predictable and price-competitive technology. It currently provides approximately 16% of the world's total electricity production and 86% of all electricity from renewable sources. While hydropower contributes to some level of power generation in 159 countries, 5 countries make up more than half of the world's hydropower production: China, Canada, Brazil, the USA and Russia. The importance of hydroelectricity in the electricity matrix of these countries differs widely, however. While Brazil and Canada are heavily dependent on hydropower to produce 84% and 59% of total generation, respectively, Russia and China produce only 19% and 16% of their total electricity from hydropower, respectively. Despite the significant growth of hydroelectric production around the globe, the percentage share of hydroelectricity has dropped during the last three decades (1973 to 2008) from 21 to 16%, because electricity load and other generation sources have grown more rapidly than has hydropower. [5.4.1]

Carbon credits benefit hydropower projects by helping to secure financing and to reduce risks. Financing is the most decisive step in the entire project development process. Hydropower projects are one of the largest contributors to the flexible mechanisms of the Kyoto Protocol and therefore to existing carbon credit markets. Out of the 2,062 projects registered by the Clean Development Mechanism (CDM) Executive Board by 1 March 2010, 562 are hydropower projects. With 27% of the total number of projects, hydropower is the CDM's leading deployed RE source. China, India, Brazil and Mexico represent roughly 75% of the hosted projects. [5.4.3.1]

Many economical hydropower projects are financially challenged. High up-front costs are a deterrent for investment. Also, hydropower tends to have lengthy lead times for planning, permitting and construction. In the evaluation of lifecycle costs, hydropower often has a very high performance, with annual O&M costs being a fraction of the capital investment. As hydropower and its industry are old and mature, it is expected that the hydropower industry will be able to meet the demand that will be created by the predicted deployment rate in the years to come. For example, in 2008 the hydropower industry managed to install more than 41 GW of new capacity worldwide. [5.4.3.2]

The development of more appropriate financing models is a major challenge for the hydropower sector, as is finding the optimum roles for the public and private sectors. The main challenges for hydropower relate to creating private-sector confidence and reducing risk, especially prior to project permitting. Green markets and trading in emissions reductions will undoubtedly provide incentives. Also, in developing regions, such as Africa, interconnection between countries and the formation of power pools is building investor confidence in these emerging markets. [5.4.3.2]

The concepts of classifying HPPs as 'small' or 'large', as defined by installed capacity (MW), can act as a barrier to the development of hydropower. For example, these classifications can impact the financing of new hydropower plants, determining how hydropower is treated in climate change and energy policies. Different incentives are used for small-scale hydropower (FITs, green certificates and bonuses) depending on the country, but no incentives are available for large-scale HPPs. The EU Linking Directive sets a limit for carbon credits issued from HPPs to 20 MW. The same limit is found in the UK Renewables Obligation, a green certificate market-based mechanism. Likewise, in several countries FITs do not apply to hydropower above a certain size limit (e.g., France 12 MW, Germany 5 MW, India 5 and 25 MW). [5.4.3.4]

The UNFCCC CDM Executive Board has decided that storage hydropower projects will have to follow the power density indicator (PDI: installed capacity/reservoir area in W/m^2) to be eligible for CDM credits. The PDI rule seems to presently exclude storage hydropower from qualifying for CDM (or Joint Implementation) credits and may lead to suboptimal development of hydropower resources as the non-storage RoR option will be favoured.

5.5 Integration into broader energy systems

Hydropower's large capacity range, its flexibility, storage capability (when coupled with a reservoir), and ability to operate in a stand-alone mode or in grids of all sizes enables it to deliver a broad range of services. [5.5]

Hydropower can be delivered through the national and regional electric grid, mini-grids and also in isolated mode. Realization has been growing in developing countries that small-scale hydropower schemes have

an important role to play in the socioeconomic development of remote rural, especially hilly, areas as those can provide power for industrial, agricultural and domestic uses. In China, small-scale HPPs have been one of the most successful examples of rural electrification, where over 45,000 small HPPs totalling over 55,000 MW of capacity and producing 160 TWh (576 PJ) of generation annually benefit over 300 million people. [5.5.2]

With a very large reservoir relative to the size of the hydropower plant (or very consistent river flows), HPPs can generate power at a near-constant level throughout the year (i.e., operate as a base-load plant). Alternatively, in the case that the hydropower capacity far exceeds the amount of reservoir storage, the hydropower plant is sometimes referred to as energy-limited. An energy-limited hydro plant would exhaust its 'fuel supply' by consistently operating at its rated capacity throughout the year. In this case, the use of reservoir storage allows hydropower generation to occur at times that are most valuable from the perspective of the power system rather than at times dictated solely by river flows. Since electrical demand varies during the day and night, during the week and seasonally, storage hydropower generation can be timed to coincide with times where the power system needs are the greatest. In part, these times will occur during periods of peak electrical demand. Operating hydropower plants in a way to generate power during times of high demand is referred to as peaking operation (in contrast to base-load). Even with storage, however, hydropower generation will still be limited by the size of the storage, the rated electrical capacity of the hydropower plant, and downstream flow constraints for irrigation, recreation or environmental uses of the river flows. Hydropower peaking may, if the outlet is directed to a river, lead to rapid fluctuations in river flow, water-covered area, depth and velocity. In turn this may, depending on local conditions, lead to negative impacts in the river unless properly managed. [5.5.3]

In addition to hydropower supporting fossil and nuclear generation technologies, it can also help reduce the challenges with integrating variable renewable resources. In Denmark, for example, the high level of variable wind energy (>20% of the annual energy demand) is managed in part through strong interconnections (1 GW) to Norway, which has substantial storage hydropower. More interconnectors to Europe may further support increasing the share of wind power in Denmark and Germany. Increasing variable generation will also increase the amount of balancing services, including regulation and load following, required by the power system. In regions with new and existing hydropower facilities, providing these services from hydropower may avoid the need to rely on increased part-load and cycling of conventional thermal plants to provide these services. [5.5.4]

Though hydro has the potential to offer significant power system services in addition to energy and capacity, interconnecting and reliably utilizing HPPs may also require changes to power systems. The interconnection of hydropower to the power system requires adequate transmission capacity from HPPs to demand centres. Adding new HPPs has in the past required network investments to extend the transmission network. Without adequate transmission capacity, HPP operation can be constrained such that the services offered by the plant are less than what it could offer in an unconstrained system. [5.5.5]

5.6 Environmental and social impacts

Like all energy and water management options, hydropower projects have negative and positive environmental and social impacts. On the environmental side, hydropower may have a significant environmental footprint at local and regional levels but offers advantages at the macro-ecological level. With respect to social impacts, hydropower projects may entail the relocation of communities living within or nearby the reservoir or the construction sites, compensation for downstream communities, public health issues, and others. A properly designed hydropower project may, however, be a driving force for socioeconomic development, though a critical question remains about how these benefits are shared. [5.6]

All hydroelectric structures affect a river's ecology, mainly by inducing a change into its hydrologic characteristics and by disrupting the ecological continuity of sediment transport and fish migration through the building of dams, dikes and weirs. However, the extent to which a river's physical, chemical, biological and ecosystem characteristics are modified depends largely on the type of HPP. Whereas RoR hydropower projects do not alter a river's flow regime, the creation of a reservoir for storage hydropower entails a major environmental change by transforming a fast-running river ecosystem into a still-standing artificial lake. [5.6.1.1–5.6.1.6]

Similar to a hydropower project's ecological effects, the extent of its social impacts on the local and regional communities, land use, economy, health and safety or heritage varies according to project type and site-specific conditions. While RoR projects generally introduce little social change, the creation of a reservoir in a densely populated area can entail significant challenges related to resettlement and impacts on the livelihoods of the downstream populations. Restoration and improvement of living standards of affected communities is a long-term and challenging task that has been managed with variable success in the past. Whether HPPs can contribute to fostering socioeconomic development depends largely on how the generated services and revenues are shared and distributed among different stakeholders. HPPs can also have positive impacts on the living conditions of local communities and the regional economy, not only by generating electricity but also by facilitating through the creation of freshwater storage schemes multiple other water-dependent activities, such as irrigation, navigation, tourism, fisheries or sufficient water supply to municipalities and industries while protecting against floods and droughts. [5.6.1.7–5.6.1.11]

The assessment and management of environmental and social impacts associated with, especially, larger HPPs represent a key challenge for hydropower development. Emphasizing transparency and an open, participatory decision-making process, the stakeholder consultation

approach is driving both present-day and future hydropower projects towards increasingly more environmentally friendly and sustainable solutions. In many countries, a national legal and regulatory framework has been put in place to determine how hydropower projects shall be developed and operated, while numerous multilateral financing agencies have developed their own guidelines and requirements to assess the economic, social and environmental performance of hydropower projects. [5.6.2]

One of hydropower's main environmental advantages is that it creates no atmospheric pollutants or waste associated with fuel combustion. However, all freshwater systems, whether they are natural or man-made, emit GHGs (e.g., CO_2, methane) due to decomposing organic material. Lifecycle assessments (LCAs) carried out on hydropower projects have so far demonstrated the difficulty of generalizing estimates of lifecycle GHG emissions for hydropower projects in all climatic conditions, pre-impoundment land cover types, ages, hydropower technologies, and other project-specific circumstances. The multipurpose nature of most hydropower projects makes allocation of total impacts to the several purposes challenging. Many LCAs to date allocate all impacts of hydropower projects to the electricity generation function, which in some cases may overstate the emissions for which they are 'responsible'. LCAs (Figure TS.5.2) that evaluate GHG emissions of HPPs during construction, operation and maintenance, and dismantling, show that the majority of lifecycle GHG emission estimates for hydropower cluster between about 4 and 14 g CO_2eq/kWh, but under certain scenarios there is potential to emit much larger quantities of GHGs, as shown by the outliers. [5.6.3.1]

While some natural water bodies and freshwater reservoirs may even absorb more GHGs than they emit, there is a definite need to properly assess the net change in GHG emissions induced by the creation of such reservoirs. All LCAs included in these assessments evaluated only gross GHG emissions from reservoirs. Whether reservoirs are net emitters of GHGs, considering emissions that would have occurred without the reservoir, is an area of active research. When considering net anthropogenic emissions as the difference in the overall carbon cycle between the situations with and without the reservoir, there is currently no consensus on whether reservoirs are net emitters or net sinks. Presently two international processes are investigating this issue: the UN Educational, Scientific and Cultural Organization/International Hydrological Programme research project and the IEA Hydropower Agreement Annex XII. [5.6.3.2]

5.7 Prospects for technology improvement and innovation

Though hydropower is a proven and well-advanced technology, there is still room for further improvement, for example, by optimizing operations, mitigating or reducing environmental impacts, adapting to new social and environmental requirements and implementing more robust and cost-effective technological solutions. Large hydropower turbines are now close to the theoretical limit for efficiency, with up to 96% efficiency when operated at the best efficiency point, but this is not always possible and continued research is needed to make more efficient operation possible over a broader range of flows. Older turbines can have lower efficiency by design or reduced efficiency due to corrosion and cavitation. There is therefore the potential to increase energy output by retrofitting with new higher efficiency equipment and usually also with increased capacity. Most of the existing electrical and mechanical equipment in operation today will need to be modernized during the next three decades, allowing for improved efficiency and higher power and energy output. Typically, generating equipment can be upgraded or replaced with more technologically advanced electro-mechanical equipment two or three times during the lifetime of the project, making more effective use of the same flow of water. [5.7]

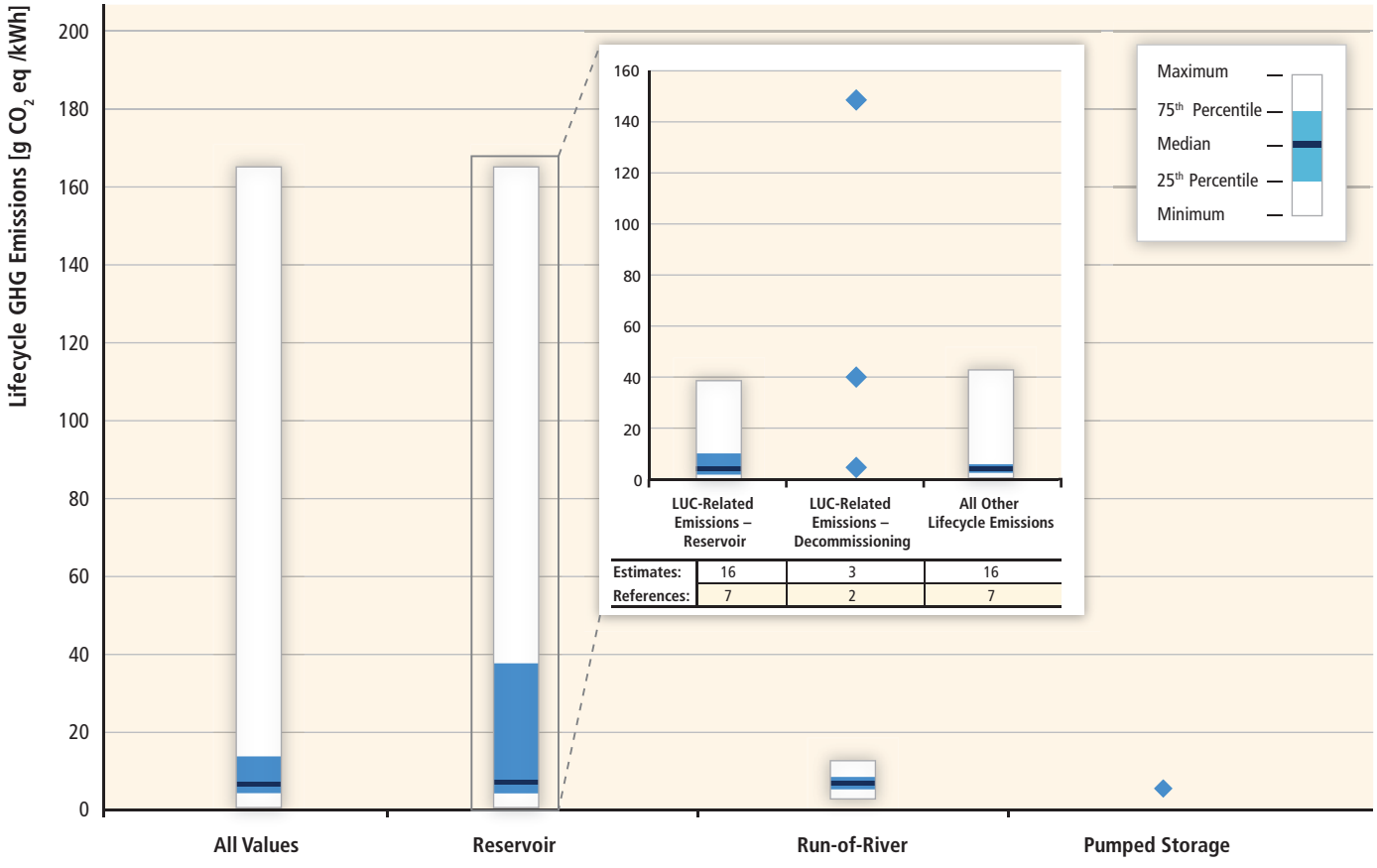
There is much ongoing technology innovation and material research aiming to extend the operational range in terms of head and discharge, and also to improve environmental performance, reliability and reduce costs. Some of the promising technologies under development are variable-speed and matrix technologies, fish-friendly turbines, hydrokinetic turbines, abrasive-resistant turbines, and new tunnelling and dam technologies. New technologies aiming at utilizing low (<15 m) or very low (<5 m) head may open up many sites for hydropower that have not been within reach of conventional technology. As most of the data available on hydropower potential are based on field work produced several decades ago, when low-head hydropower was not a high priority, existing data on low-head hydropower potential may not be complete. Finally, there is a significant potential for improving operation of HPPs by utilizing new methods for optimizing plant operation. [5.7.1–5.7.8]

5.8 Cost trends

Hydropower is often economically competitive with current market energy prices, though the cost of developing, deploying and operating new hydropower projects will vary from project to project. Hydropower projects often require a high initial investment, but have the advantage of very low O&M costs and a long lifespan. [5.8]

Investment costs for hydropower include costs of planning; licensing; plant construction; impact reductions for fish and wildlife, recreational, historical and archaeological sites; and water quality monitoring. Overall, there are two major cost groups: the civil construction costs, which normally are the greatest costs of the hydropower project; and electromechanical equipment costs. The civil construction costs follow the price trends in the country where the project is going to be developed. In the case of countries with economies in transition, the costs are likely to be relatively low due to the use of local labour and local materials. The costs of electromechanical equipment follow the tendency of prices at a global level. [5.8.1]

Based on a standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOE for hydropower projects over a large set and range of input parameters has been



	All Values	Reservoir	Run-of-River	Pumped Storage
Estimates:	27	18	8	1
References:	11	9	2	1

Figure TS.5.2 | Life-cycle GHG emissions of hydropower technologies (unmodified literature values, after quality screen). See Annex I for details of literature search and citations of literature contributing to the estimates displayed. Surface emissions from reservoirs are referred to as gross GHG emissions. [Figure 5.15]

calculated to range from as low as US cent$_{2005}$ 1.1/kWh to US cent$_{2005}$ 15/kWh, depending on site-specific parameters for investment costs of each project and on assumptions regarding the discount rate, capacity factor, lifetime and O&M costs. [1.3.2, 5.8, 10.5.1, Annex II, Annex III]

Figure TS.5.3 presents the LCOE for hydropower projects over a somewhat different and more typical set and range of parameters consistent with the majority of hydropower projects, and does so as a function of capacity factor while applying different investment costs and discount rates.

Capacity factors will be determined by hydrological conditions, installed capacity and plant design, and the way the plant is operated. For power plant designs intended for maximum energy production (base-load) and/or with some regulation, capacity factors will often be from 30 to 60%, with average capacity factors for different world regions shown in the graph. For peaking-type power plants, the capacity factor can be even lower, whereas capacity factors for RoR systems vary across a wide range (20 to 95%) depending on the geographical and climatological conditions, technology, and operational characteristics. For an average capacity factor of 44% and investment costs between USD$_{2005}$ 1,000/kW and USD$_{2005}$ 3,000/kW, the LCOE ranges from US cent$_{2005}$ 2.5/kWh to US cent$_{2005}$ 7.5/kWh.

Most of the projects developed in the near-term future (up to 2020) are expected to have investment costs and LCOE in this range, though projects with both lower and higher costs are possible. Under good conditions, the LCOE of hydropower can be in the range of US cent$_{2005}$ 3/kWh to US cent$_{2005}$ 5/kWh. [5.8.3, 8.2.1.2, Annex III]

There is relatively little information on historical trends in hydropower costs in the literature. One reason for this—besides the fact that project costs are highly site-specific—may be the complex cost structure for hydropower plants, where some components may have decreasing cost trends (e.g., tunnelling costs), while others may have increasing cost trends (e.g., social and environmental mitigation costs). [5.8.4]

One complicating factor when considering the cost of hydropower is that, for multipurpose reservoirs, there is a need to share or allocate the cost of serving other water uses like irrigation, flood control, navigation, roads, drinking water supply, fish, and recreation. There are

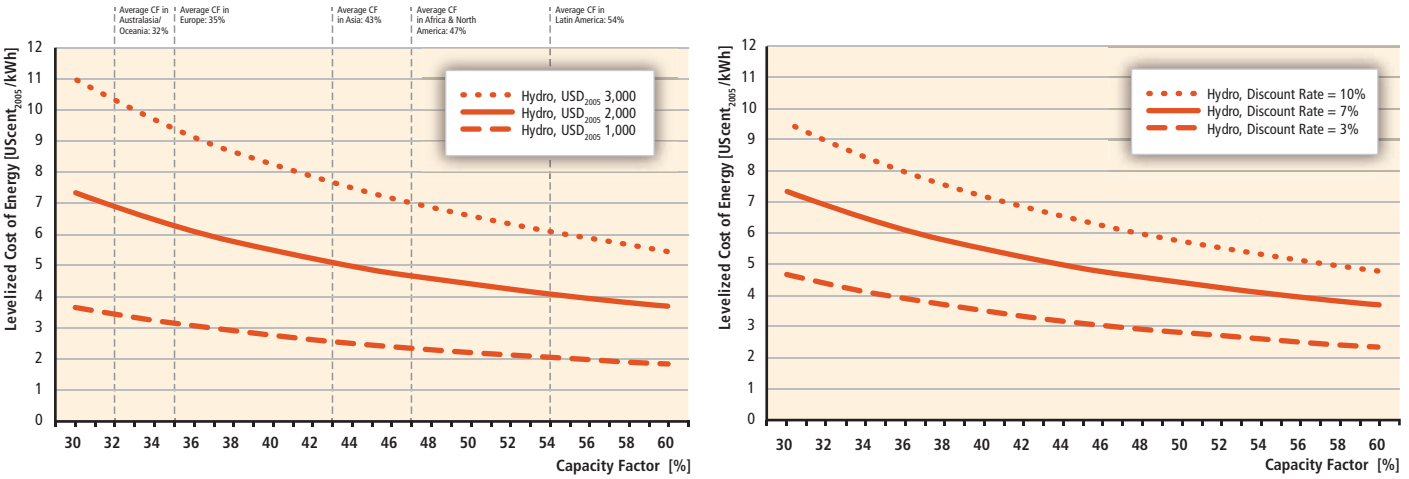


Figure TS.5.3 | Recent and near-term estimated levelized cost of hydropower (a) as a function of capacity factor and investment cost*, ***; and (b) as a function of capacity factor and discount rate**,***. [Figure 5.20]

Notes: * Discount rate is assumed to equal 7%. ** Investment cost is assumed to be USD 2,000/kW. *** Annual O&M cost is assumed at 2.5%/yr of investment cost and plant lifetime as 60 years.

different methods of allocating the cost to individual purposes, each of which has advantages and drawbacks. The basic rules are that the allocated cost to any purpose does not exceed that benefit of that purpose and each purpose will be carried out at its separable cost. Separable cost for any purpose is obtained by subtracting the cost of a multipurpose project without that purpose from the total cost of the project with the purpose included. Merging economic elements (energy and water selling prices) with social benefits (supplying water to farmers in case of lack of water) and the value of the environment (to preserve a minimum environmental flow) is becoming a tool for consideration of cost sharing for multipurpose reservoirs. [5.8.5]

5.9 Potential deployment

Hydropower offers a significant potential for near- and long-term carbon emissions reduction. On a global basis, the hydropower resource is unlikely to constrain further development in the near to medium term, though environmental and social concerns may limit deployment opportunities if not carefully managed. [5.9]

So far, only 25% of the hydropower potential has been developed across the world (that is, 3,551 TWh out of 14,575 TWh) (12.78 EJ out of 52.47 EJ). The different long-term prospective scenarios propose a continuous increase for the next decades. The increase in hydropower capacity over the last 10 years is expected by several studies to continue in the near to medium term: from 926 GW in 2009 to between 1,047 and 1,119 GW by 2015; an annual addition ranging from 14 to 25 GW. [5.9, 5.9.1]

The reference-case projections presented in Chapter 10 (based on 164 analyzed longer-term scenarios) show hydropower's role in the global energy supply covering a broad range, with a median of roughly 13 EJ (3,600 TWh) in 2020, 16 EJ (4,450 TWh) in 2030 and 19 EJ (5,300 TWh) in 2050. 12.78 EJ was reached already in 2009 and thus the average estimate of 13 EJ for 2020 has probably been exceeded today. Also, some scenario results provide lower values than the current installed capacity for 2020, 2030 and 2050, which is counterintuitive given, for example, hydropower's long lifetimes, its significant market potential and other important services. These results could maybe be explained by model/scenario weaknesses (see discussions in Section 10.2.1.2 of this report). Growth of hydropower is therefore projected to occur even in the absence of GHG mitigation policies, even with hydropower's median contribution to global electricity supply dropping from about 16% today to less than 10% by 2050. As GHG mitigation policies are assumed to become more stringent in the alternative scenarios, the contribution of hydropower grows: by 2030, hydropower's median contribution equals roughly 16.5 EJ (4,600 TWh) in the 440 to 600 and <440 ppm CO_2 stabilization ranges (compared to the median of 15 EJ in the baseline cases), increasing to about 19 EJ by 2050 (compared to the median of 18 EJ in the baseline cases). [5.9.2]

Regional projections of hydropower generation in 2035 show a 98% increase in the Asia Pacific region compared to 2008 levels and a 104% increase in Africa. Brazil is the main driving force behind the projected 46% increase in hydropower generation in the South and Central America region over the same time period. North America and Europe/Eurasia expect more modest increases of 13 and 27%, respectively, over the period. [5.9.2]

Overall, evidence suggests that relatively high levels of deployment in the next 20 years are feasible. Even if hydropower's share in global electricity supply decreases by 2050, hydropower would remain an attractive RE source within the context of global carbon mitigation scenarios. Furthermore, increased development of storage hydropower

may enable investment into water management infrastructure, which is needed in response to growing problems related to water resources. [5.9.3]

5.10 Integration into water management systems

Water, energy and climate change are inextricably linked. Water availability is crucial for many energy technologies, including hydropower, while energy is needed to secure water supply for agriculture, industries and households, in particular in water-scarce areas in developing countries. This close relationship has led to the understanding that the water-energy nexus must be addressed in a holistic way, in particular with regard to climate change and sustainable development. Providing energy and water for sustainable development may require improved regional and global water governance. As it is often associated with the creation of water storage facilities, hydropower is at the crossroads of these issues and can play an important role in enhancing both energy and water security. [5.10]

Today, about 700 million people live in countries experiencing water stress or scarcity. By 2035, it is projected that three billion people will be living in conditions of severe water stress. Many countries with limited water availability depend on shared water resources, increasing the risk of conflict over these scarce resources. Therefore, adaptation to climate change impacts will become very important in water management. [5.10.1]

In a context where multipurpose hydropower can be a tool to mitigate both climate change and water scarcity, these projects may have an enabling role beyond the electricity sector as a financing instrument for reservoirs, helping to secure freshwater availability. However, multiple uses may increase the potential for conflicts and reduce energy production during times of low water levels. As major watersheds are shared by several nations, regional and international cooperation is crucial. Both intergovernmental agreements and initiatives by international institutions are actively supporting these important processes. [5.10.2, 5.10.3]

6. Ocean Energy

6.1 Introduction

Ocean energy offers the potential for long-term carbon emissions reduction but is unlikely to make a significant short-term contribution before 2020 due to its nascent stage of development. The theoretical potential of 7,400 EJ/yr contained in the world's oceans easily exceeds present human energy requirements. Government policies are contributing to accelerate the deployment of ocean energy technologies, heightening expectations that rapid progress may be possible. The six main classes of ocean energy technology offer a diversity of potential development pathways, and most offer potentially low environmental impacts as currently understood. There are encouraging signs that the investment cost of ocean energy technologies and the levelized cost of electricity generated will decline from their present non-competitive levels as R&D and demonstrations proceed, and as deployment occurs. Whether these cost reductions are sufficient to enable broad-scale deployment of ocean energy is the most critical uncertainty in assessing the future role of ocean energy in mitigating climate change. [6 ES, 6.1]

6.2 Resource potential

Ocean energy can be defined as energy derived from technologies that utilize seawater as their motive power or harness the water's chemical or heat potential. The RE resource in the ocean comes from six distinct sources, each with different origins and each requiring different technologies for conversion. These sources are:

Wave energy derived from the transfer of the kinetic energy of the wind to the upper surface of the ocean. The total theoretical wave energy resource is 32,000 TWh/yr (115 EJ/yr), but the technical potential is likely to be substantially less and will depend on development of wave energy technologies. [6.2.1]

Tidal range (tidal rise and fall) derived from gravitational forces of the Earth-Moon-Sun system. The world's theoretical tidal power potential is in the range of 1 to 3 TW, located in relatively shallow waters. Again, technical potential is likely to be significantly less than theoretical potential. [6.2.2]

Tidal currents derived from water flow that results from the filling and emptying of coastal regions associated with tides. Current regional estimates of tidal current technical potential include 48 TWh/yr (0.17 EJ) for Europe and 30 TWh/yr (0.11 EJ/yr) for China. Commercially attractive sites have also been identified in the Republic of Korea, Canada, Japan, the Philippines, New Zealand and South America. [6.2.3]

Ocean currents derived from wind-driven and thermohaline ocean circulation. The best-characterized system of ocean currents is the Gulf Stream in North America, where the Florida Current has a technical potential for 25 GW of electricity capacity. Other regions with potentially promising ocean circulation include the Agulhas/Mozambique Currents off South Africa, the Kuroshio Current off East Asia and the East Australian Current. [6.2.4]

Ocean thermal energy conversion (OTEC) derived from temperature differences arising from solar energy stored as heat in upper ocean layers and colder seawater, generally below 1,000 m. Although the energy density of OTEC is relatively low, the overall resource potential is much

larger than for other forms of ocean energy. One 2007 study estimates that about 44,000 TWh/yr (159 EJ/yr) of steady-state power may be possible. [6.2.5]

Salinity gradients (osmotic power) derived from salinity differences between fresh and ocean water at river mouths. The theoretical potential of salinity gradients is estimated at 1,650 TWh/yr (6 EJ/yr). [6.2.6]

Figure TS.6.1 provides examples of how selected ocean energy resources are distributed across the globe. Some ocean energy resources, such as ocean currents or power from salinity gradients, are globally distributed. Ocean thermal energy is principally located in the Tropics around the equatorial latitudes (latitudes 0° to 35°), whilst the highest annual wave power occurs between latitudes of 30° to 60°. Wave power in the southern hemisphere undergoes smaller seasonal variation than in the northern hemisphere. Ocean currents, ocean thermal energy, salinity gradients and, to some extent, wave energy are consistent enough to generate base-load power. Given the early state of the available literature and the substantial uncertainty in ocean energy's technical potential, the estimates for technical ocean energy potential vary widely. [6.2.1–6.2.6]

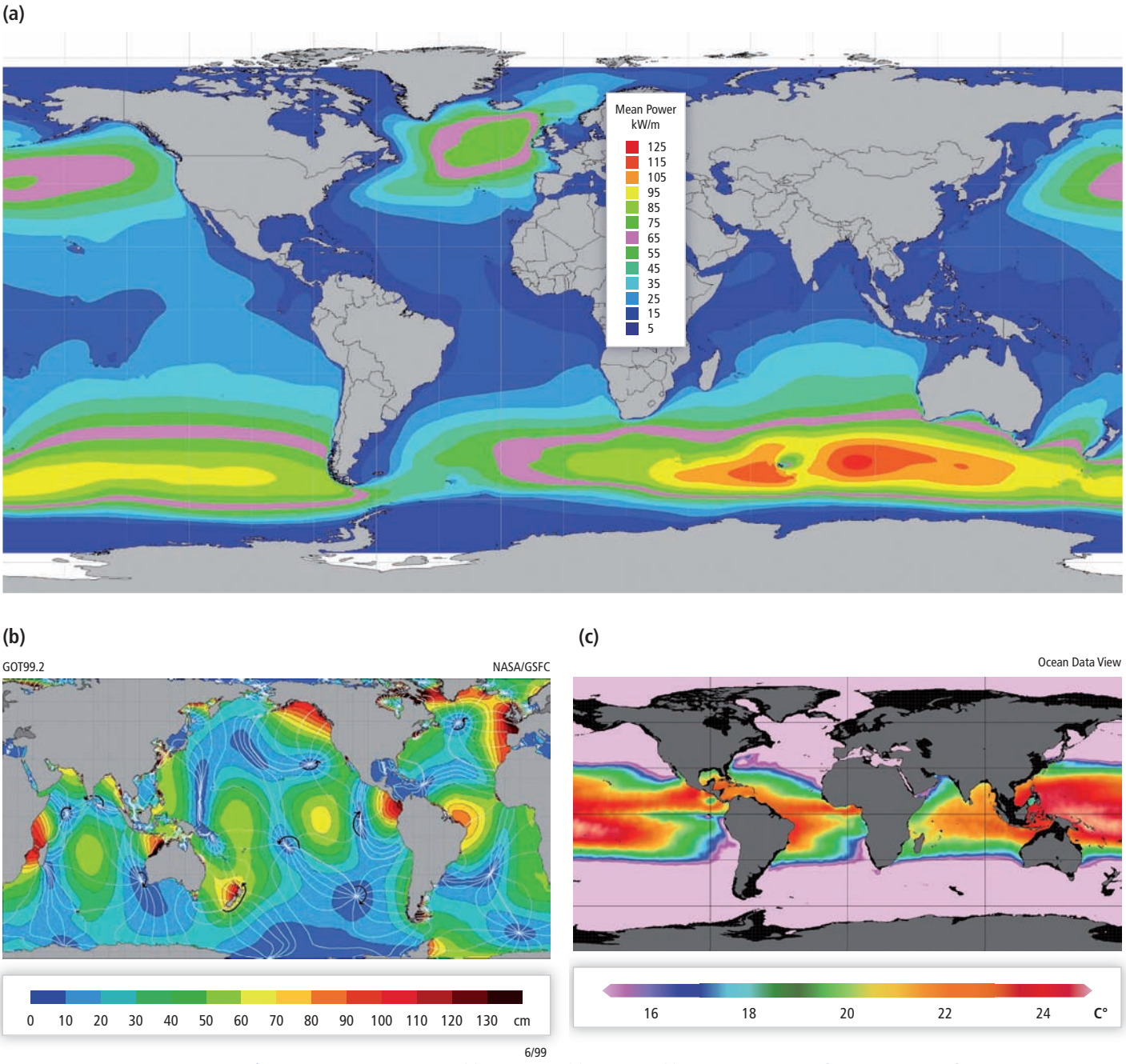


Figure TS.6.1a-c | Global distribution of various ocean energy resources: (a) Wave power; (b) Tidal range, (c) Ocean thermal energy. [Figures 6.1, 6.2, 6.4]

(d)

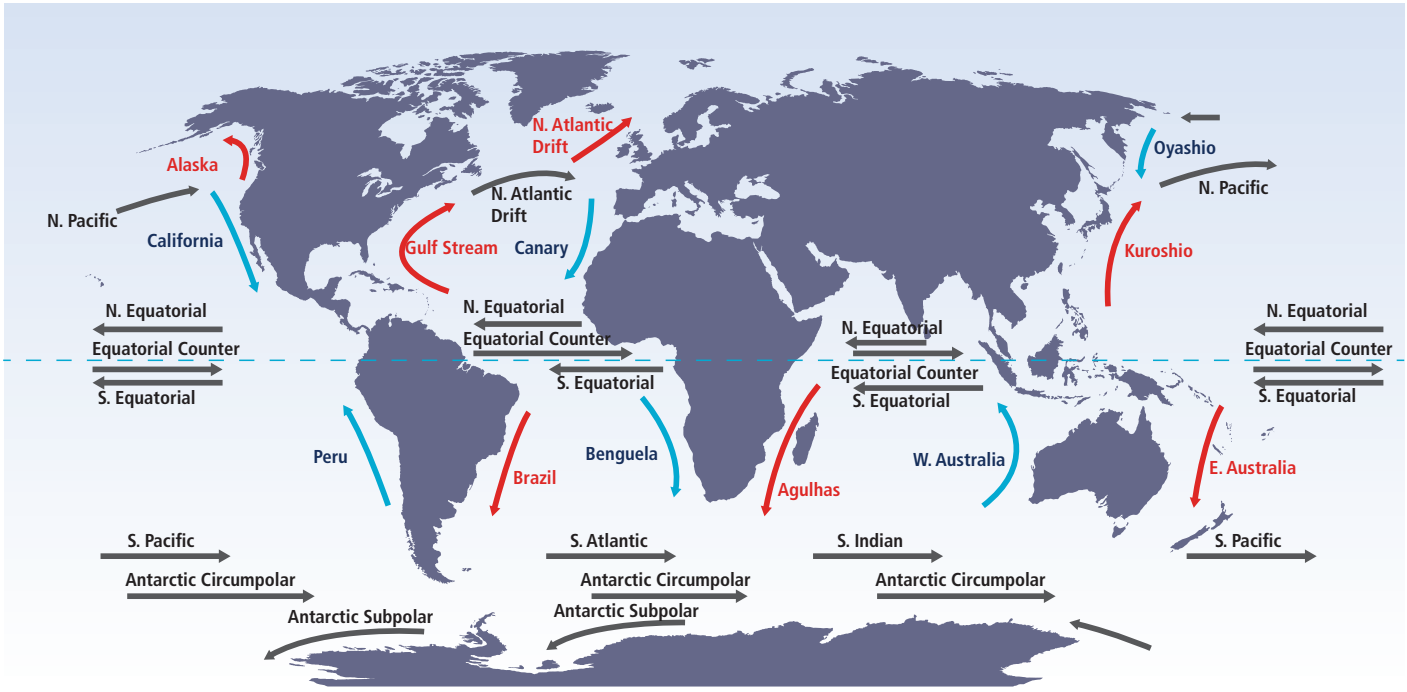


Figure TS.6.1d | Global distribution of various ocean energy resources: (d) Ocean currents. [Figure 6.3]

6.3 Technology and applications

The current development status of ocean energy technologies ranges from the conceptual and pure R&D stages to the prototype and demonstration stage, and only tidal range technology can be considered mature. Presently there are many technology options for each ocean energy source and, with the exception of tidal range barrages, technology convergence has not yet occurred. Over the past four decades, other marine industries (primarily offshore oil and gas) have made significant advances in the fields of materials, construction, corrosion, submarine cables and communications. Ocean energy is expected to directly benefit from these advances. [6.3.1]

Many wave energy technologies representing a range of operating principles have been conceived, and in many cases demonstrated, to convert energy from waves into a usable form of energy. Major variables include the method of wave interaction with respective motions (heaving, surging, pitching) as well as water depth (deep, intermediate, shallow) and distance from shore (shoreline, near-shore, offshore). Wave energy technologies can be classified into three groups: oscillating water columns (OWC: shore-based, floating), oscillating bodies (surface buoyant, submerged), and overtopping devices (shore-based, floating). [6.2.3] Principles of operation are presented in Figure TS.6.2.

Tidal range energy can be harnessed by the adaptation of river-based hydroelectric dams to estuarine situations, where a barrage encloses an estuary. The barrage may generate electricity on both the ebb and flood tides and some future barrages may have multiple basins to enable almost continuous generation. The most recent technical concepts are stand-alone offshore 'tidal lagoons'. [6.3.3]

Technologies to harness power from tidal and ocean currents are also under development, but tidal energy turbines are more advanced. Some of the tidal/ocean current energy technologies are similar to mature wind turbine generators but submarine turbines must also account for reversing flow, cavitation at blade tips and harsh underwater marine conditions. Tidal currents tend to be bidirectional, varying with the tidal cycle, and relatively fast-flowing, compared with ocean currents, which are usually unidirectional and slow-moving but continuous. Converters are classified by their principle of operation into axial flow turbines, cross flow turbines and reciprocating devices as presented in Figure TS.6.3. [6.3.4]

Ocean thermal energy conversion (OTEC) plants use the temperature differences between warm seawater from the ocean surface and cool seawater from depth (1,000 m is often used as a reference level) to produce electricity. Open-cycle OTEC systems use seawater directly as the circulating fluid, whilst closed-cycle systems use heat exchangers and a secondary working fluid (most commonly ammonia) to drive a turbine. Hybrid systems use both open- and closed-cycle operation. Although there have been trials of OTEC technologies, problems have been encountered with maintenance of vacuums, heat exchanger biofouling and corrosion issues. Current research is focused on overcoming these problems. [6.3.5]

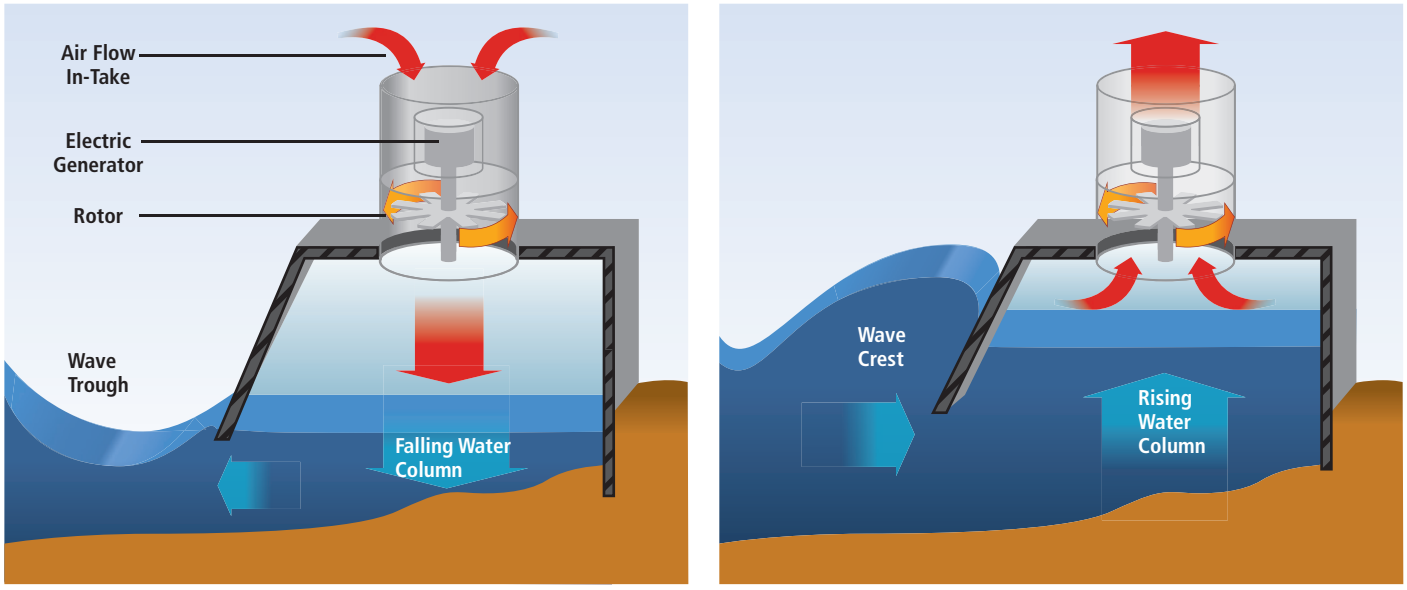
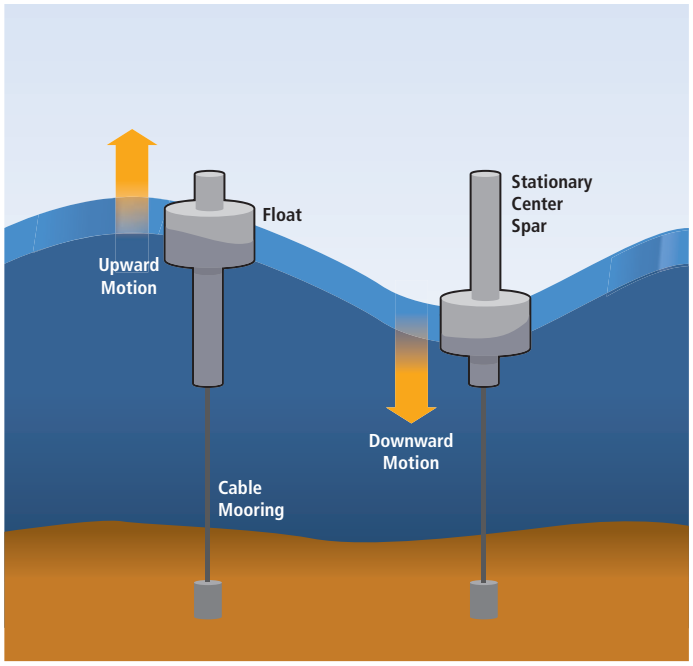


Figure TS.6.2a/b | Type of wave energy converter and its operation: oscillating water column device. [Figure 6.6] (design by the National Renewable Energy Laboratory (NREL))



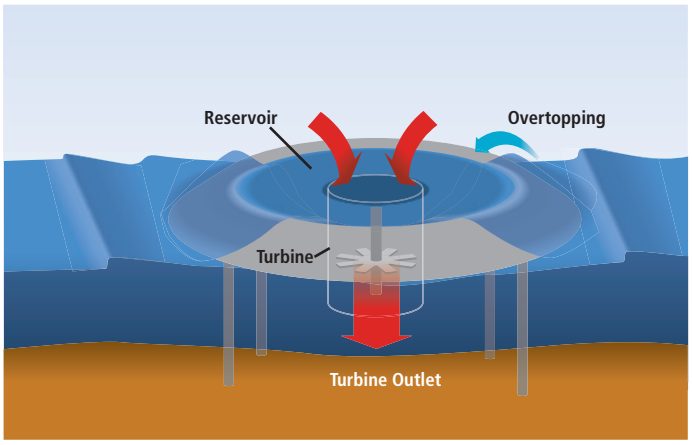


Figure TS.6.2c/d | Wave energy converters and their operation: (left) oscillating body device; and (right) overtopping device. [Figure 6.6] (design by the National Renewable Energy Laboratory (NREL))

The salinity gradient between freshwater from rivers and seawater can be utilized as a source of power with at least two concepts under development. The reversed electro dialysis (RED) process is a concept in which the difference in chemical potential between the two solutions is the driving force (Figure TS.6.4). The pressure-retarded osmosis, or osmotic power process, utilizes the concept of naturally occurring osmosis, a hydraulic pressure potential, caused by the tendency of freshwater to mix with seawater due to the difference in salt concentration (Figure TS.6.5). [6.3.6]

6.4 Global and regional status of the markets and industry development

R&D projects on wave and tidal current energy technologies have proliferated over the past two decades, with some now reaching the full-scale pre-commercial prototype stage. Presently, the only full-size and operational ocean energy technology available is the tidal barrage, of which the best example is the 240 MW La Rance Barrage in north-western France, completed in 1966. The 254 MW Sihwa Barrage (South Korea) is due to become operational in 2011. Technologies to develop other ocean energy sources including OTEC, salinity gradients and ocean currents are still at the conceptual, R&D or early prototype stages. Currently, more than 100 different ocean energy technologies are under development in over 30 countries. [6.4.1]

The principal investors in ocean energy R&D and deployments are national, federal and state governments, followed by major energy utilities and investment companies. National and regional governments are

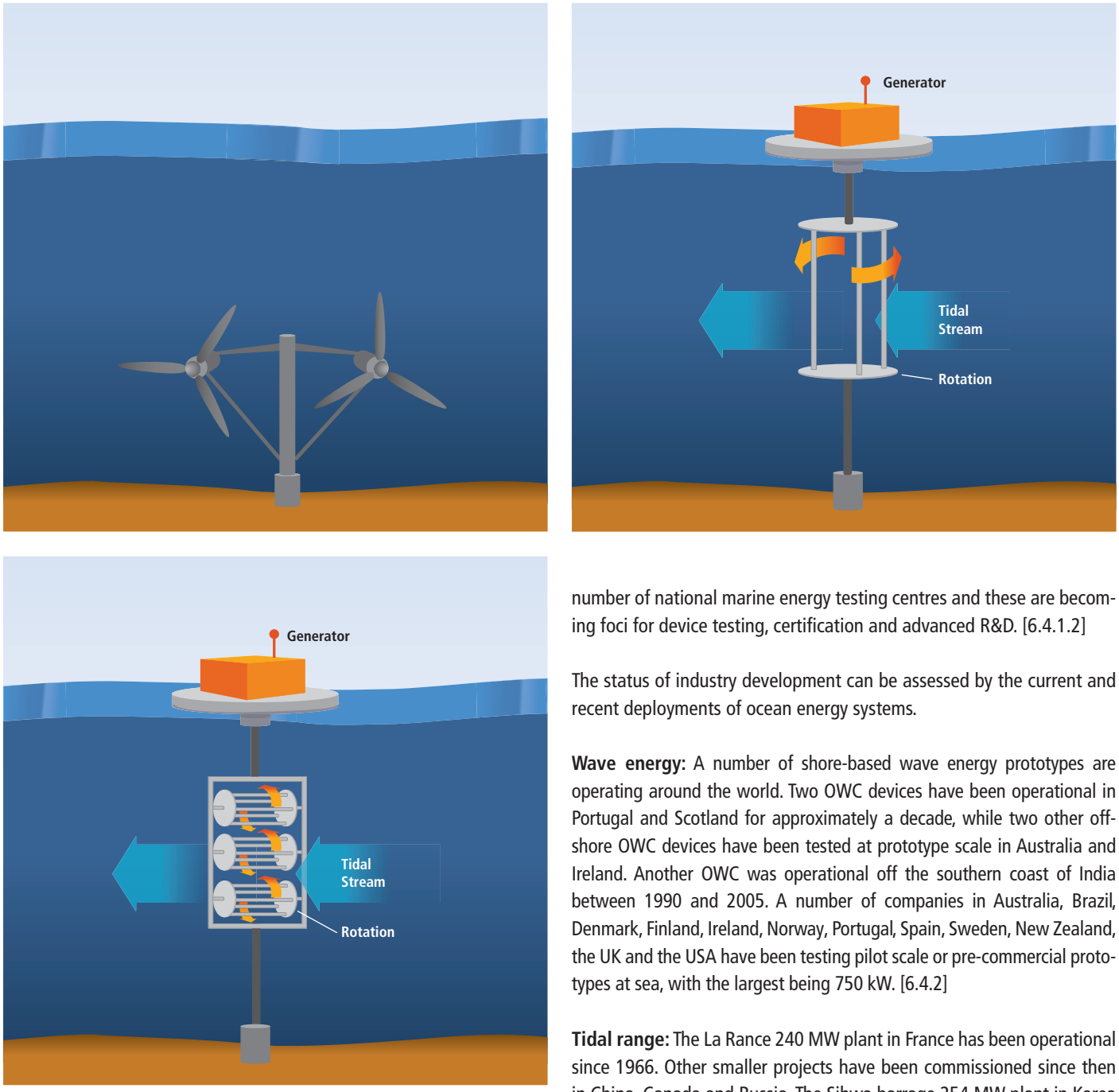


Figure TS.6.3 | Tidal current energy converters and their operation: (Top left) twin turbine horizontal axis device; (Bottom left) cross-flow device; and (Top right) vertical axis device. [Figure 6.8]

particularly supportive of ocean energy through a range of financial, regulatory and legislative initiatives to support developments. [6.4.7]

Industrial involvement in ocean energy is at a very early stage and there is no manufacturing industry for these technologies at present. The growth of interest may lead to the transfer of capacity, skills and capabilities from related industries, combined with new specific innovative aspects. One interesting feature of ocean energy is the development of a number of national marine energy testing centres and these are becoming foci for device testing, certification and advanced R&D. [6.4.1.2]

The status of industry development can be assessed by the current and recent deployments of ocean energy systems.

Wave energy: A number of shore-based wave energy prototypes are operating around the world. Two OWC devices have been operational in Portugal and Scotland for approximately a decade, while two other offshore OWC devices have been tested at prototype scale in Australia and Ireland. Another OWC was operational off the southern coast of India between 1990 and 2005. A number of companies in Australia, Brazil, Denmark, Finland, Ireland, Norway, Portugal, Spain, Sweden, New Zealand, the UK and the USA have been testing pilot scale or pre-commercial prototypes at sea, with the largest being 750 kW. [6.4.2]

Tidal range: The La Rance 240 MW plant in France has been operational since 1966. Other smaller projects have been commissioned since then in China, Canada and Russia. The Sihwa barrage 254 MW plant in Korea will be commissioned during 2011, and several other large projects are under consideration. [6.4.3]

Tidal and ocean currents: There are probably more than 50 tidal current devices at the proof-of-concept or prototype development stage, but large-scale deployment costs are yet to be demonstrated. The most advanced example is the SeaGen tidal turbine, which was installed near Northern Ireland and has delivered electricity into the electricity grid for more than one year. An Irish company has tested its open-ring turbine in Scotland, and more recently in Canada. Two companies have demonstrated horizontal-axis turbines at full scale in Norway and Scotland, whilst another has demonstrated a vertical-axis turbine in Italy. Lastly,

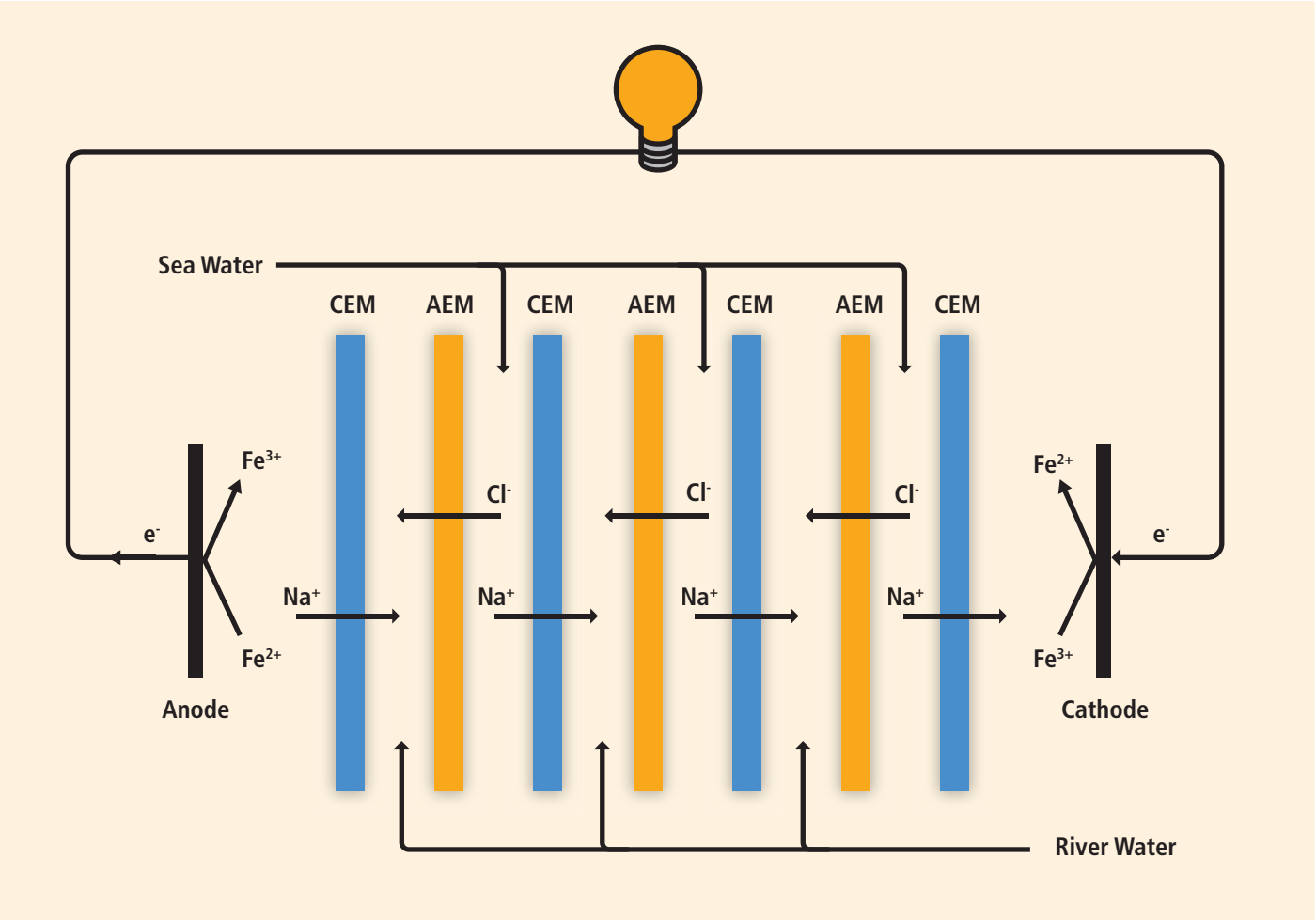


Figure TS.6.4 | Reversed electro dialysis (RED) system. [Figure 6.9]

Notes: CEM = cation exchange membrane; AEM = anion exchange membrane, Na = sodium, Cl = Chlorine, Fe = iron.

a reciprocating device was demonstrated in the UK in 2009. No pilot or demonstration plants have been deployed for ocean currents to date, although much larger scales are envisioned if technologies are able to capture the slower-velocity currents. [6.4.4]

OTEC: Japan, India, the USA and several other countries have tested pilot OTEC projects. Many have experienced engineering challenges related to pumping, vacuum retention and piping. Larger-scale OTEC developments could have significant markets in tropical maritime nations, including the Pacific Islands, Caribbean Islands, and Central American and African nations if the technology develops to the point of being a cost-effective energy supply option. [6.4.5]

Salinity gradients: Research into osmotic power is being pursued in Norway, with a prototype in operation since 2009 as part of a drive to deliver a commercial osmotic power plant. At the same time, the RED technology has been proposed for retrofitting the 75-year-old Afsluitdijk dike in The Netherlands. [6.4.6]

6.5 Environmental and social impacts

Ocean energy does not directly emit CO_2 during operation; however, GHG emissions may arise from different aspects of the lifecycle of ocean energy systems, including raw material extraction, component manufacturing, construction, maintenance and decommissioning. A comprehensive review of lifecycle assessment studies published since 1980 suggests that lifecycle GHG emissions from wave and tidal energy systems are less than 23 g CO_2eq/kWh, with a median estimate of lifecycle GHG emissions of around 8 g CO_2eq/kWh for wave energy. Insufficient studies are available to estimate lifecycle emissions from the other classes of ocean energy technology. Regardless, in comparison to fossil energy generation technologies, the lifecycle GHG emissions from ocean energy devices appear low. [6.5.1]

The local social and environmental impacts of ocean energy projects are being evaluated as actual deployments multiply, but can be estimated based on the experience of other maritime and offshore

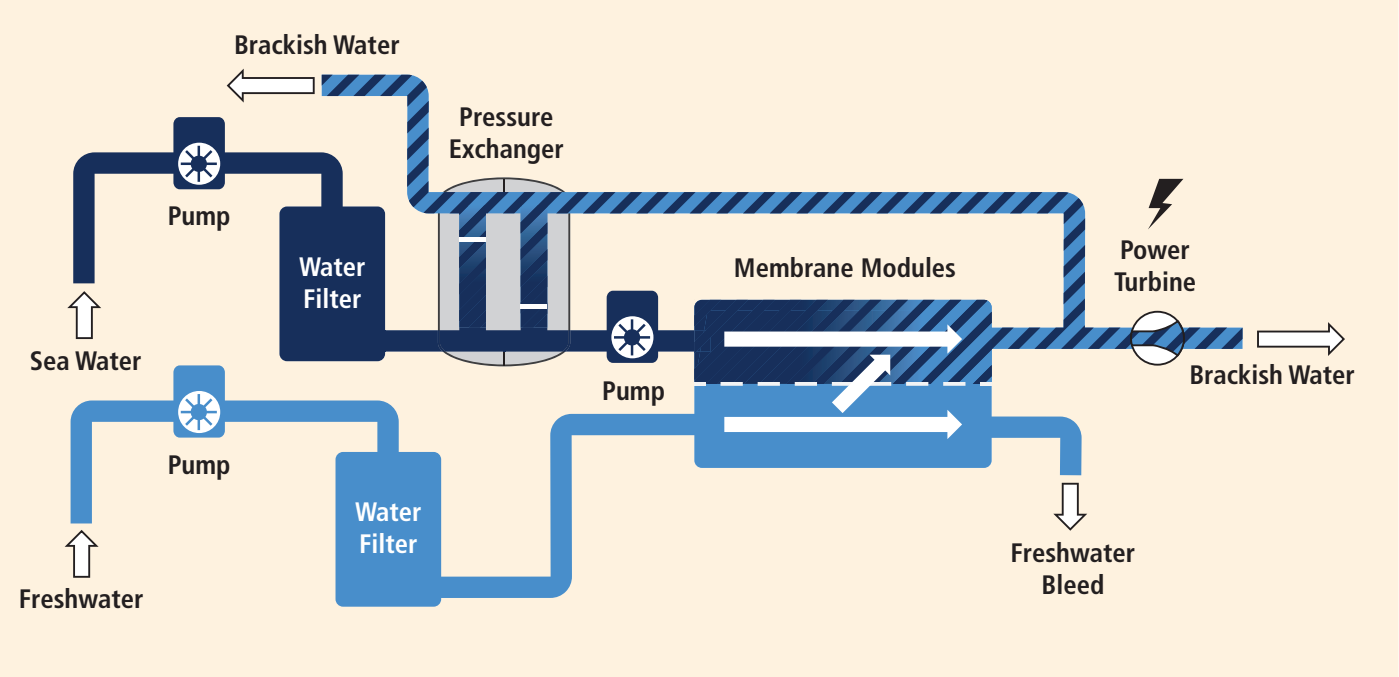


Figure TS.6.5 | Pressure-retarded osmosis (PRO) process. [Figure 6.10]

industries. Environmental risks from ocean energy technologies appear to be relatively low, but the early stage of ocean energy deployment creates uncertainty about the degree to which social and environmental concerns might eventually constrain development. [6 ES]

Each ocean power technology has its own specific set of environmental and social impacts. Possible positive effects from ocean energy may include avoidance of adverse effects on marine life by virtue of reducing other human activities in the area around the ocean devices, and the strengthening of energy supply and regional economic growth, employment and tourism. Negative effects may include a reduction in visual amenity and loss of access to space for competing users, noise during construction, noise and vibration during operation, electromagnetic fields, disruption to biota and habitats, water quality changes and possible pollution, for instance from chemical or oil leaks, and other limited specific impacts on local ecosystems. [6.5.2]

6.6 Prospects for technology improvement, innovation and integration

As emerging technologies, ocean energy devices have the potential for significant technological advances. Not only will device-specific R&D and deployment be important to achieving these advances, but technology improvements and innovation in ocean energy converters are also likely to be influenced by developments in related fields. [6.6]

Integration of ocean energy into wider energy networks will need to recognize the widely varying generation characteristics arising from the different resources. For example, electricity generation from tidal stream resources shows very high variability over one to four hours, yet extremely limited variability over monthly or longer time horizons. [6.6]

6.7 Cost trends

Commercial markets are not yet driving marine energy technology development. Government-supported R&D and national policy incentives are the key motivations. Because none of the ocean energy technologies but tidal barrages are mature (experience with other technologies is only now becoming available for validation of demonstration/prototype devices), it is difficult to accurately assess the economic viability of most ocean energy technologies. [6.7.1]

Table TS.6.1 shows the best available data for some of the primary cost factors that affect the levelized cost of electricity by each of the ocean energy sub-types. In most cases, these cost and performance parameters are based on sparse information due to the lack of peer-reviewed reference data and actual operating experience, and in many cases therefore reflect estimated cost and performance assumptions based on engineering knowledge. Present-day investment costs were found in a few instances but are based on a small sample of projects and studies, which may not be representative of the entire industry. [6.7.1]

Based on a standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOE for tidal barrages (which is currently the only commercially available ocean energy technology) over a large set and range of input parameters has been

Table TS.6.1 | Summary of core available cost and performance parameters for all ocean energy technology sub-types. [Table 6.3]

Ocean Energy Technology	Investment Costs (USD_{2005}/kW)	Annual O&M Costs (USD_{2005}/kW)	Capacity Factor (CF) (%)	Design Life (years)
Wave	6,200–16,100	180	25–40	20
Tidal Range	4,500–5,000	100	22.5–28.5	40
Tidal Current	5,400–14,300	140	26–40	20
Ocean Current	N/A	N/A	N/A	20
Ocean Thermal	4,200–12,300[1]	N/A	N/A	20
Salinity Gradient	N/A	N/A	N/A	20

Note: 1. Cost figures for ocean thermal energy have not been converted to 2005 USD.

calculated to range from US $cent_{2005}$ 12/kWh to US $cent_{2005}$ 32/kWh. This range should, however, only be considered as indicative given the present state of deployment experience. [1.3.2, 6.7.1, 6.7.3, 10.5.1, Annex II, Annex III]

Because of the early stage of technology development, estimates of future costs for ocean energy should be considered speculative. Nonetheless, the cost of ocean energy is expected to decline over time as R&D, demonstrations, and deployments proceed. [6.7.1–6.7.5]

6.8 Potential deployment

Until about 2008, ocean energy was not considered in any of the major global energy scenario modelling activities and therefore its potential impact on future world energy supplies and climate change mitigation is just now beginning to be investigated. As such, the results of the published scenarios literature as they relate to ocean energy are sparse and preliminary, reflecting a wide range of possible outcomes. Specifically, scenarios for ocean energy deployment are considered in only three major sources here: Energy [R]evolution (E[R]) 2010, IEA World Energy Outlook (WEO) 2009 and Energy Technology Perspectives (ETP) 2010. Multiple scenarios were considered in the E[R] and the ETP reports and a single reference scenario was documented in the WEO report. Each scenario is summarized in Table TS.6.2.

This preliminary presentation of scenarios that describe alternative levels of ocean energy deployment is among the first attempts to review the potential role of ocean energy in the medium- to long-term scenarios literature with the intention of establishing the potential contribution of ocean energy to future energy supplies and climate change mitigation. As shown by the limited number of existing scenarios, ocean energy has the potential to help mitigate long-term climate change by offsetting GHG emissions with projected deployments resulting in energy delivery of up to 1,943 TWh/yr (~7 EJ/yr) by 2050. Other scenarios have been developed that indicate deployment as low as 25 TWh/yr (0.9 EJ/yr) from ocean energy. The wide range in results is based in part on uncertainty about the degree to which climate change mitigation will drive energy

Table TS.6.2 | Main characteristics of medium- to long-term scenarios from major published studies that include ocean energy. [Table 6.5]

	Deployment TWh/yr (PJ/yr)				GW	
Scenario	2010	2020	2030	2050	2050	Notes
Energy [R]evolution - Reference	N/A	3 (10.8)	11 (36.6)	25 (90)	N/A	No policy changes
Energy [R]evolution	N/A	53 (191)	128 (461)	678 (2,440)	303	Assumes 50% carbon reduction
Energy [R]evolution – Advanced	N/A	119 (428)	420 (1,512)	1,943 (6,994)	748	Assumes 80% carbon reduction
WEO 2009	N/A	3 (10.8)	13 (46.8)	N/A	N/A	Basis for E[R] reference case
ETP BLUE map 2050	N/A	N/A	N/A	133 (479)	N/A	Power sector is virtually decarbonized
ETP BLUE map no CCS 2050	N/A	N/A	N/A	274 (986)	N/A	BLUE Map Variant – Carbon capture and storage is found to not be possible
ETP BLUE map hi NUC 2050	N/A	N/A	N/A	99 (356)	N/A	BLUE Map Variant – Nuclear share is increased to 2,000 GW
ETP BLUE Map hi REN 2050	N/A	N/A	N/A	552 (1,987)	N/A	BLUE Map Variant – Renewable share is increased to 75%
ETP BLUE map 3%	N/A	N/A	N/A	401 (1,444)	N/A	BLUE Map Variant – Discount rates are set to 3% for energy generation projects.

sector transformation, but for ocean energy, is also based on inherent uncertainty as to when and if various ocean energy technologies become commercially available at attractive costs. To better understand the possible role of ocean energy in climate change mitigation, not only will continued technical advances be necessary, but the scenarios modelling process will need to increasingly incorporate the range of potential ocean energy technology sub-types, with better data for resource potential, present and future investment costs, O&M costs, and anticipated capacity factors. Improving the availability of the data at global and regional scales will be an important ingredient to improving coverage of ocean energy in the scenarios literature. [6.8.4]

7. Wind Energy

7.1 Introduction

Wind energy has been used for millennia in a wide range of applications. The use of wind energy to generate electricity on a commercial scale, however, became viable only in the 1970s as a result of technical advances and government support. A number of different wind energy technologies are available across a range of applications, but the primary use of wind energy of relevance to climate change mitigation is to generate electricity from larger, grid-connected wind turbines, deployed either on land ('onshore') or in sea- or freshwater ('offshore').[11] [7.1]

Wind energy offers significant potential for near-term (2020) and long-term (2050) GHG emissions reductions. The wind power capacity installed by the end of 2009 was capable of meeting roughly 1.8% of worldwide electricity demand, and that contribution could grow to in excess of 20% by 2050 if ambitious efforts are made to reduce GHG emissions and to address other impediments to increased wind energy deployment. Onshore wind energy is already being deployed at a rapid pace in many countries, and no insurmountable technical barriers exist that preclude increased levels of wind energy penetration into electricity supply systems. Moreover, though average wind speeds vary considerably by location, ample technical potential exists in most regions of the world to enable significant wind energy deployment. In some areas with good wind resources, the cost of wind energy is already competitive with current energy market prices, even without considering relative environmental impacts. Nonetheless, in most regions of the world, policy measures are still required to ensure rapid deployment. Continued advancements in on- and offshore wind energy technology are expected, however, further reducing the cost of wind energy and improving wind energy's GHG emissions reduction potential. [7.9]

11 Smaller wind turbines, higher-altitude wind electricity, and the use of wind energy in mechanical and propulsion applications are only briefly discussed in Chapter 7.

7.2 Resource potential

The global technical potential for wind energy is not fixed, but is instead related to the status of the technology and assumptions made regarding other constraints to wind energy development. Nonetheless, a growing number of global wind resource assessments have demonstrated that the world's technical potential exceeds current global electricity production. [7.2]

No standardized approach has been developed to estimate the global technical potential of wind energy: the diversity in data, methods, assumptions, and even definitions for technical potential complicate comparisons. The AR4 identified the technical potential for onshore wind energy as 180 EJ/yr (50,000 TWh/yr). Other estimates of the global technical potential for wind energy that consider relatively more development constraints range from a low of 70 EJ/yr (19,400 TWh/yr) (onshore only) to a high of 450 EJ/yr (125,000 TWh/yr) (on- and near-shore). This range corresponds to roughly one to six times global electricity production in 2008, and may understate the technical potential due to several of the studies relying on outdated assumptions, the exclusion or only partial inclusion of offshore wind energy in some of the studies, and methodological and computing limitations. Estimates of the technical potential for offshore wind energy alone range from 15 EJ/yr to 130 EJ/yr (4,000 to 37,000 TWh/yr) when only considering relatively shallower and near-shore applications; greater technical potential is available if also considering deeper-water applications that might rely on floating wind turbine designs. [7.2.1]

Regardless of whether existing estimates under- or overstate the technical potential for wind energy, and although further advances in wind resource assessment methods are needed, it is evident that the technical potential of the resource itself is unlikely to be a limiting factor for global wind energy deployment. Instead, economic constraints associated with the cost of wind energy, institutional constraints and costs associated with transmission access and operational integration, and issues associated with social acceptance and environmental impacts are likely to restrict growth well before any absolute limit to the global technical potential is encountered. [7.2.1]

In addition, ample technical potential exists in most regions of the world to enable significant wind energy deployment. The wind resource is not evenly distributed across the globe nor uniformly located near population centres, however, and wind energy will therefore not contribute equally in meeting the needs of every country. The technical potentials for onshore wind energy in OECD North America and Eastern Europe/Eurasia are found to be particularly sizable, whereas some areas of non-OECD Asia and OECD Europe appear to have more limited onshore technical potential. Figure TS.7.1, a global wind resource map, also shows limited technical potential in certain areas of Latin America and Africa, though other portions of those continents have significant

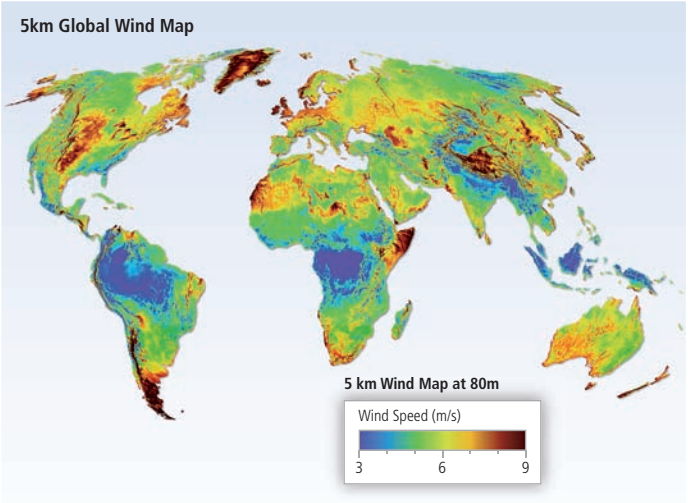


Figure TS.7.1 | Example global wind resource map with 5 km x 5 km resolution. [Figure 7.1]

technical potential. Recent, detailed regional assessments have generally found the size of the wind resource to be greater than estimated in previous assessments. [7.2.2]

Global climate change may alter the geographic distribution and/or the inter- and intra-annual variability of the wind resource, and/or the quality of the wind resource, and/or the prevalence of extreme weather events that may impact wind turbine design and operation. Research to date suggests that it is unlikely that multi-year annual mean wind speeds will change by more than a maximum of ±25% over most of Europe and North America during the present century, while research covering northern Europe suggests that multi-year annual mean wind power densities will likely remain within ±50% of current values. Fewer studies have been conducted for other regions of the world. Though research in this field is nascent and additional study is warranted, research to date suggests that global climate change may alter the geographic distribution of the wind resource, but that those effects are unlikely to be of a magnitude to greatly impact the global potential for wind energy deployment. [7.2.3]

7.3 Technology and applications

Modern, commercial grid-connected wind turbines have evolved from small, simple machines to large, highly sophisticated devices. Scientific and engineering expertise and advances, as well as improved computational tools, design standards, manufacturing methods and O&M procedures, have all supported these technology developments. [7.3]

Generating electricity from the wind requires that the kinetic energy of moving air be converted to electrical energy, and the engineering challenge for the wind energy industry is to design cost-effective wind turbines and power plants to perform this conversion. Though a variety of turbine configurations have been investigated, commercially available turbines are primarily horizontal-axis machines with three blades positioned upwind of the tower. In order to reduce the levelized cost of wind energy, typical wind turbine sizes have grown significantly (Figure TS.7.2), with the largest fraction of onshore wind turbines installed globally in 2009 having a rated capacity of 1.5 to 2.5 MW. As of 2010, onshore wind turbines typically stand on 50- to 100-m towers, with rotors that are often 50 to 100 m in diameter; commercial machines

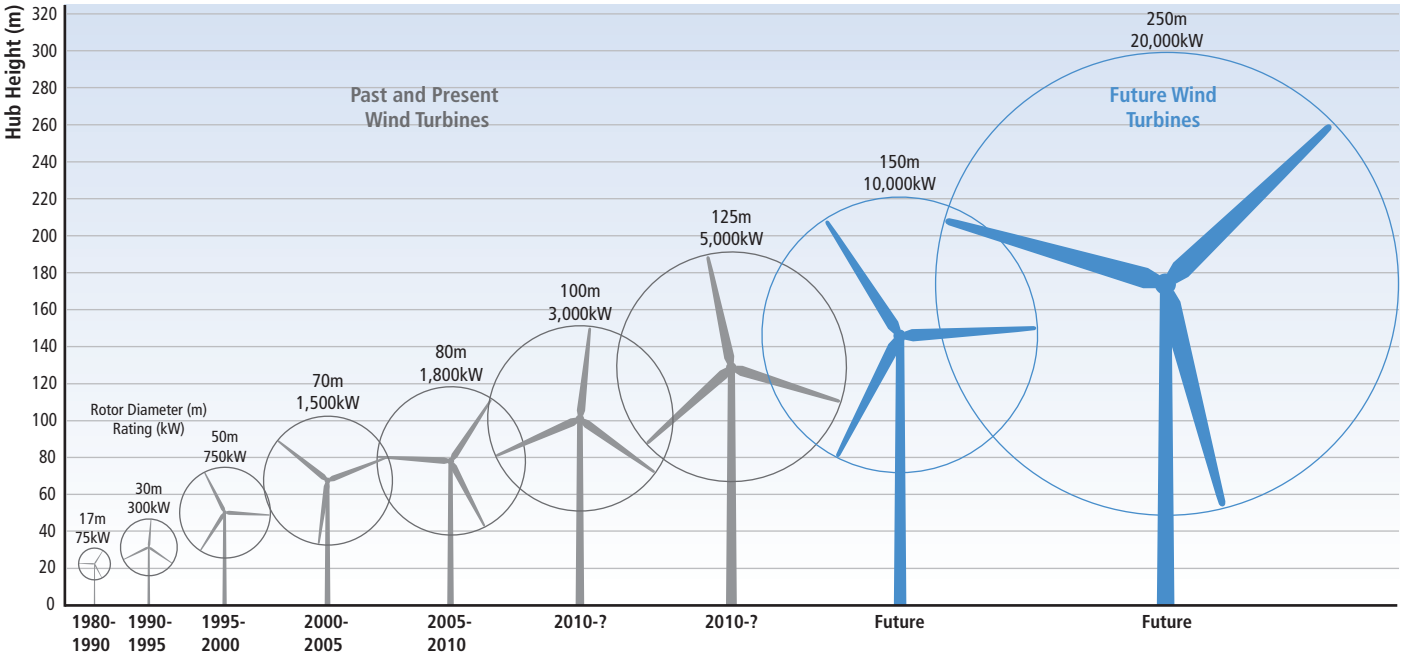


Figure TS.7.2 | Growth in size of typical commercial wind turbines. [Figure 7.6]

with rotor diameters and tower heights in excess of 125 m are operating, and even larger machines are under development. Onshore wind energy technology is already being commercially manufactured and deployed at a large scale. [7.3.1]

Offshore wind energy technology is less mature than onshore, with higher investment costs. Lower power plant availabilities and higher O&M costs have also been common both because of the comparatively less mature state of the technology and because of the inherently greater logistical challenges of maintaining and servicing offshore turbines. Nonetheless, considerable interest in offshore wind energy exists in the EU and, increasingly, in other regions. The primary motivation to develop offshore wind energy is to provide access to additional wind resources in areas where onshore wind energy development is constrained by limited technical potential and/or by planning and siting conflicts with other land uses. Other motivations include the higher-quality wind resources located at sea; the ability to use even larger wind turbines and the potential to thereby gain additional economies of scale; the ability to build larger power plants than onshore, gaining plant-level economies of scale; and a potential reduction in the need for new, long-distance, land-based transmission infrastructure to access distant onshore wind energy. To date, offshore wind turbine technology has been very similar to onshore designs, with some modifications and with special foundations. As experience is gained, water depths are expected to increase and more exposed locations with higher winds will be utilized. Wind energy technology specifically tailored for offshore applications will become more prevalent as the offshore market expands, and it is expected that larger turbines in the 5 to 10 MW range may come to dominate this segment. [7.3.1.3]

Alongside the evolution of wind turbine design, improved design and testing methods have been codified in International Electrotechnical Commission standards. Certification agencies rely on accredited design and testing bodies to provide traceable documentation demonstrating conformity with the standards in order to certify that turbines, components or entire wind power plants meet common guidelines relating to safety, reliability, performance and testing. [7.3.2]

From an electric system reliability perspective, an important part of the wind turbine is the electrical conversion system. For modern turbines, variable-speed machines now dominate the market, allowing for the provision of real and reactive power as well as some fault ride-through capability, but no intrinsic inertial response (i.e., turbines do not increase or decrease power output in synchronism with system power imbalances); wind turbine manufacturers have recognized this latter limitation and are pursuing a variety of solutions. [7.3.3]

7.4 Global and regional status of market and industry development

The wind energy market has expanded substantially, demonstrating the commercial and economic viability of the technology and industry. Wind energy expansion has been concentrated in a limited number of regions, however, and further expansion, especially in regions with little wind energy deployment to date and in offshore locations, is likely to require additional policy measures. [7.4]

Wind energy has quickly established itself as part of the mainstream electricity industry. From a cumulative capacity of 14 GW at the end of 1999, global installed capacity increased twelve-fold in 10 years to reach almost 160 GW by the end of 2009. The majority of the capacity has been installed onshore, with offshore installations primarily in Europe and totalling a cumulative 2.1 GW. The countries with the highest installed capacity by the end of 2009 were the USA (35 GW), China (26 GW), Germany (26 GW), Spain (19 GW) and India (11 GW). The total investment cost of new wind power plants installed in 2009 was USD_{2005} 57 billion, while worldwide direct employment in the sector in 2009 has been estimated at approximately 500,000. [7.4.1, 7.4.2]

In both Europe and the USA, wind energy represents a major new source of electric capacity additions. In 2009, roughly 39% of all capacity additions in the USA and the EU came from wind energy; in China, 16% of the net capacity additions in 2009 came from wind energy. On a global basis, from 2000 through 2009, roughly 11% of all newly installed net electric capacity additions came from new wind power plants; in 2009 alone, that figure was probably more than 20%. As a result, a number of countries are beginning to achieve relatively high levels of annual wind electricity penetration in their respective electric systems. By the end of 2009, wind power capacity was capable of supplying electricity equal to roughly 20% of Denmark's annual electricity demand, 14% of Portugal's, 14% of Spain's, 11% of Ireland's and 8% of Germany's. [7.4.2]

Despite these trends, wind energy remains a relatively small fraction of worldwide electricity supply. The total wind power capacity installed by the end of 2009 would, in an average year, meet roughly 1.8% of worldwide electricity demand. Additionally, though the trend over time has been for the wind energy industry to become less reliant on European markets, with significant recent expansion in the USA and China, the market remains concentrated regionally: Latin America, Africa and the Middle East, and the Pacific regions have installed relatively little wind power capacity despite significant technical potential for wind energy in each region (Figure TS.7.3). [7.4.1, 7.4.2]

The deployment of wind energy must overcome a number of challenges, including: the relative cost of wind energy compared to energy market prices, at least if environmental impacts are not internalized and monetized; concerns about the impact of wind energy's variability; challenges of building new transmission; cumbersome and slow planning, siting and permitting procedures; the technical advancement needs and higher cost of offshore wind energy technology; and lack of institutional and technical knowledge in regions that have not yet experienced substantial wind energy deployment. As a result, growth is affected by a wide range of government policies. [7.4.4]

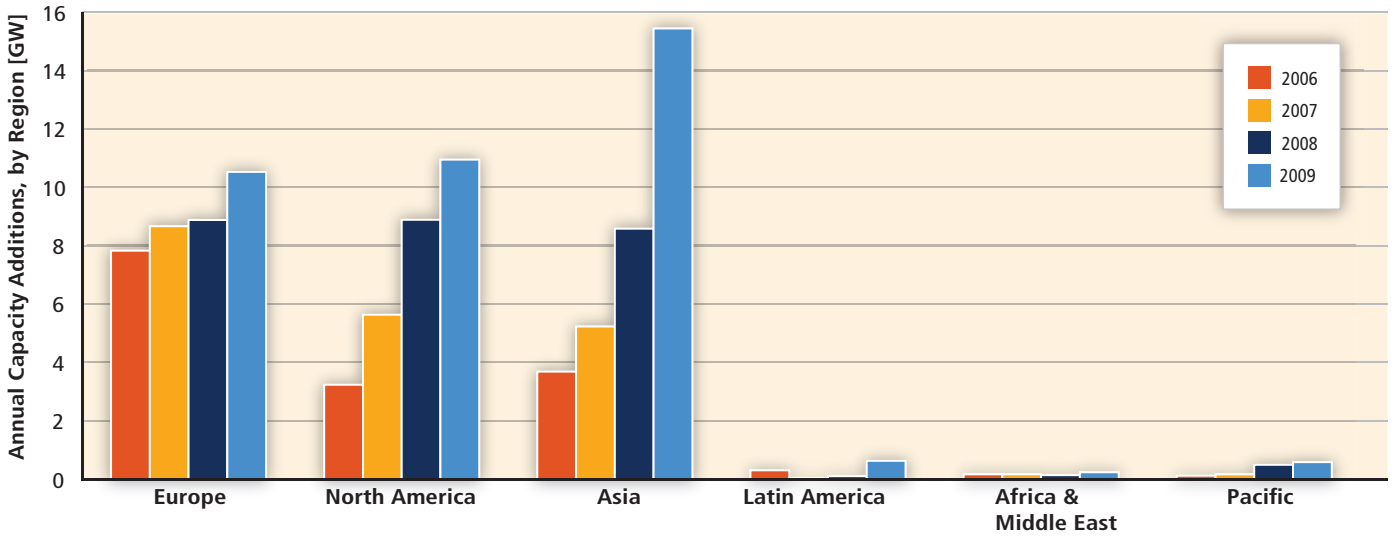


Figure TS.7.3 | Annual wind power capacity additions by region. [Figure 7.10]

Note: Regions shown in the figure are defined by the study.

7.5 Near-term grid integration issues

As wind energy deployment has increased, so have concerns about the integration of that energy into electric systems. The nature and magnitude of the integration challenge will depend on the characteristics of the existing electric system and the level of wind electricity penetration. Moreover, as discussed in Chapter 8, integration challenges are not unique to wind energy. Nevertheless, analysis and operating experience primarily from certain OECD countries suggests that, at low to medium levels of wind electricity penetration (defined here as up to 20% of total annual average electrical energy demand)[12], the integration of wind energy generally poses no insurmountable technical barriers and is economically manageable. At the same time, even at low to medium levels of wind electricity penetration, certain (and sometimes system-specific) technical and/or institutional challenges must be addressed. Concerns about (and the costs of) wind energy integration will grow with wind energy deployment, and even higher levels of penetration may depend on or benefit from the availability of additional technological and institutional options to increase flexibility and maintain a balance between supply and demand, as discussed further in Chapter 8 (Section 8.2). [7.5]

Wind energy has characteristics that present integration challenges, and that must be considered in electric system planning and operation to ensure the reliable and economical operation of the electric power system. These include: the localized nature of the wind resource with possible implications for new transmission for both on- and offshore wind energy; the variability of wind power output over multiple time scales; and the lower levels of predictability of wind power output than are common for many other types of power plants. The aggregate variability and uncertainty of wind power output depends, in part, on the degree of correlation between the output of different geographically dispersed wind power plants: generally, the outputs of wind power plants that are farther apart are less correlated with each other, and variability over shorter time periods (minutes) is less correlated than variability over longer time periods (multiple hours). Forecasts of wind power output are also more accurate over shorter time periods, and when multiple plants are considered together. [7.5.2]

Detailed system planning for new generation and transmission infrastructure is used to ensure that the electric system can be operated reliably and economically in the future. To do so, planners need computer-based simulation models that accurately characterize wind energy. Additionally, as wind power capacity has increased, so has the need for wind power plants to become more active participants in maintaining the operability and power quality of the electric system, and technical standards for grid connection have been implemented to help prevent wind power plants from adversely affecting the electric system during normal operation and contingencies. Transmission adequacy evaluations, meanwhile, must account for the location dependence of the wind resource, and consider any trade-offs between the costs of expanding the transmission system to access higher-quality wind resources in comparison to the costs of accessing lower-quality wind resources that require less transmission investment. Even at low to medium levels of wind electricity penetration, the addition of large quantities of on- or offshore wind energy in areas with higher-quality wind resources may require significant new additions or upgrades to the transmission system. Depending on the legal and regulatory framework in any particular region, the institutional challenges of transmission expansion can be substantial. Finally, planners need to account for wind

12 This level of penetration was chosen to loosely separate the integration needs for wind energy in the relatively near term from the broader, longer- term, and non-wind-specific discussion of power system changes provided in Chapter 8.

power output variability in assessing the contribution of wind energy to generation adequacy and therefore the long-term reliability of the electric system. Though methods and objectives vary from region to region, the contribution of wind energy to generation adequacy usually depends on the correlation of wind power output with the periods of time when there is a higher risk of a supply shortage, typically periods of high electricity demand. The marginal contribution of wind energy to generation adequacy typically declines as wind electricity penetration increases, but aggregating wind power plants over larger areas may slow this decline if adequate transmission capacity is available. The relatively low average contribution of wind energy to generation adequacy (compared to fossil units) suggests that electric systems with large amounts of wind energy will also tend to have significantly more total nameplate generation capacity to meet the same peak electricity demand than will electric systems without large amounts of wind energy. Some of this generation capacity will operate infrequently, however, and the mix of other generation will therefore tend (on economic grounds) to increasingly shift towards flexible 'peaking' and 'intermediate' resources and away from 'base-load' resources. [7.5.2]

The unique characteristics of wind energy also have important implications for electric system operations. Because wind energy is generated with a very low marginal operating cost, it is typically used to meet demand when it is available; other generators are then dispatched to meet demand minus any available wind energy (i.e., 'net demand'). As wind electricity penetration grows, the variability of wind energy results in an overall increase in the magnitude of changes in net demand, and also a decrease in the minimum net demand. As a result of these trends, wholesale electricity prices will tend to decline when wind power output is high and transmission interconnector capacity to other energy markets is constrained, and other generating units will be called upon to operate in a more flexible manner than required without wind energy. At low to medium levels of wind electricity penetration, the increase in minute-to-minute variability is expected to be relatively small. The more significant operational challenges relate to the need to manage changes in wind power output over one to six hours. Incorporating wind energy forecasts into electric system operations can reduce the need for flexibility from other generators, but even with high-quality forecasts, system operators will need a broad range of strategies to actively maintain the supply/demand balance, including the use of flexible power generation technologies, wind energy output curtailment, and increased coordination and interconnection between electric systems. Mass-market demand response, bulk energy storage technologies, large-scale deployment of electric vehicles and their associated contributions to system flexibility through controlled battery charging, diverting excess wind energy to fuel production or local heating, and geographic diversification of wind power plant siting will also become increasingly beneficial as wind electricity penetration rises. Despite the challenges, actual operating experience in different parts of the world demonstrates that electric systems can operate reliably with increased contributions of wind energy; in four countries (Denmark, Portugal, Spain, Ireland), wind energy in 2010 was already able to supply from 10 to roughly 20% of annual electricity demand. Experience is limited, in particular with regard to system faults at high instantaneous penetration levels, however, and as more wind energy is deployed in diverse regions and electric systems, additional knowledge about wind energy integration will be gained. [7.5.3]

In addition to actual operating experience, a number of high-quality studies of the increased transmission and generation resources required to accommodate wind energy have been completed, primarily covering OECD countries. These studies employ a wide variety of methodologies and have diverse objectives, but the results demonstrate that the cost of integrating up to 20% wind energy into electric systems is, in most cases, modest but not insignificant. Specifically, at low to medium levels of wind electricity penetration, the available literature (again, primarily from a subset of OECD countries) suggests that the additional costs of managing electric system variability and uncertainty, ensuring generation adequacy, and adding new transmission to accommodate wind energy will be system specific but generally in the range of US cent$_{2005}$ 0.7/kWh to US cent$_{2005}$ 3/kWh. The technical challenges and costs of integration are found to increase with wind electricity penetration. [7.5.4]

7.6 Environmental and social impacts

Wind energy has significant potential to reduce (and is already reducing) GHG emissions. Moreover, attempts to measure the relative impacts of various electricity supply technologies suggest that wind energy generally has a comparatively small environmental footprint. [9.3.4, 10.6] As with other industrial activities, however, wind energy has the potential to produce some detrimental impacts on the environment and on human activities and well being, and many local and national governments have established planning and siting requirements to reduce those impacts. As wind energy deployment increases and as larger wind power plants are considered, existing concerns may become more acute and new concerns may arise. [7.6]

Although the major environmental benefits of wind energy result from displacing electricity generated from fossil fuel-based power plants, estimating those benefits is somewhat complicated by the operational characteristics of the electric system and the investment decisions that are made about new power plants. In the short run, increased wind energy will typically displace the operations of existing fossil fuel-fired plants. In the longer term, however, new generating plants may be needed, and the presence of wind energy can influence what types of power plants are built. The impacts arising from the manufacture, transport, installation, operation and decommissioning of wind turbines should also be considered, but a comprehensive review of available studies demonstrates that the energy used and GHG emissions produced during these steps are small compared to the energy generated and emissions avoided over the lifetime of wind power plants. The GHG emissions intensity of wind energy is estimated to range from 8 to 20 g CO_2/kWh in most instances, whereas energy payback times are between 3.4 and 8.5 months. In addition, managing the variability of wind power

output has not been found to significantly degrade the GHG emissions benefits of wind energy. [7.6.1]

Other studies have considered the local ecological impacts of wind energy development. The construction and operation of both on- and offshore wind power plants impacts wildlife through bird and bat collisions and through habitat and ecosystem modifications, with the nature and magnitude of those impacts being site- and species-specific. For offshore wind energy, implications for benthic resources, fisheries and marine life more generally must be considered. Research is also underway on the potential impact of wind power plants on the local climate. Bird and bat fatalities through collisions with wind turbines are among the most publicized environmental concerns. Though much remains unknown about the nature and population-level implications of these impacts, avian fatality rates have been reported at between 0.95 and 11.67 per MW per year. Raptor fatalities, though much lower in absolute number, have raised special concerns in some cases, and as offshore wind energy has increased, concerns have also been raised about seabirds. Bat fatalities have not been researched as extensively, but fatality rates ranging from 0.2 to 53.3 per MW per year have been reported; the impact of wind power plants on bat populations is of particular contemporary concern. The magnitude and population-level consequences of bird and bat collision fatalities can also be viewed in the context of other fatalities caused by human activities. The number of bird fatalities at existing wind power plants appears to be orders of magnitude lower than other anthropogenic causes of bird deaths, it has been suggested that onshore wind power plants are not currently causing meaningful declines in bird population levels, and other energy supply options also impact birds and bats through collisions, habitat modifications and contributions to global climate change. Improved methods to assess species-specific population-level impacts and their possible mitigation are needed, as are robust comparisons between the impacts of wind energy and of other electricity supply options. [7.6.2]

Wind power plants can also impact habitats and ecosystems through avoidance of or displacement from an area, habitat destruction and reduced reproduction. Additionally, the impacts of wind power plants on marine life have moved into focus as offshore development has increased. The impacts of offshore wind energy on marine life vary between the installation, operation and decommissioning phases, depend greatly on site-specific conditions, and may be negative or positive. Potential negative impacts include underwater sounds and vibrations, electromagnetic fields, physical disruption and the establishment of invasive species. The physical structures may, however, create new breeding grounds or shelters and act as artificial reefs or fish aggregation devices. Additional research is warranted on these impacts and their long-term and population-level consequences, but they do not appear to be disproportionately large compared to onshore wind energy. [7.6.2]

Surveys have consistently found wind energy to be widely accepted by the general public. Translating this support into increased deployment, however, often requires the support of local host communities and/or decision makers. To that end, in addition to ecological concerns, a number of concerns are often raised about the impacts of wind power plants on local communities. Perhaps most importantly, modern wind energy technology involves large structures, so wind turbines are unavoidably visible in the landscape. Other impacts of concern include land and marine usage (including possible radar interference), proximal impacts such as noise and flicker, and property value impacts. Regardless of the type and degree of social and environmental concerns, addressing them is an essential part of any successful wind power planning and plant siting process, and engaging local residents is often an integral aspect of that process. Though some of the concerns can be readily mitigated, others—such as visual impacts—are more difficult to address. Efforts to better understand the nature and magnitude of the remaining impacts, together with efforts to minimize and mitigate those impacts, will need to be pursued in concert with increasing wind energy deployment. In practice, planning and siting regulations vary dramatically by jurisdiction, and planning and siting processes have been obstacles to wind energy development in some countries and contexts. [7.6.3]

7.7 Prospects for technology improvement and innovation

Over the past three decades, innovation in wind turbine design has led to significant cost reductions. Public and private R&D programmes have played a major role in these technical advances, leading to system- and component-level technology improvements, as well as improvements in resource assessment, technical standards, electric system integration, wind energy forecasting and other areas. From 1974 to 2006, government R&D budgets for wind energy in IEA countries totalled USD_{2005} 3.8 billion, representing 1% of total energy R&D expenditure. In 2008, OECD research funding for wind energy totalled USD_{2005} 180 million. [7.7, 7.7.1]

Though onshore wind energy technology is already commercially manufactured and deployed at a large scale, continued incremental advances are expected to yield improved turbine design procedures, more efficient materials usage, increased reliability and energy capture, reduced O&M costs and longer component lifetimes. In addition, as offshore wind energy gains more attention, new technology challenges arise and more radical technology innovations are possible. Wind power plants and turbines are complex systems that require integrated design approaches to optimize cost and performance. At the plant level, considerations include the selection of a wind turbine for a given wind resource regime; wind turbine siting, spacing and installation procedures; O&M methodologies; and electric system integration. Studies have identified a number of areas where technology advances could result in changes in the investment cost, annual energy production, reliability, O&M cost and electric system integration of wind energy. [7.3.1, 7.7.1, 7.7.2]

At the component level, a range of opportunities are being pursued, including: advanced tower concepts that reduce the need for large cranes and minimize materials demands; advanced rotors and blades

through better designs, coupled with better materials and advanced manufacturing methods; reduced energy losses and improved availability through advanced turbine control and condition monitoring; advanced drive trains, generators and power electronics; and manufacturing learning improvements. [7.7.3]

In addition, there are several areas of possible advancement that are more specific to offshore wind energy, including O&M procedures, installation and assembly schemes, support structure design, and the development of larger turbines, possibly including new turbine concepts. Foundation structure innovation, in particular, offers the potential to access deeper waters, thereby increasing the technical potential of wind energy. Offshore turbines have historically been installed primarily in relatively shallow water, up to 30 m deep, on a mono-pile structure that is essentially an extension of the tower, but gravity-based structures have become more common. These approaches, as well as other concepts that are more appropriate for deeper waters, including floating platforms, are depicted in Figure TS.7.4. Additionally, offshore turbine size is not restricted in the same way as onshore wind turbines, and the relatively higher cost of offshore foundations provides motivation for larger turbines. [7.7.3]

Wind turbines are designed to withstand a wide range of challenging conditions with minimal attention. Significant effort is therefore needed to enhance fundamental understanding of the operating environment in which turbines operate in order to facilitate a new generation of reliable, safe, cost-effective wind turbines, and to further optimize wind power plant siting and design. Research in the areas of aeroelastics, unsteady aerodynamics, aeroacoustics, advanced control systems, and atmospheric science, for example, is anticipated to lead to improved design tools, and thereby increase the reliability of the technology and encourage further design innovation. Fundamental research of this nature will help improve wind turbine design, wind power plant performance estimates, wind resource assessments, short-term wind energy forecasting, and estimates of the impact of large-scale wind energy deployment on the local climate, as well as the impact of potential climate change effects on wind resources. [7.7.4]

7.8 Cost trends

Though the cost of wind energy has declined significantly since the 1980s, policy measures are currently required to ensure rapid deployment in most regions of the world. In some areas with good wind resources, however, the cost of wind energy is competitive with current energy market prices, even without considering relative environmental impacts. Moreover, continued technology advancements are expected, supporting further cost reduction. [7.8]

The levelized cost of energy from on- and offshore wind power plants is affected by five primary factors: annual energy production; investment costs; O&M costs; financing costs; and the assumed economic life of

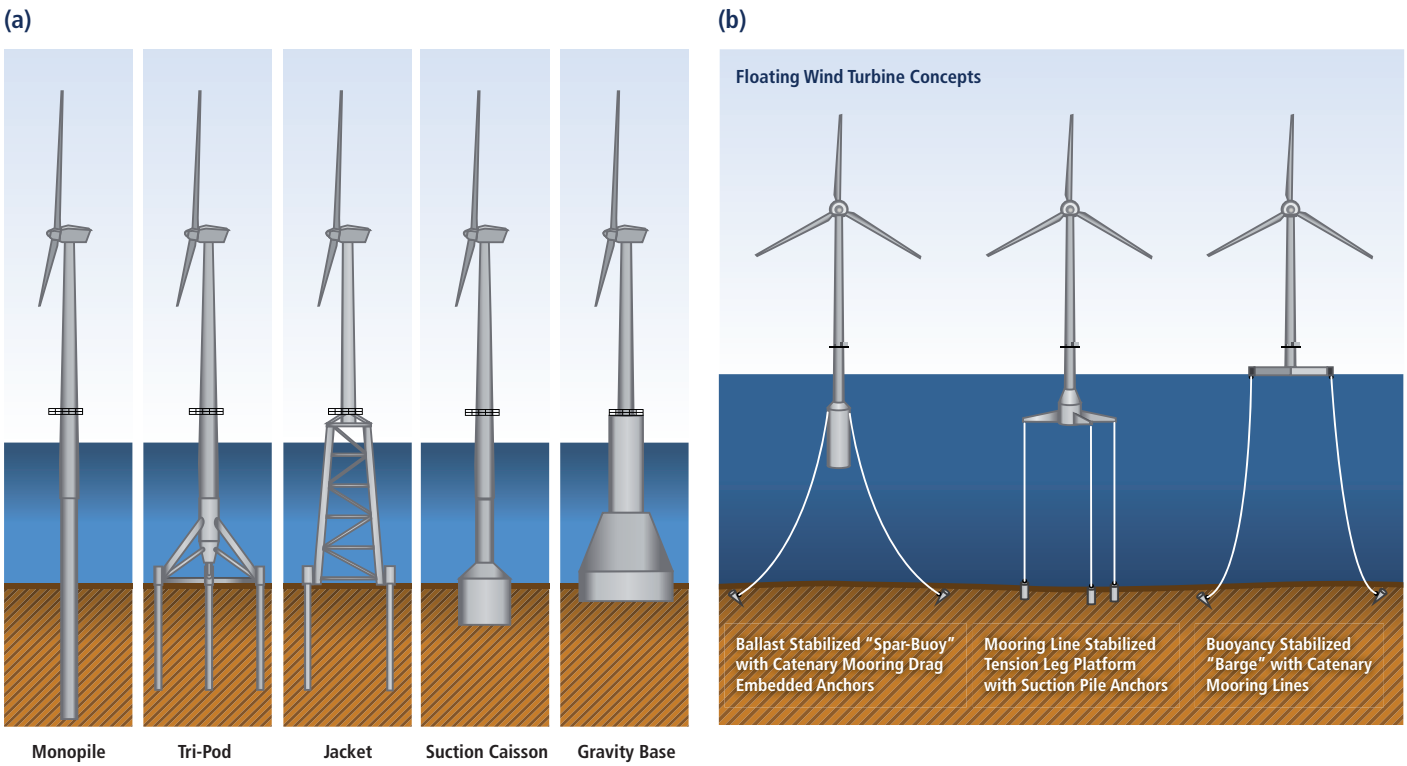


Figure TS.7.4 | Offshore wind turbine foundation designs: (a) near-term concepts and (b) floating offshore turbine concepts. [Figure 7.19]

the power plant.[13] From the 1980s to roughly 2004, the investment cost of onshore wind power plants dropped. From 2004 to 2009, however, investment costs increased, the primary drivers of which were: escalation in the cost of labour and materials inputs; increasing profit margins among turbine manufacturers and their suppliers; the relative strength of the Euro currency; and the increased size of turbine rotors and hub heights. In 2009, the average investment cost for onshore wind power plants installed worldwide was approximately USD_{2005} 1,750/kW, with many plants falling in the range of USD_{2005} 1,400 to 2,100/kW; investment costs in China in 2008 and 2009 were around USD_{2005} 1,000 to 1,350/kW. There is far less experience with offshore wind power plants, and the investment costs of offshore plants are highly site-specific. Nonetheless, the investment costs of offshore plants have historically been 50 to more than 100% higher than for onshore plants; O&M costs are also greater for offshore plants. Offshore costs have also been influenced by some of the same factors that caused rising onshore costs from 2004 through 2009, as well as by several unique factors. The most recently installed or announced offshore plants have investment costs that are reported to range from roughly USD_{2005} 3,200/kW to USD_{2005} 5,000/kW. Notwithstanding the increased water depth of offshore plants over time, the majority of the operating plants have been built in relatively shallow water. The performance of wind power plants is highly site-specific, and is primarily governed by the characteristics of the local wind regime, but is also impacted by wind turbine design optimization, performance and availability, and by the effectiveness of O&M procedures. Performance therefore varies by location, but has also generally improved with time. Offshore wind power plants are often exposed to better wind resources. [7.8.1–7.8.3]

Based on a standardized methodology outlined in Annex II and the cost and performance data summarized in Annex III, the LCOE for on- and offshore wind power plants over a large set and range of input parameters has been calculated to range from US $cent_{2005}$ 3.5/kWh to US $cent_{2005}$ 17/kWh and from US $cent_{2005}$ 7.5/kWh to US $cent_{2005}$ 23/kWh, respectively. [1.3.2, 10.5.1, Annex II, Annex III]

Figure TS.7.5 presents the LCOE of on- and offshore wind energy over a somewhat different set and range of parameters, and shows that the LCOE varies substantially depending on assumed investment costs, energy production and discount rates. For onshore wind energy, estimates are provided for plants built in 2009; for offshore wind energy, estimates are provided for plants built from 2008 to 2009 as well as those plants that were planned for completion in the early 2010s. The LCOE for onshore wind energy in good to excellent wind resource regimes are estimated to average approximately US $cent_{2005}$ 5/kWh to US $cent_{2005}$ 10/kWh, and can reach more than US $cent_{2005}$ 15/kWh in lower-resource areas. Though

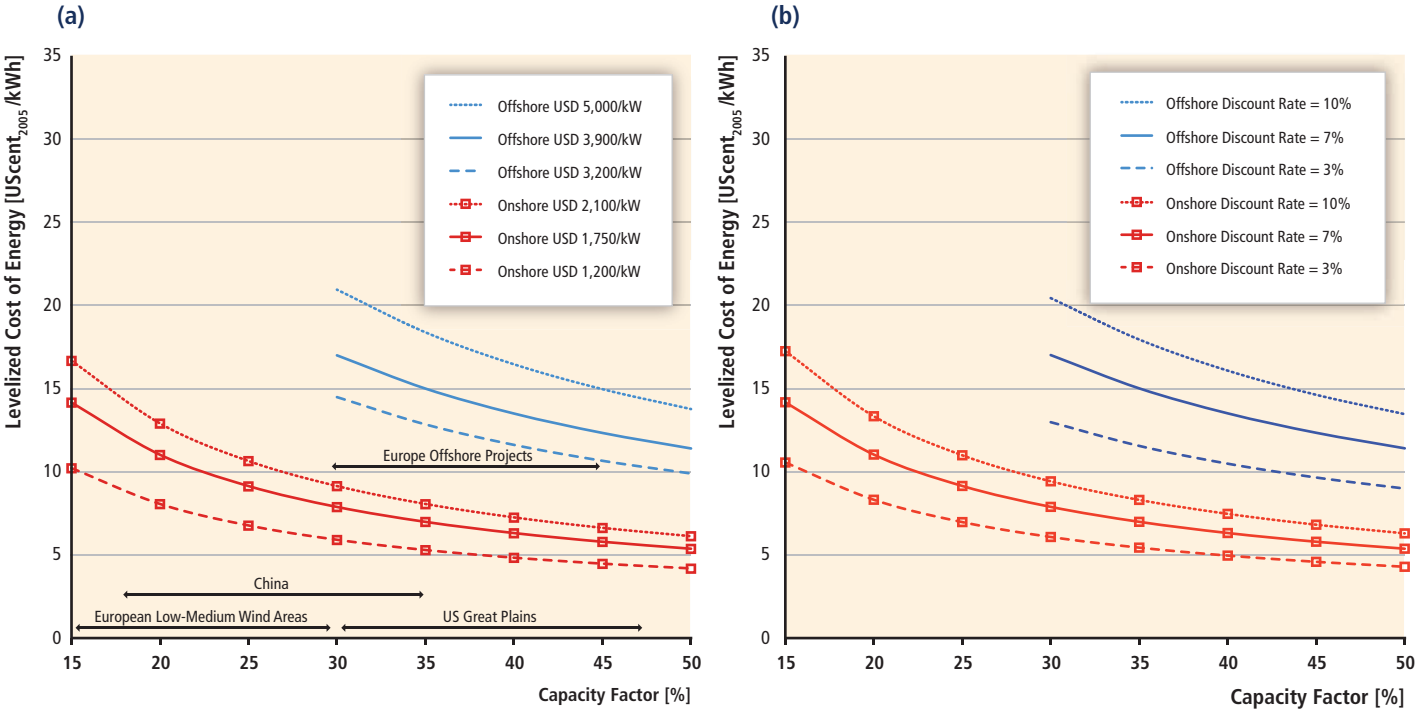


Figure TS.7.5 | Estimated levelized cost of on- and offshore wind energy, 2009: (a) as a function of capacity factor and investment cost* and (b) as a function of capacity factor and discount rate**. [Figure 7.23]

Notes: * Discount rate assumed to equal 7%. ** Onshore investment cost assumed at USD_{2005} 1,750/kW, and offshore at USD_{2005} 3,900/kW.

13 The economic competitiveness of wind energy in comparison to other energy sources, which necessarily must also include other factors such as subsidies and environmental externalities, is not covered in this section.

the offshore cost estimates are more uncertain, typical LCOE are estimated to range from US cent$_{2005}$ 10/kWh to more than US cent$_{2005}$ 20/kWh for recently built or planned plants located in relatively shallow water. Where the exploitable onshore wind resource is limited, offshore plants can sometimes compete with onshore plants. [7.8.3, Annex II, Annex III]

A number of studies have developed forecasted cost trajectories for on- and offshore wind energy based on differing combinations of learning curve estimates, engineering models and/or expert judgement. Among these studies, the starting year of the forecasts, the methodological approaches and the assumed wind energy deployment levels vary. Nonetheless, a review of this literature supports the idea that continued R&D, testing and experience could yield reductions in the levelized cost of onshore wind energy of 10 to 30% by 2020. Offshore wind energy is anticipated to experience somewhat deeper cost reductions of 10 to 40% by 2020, though some studies have identified scenarios in which market factors lead to cost increases in the near to medium term. [7.8.4]

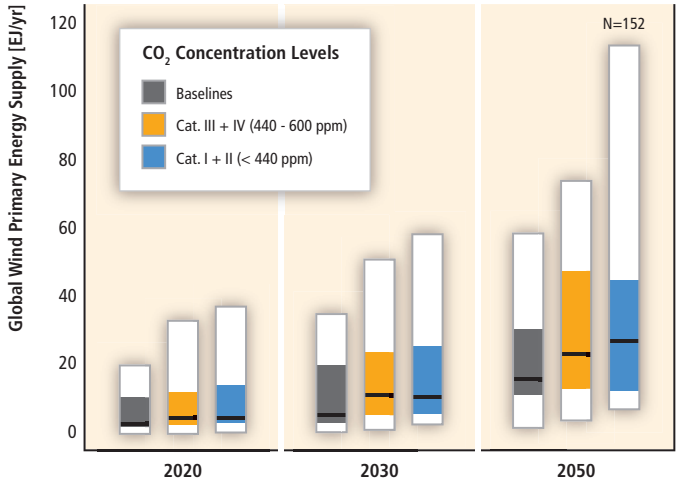


Figure TS.7.6 | Global primary energy supply of wind energy in long-term scenarios (median, 25th to 75th percentile range, and full range of scenario results; colour coding is based on categories of atmospheric CO_2 concentration level in 2100; the specific number of scenarios underlying the figure is indicated in the right upper corner). [Figure 7.24]

7.9 Potential deployment

Given the commercial maturity and cost of onshore wind energy technology, increased utilization of wind energy offers the potential for significant near-term GHG emission reductions: this potential is not conditioned on technology breakthroughs, and no insurmountable technical barriers exist that preclude increased levels of wind energy penetration into electricity supply systems. As a result, in the near to medium term, the rapid increase in wind power capacity from 2000 to 2009 is expected by many studies to continue. [7.9, 7.9.1]

Moreover, a number of studies have assessed the longer-term potential of wind energy, often in the context of GHG concentration stabilization scenarios. [10.2, 10.3] Based on a review of this literature (including 164 different long-term scenarios), and as summarized in Figure TS.7.6, wind energy could play a significant long-term role in reducing global GHG emissions. By 2050, the median contribution of wind energy among the scenarios with GHG concentration stabilization ranges of 440 to 600 ppm CO_2 and <440 ppm CO_2 is 23 to 27 EJ/yr (6,500 to 7,600 TWh/yr), increasing to 45 to 47 EJ/yr at the 75th percentile of scenarios (12,400 to 12,900 TWh/yr), and to more than 100 EJ/yr in the highest study (31,500 TWh). Achieving this contribution would require wind energy to deliver around 13 to 14% of global electricity supply in the median scenario result by 2050, increasing to 21 to 25% at the 75th percentile of the reviewed scenarios. [7.9.2]

Achieving the higher end of this range of global wind energy utilization would likely require not only economic support policies of adequate size and predictability, but also an expansion of wind energy utilization regionally, increased reliance on offshore wind energy in some regions, technical and institutional solutions to transmission constraints and operational integration concerns, and proactive efforts to mitigate and manage social and environmental concerns. Additional R&D is expected to lead to incremental cost reductions for onshore wind energy, and enhanced R&D expenditures may be especially important for offshore wind energy technology. Finally, for those markets with good wind resource potential but that are new to wind energy deployment, both knowledge and technology transfer may help facilitate early wind power plant installations. [7.9.2]

8. Integration of Renewable Energy into Present and Future Energy Systems

8.1 Introduction

In many countries, energy supply systems have evolved over decades, enabling the efficient and cost-effective distribution of electricity, gas, heat and transport energy carriers to provide useful energy services to end users. The transition to a low-carbon future that employs high shares of RE may require considerable investment in new RE technologies and infrastructure, including more flexible electricity grids, expansion of district heating and cooling schemes, distribution systems for RE-derived gases and liquid fuels, energy storage systems, novel methods of transport, and innovative distributed energy and control systems in buildings. Enhanced RE integration can lead to the provision of the full range of energy services for large and small communities in both developed and developing countries. Regardless of the energy supply system presently in place, whether in energy-rich or energy-poor communities, over the long term, and through measured system planning and integration,

there are few, if any, technical limits to increasing the shares of RE at the national, regional and local scales as well as for individual buildings, although other barriers may need to be overcome. [8.1, 8.2]

Energy supply systems are continuously evolving, with the aim of increasing conversion technology efficiencies, reducing losses and lowering the costs of providing energy services to end users. To provide a greater share of RE heating, cooling, transport fuels and electricity may require modification of current policies, markets and existing energy supply systems over time so that they can accommodate higher rates of deployment leading to greater supplies of RE. [8.1]

All countries have access to some RE resources and in many parts of the world these are abundant. The characteristics of many of these resources distinguish them from fossil fuels and nuclear systems. Some resources, such as solar and ocean energy, are widely distributed, whereas others, such as large-scale hydropower, are constrained by geographic location and hence integration options are more centralized. Some RE resources are variable and have limited predictability. Others have lower energy densities and their technical specifications differ from solid, liquid and gaseous fossil fuels. Such RE resource characteristics can constrain the ease of integration and invoke additional system costs, particularly when reaching higher shares of RE. [8.1, 8.2]

Following the structural outline of Chapter 8, RE resources can be used through integration into energy supply networks delivering energy to consumers using energy carriers with varying shares of RE embedded or by direct integration into the transport, buildings, industry and agriculture end-use sectors (Figure TS.8.1). [8.2, 8.3]

The general and specific requirements for enhanced integration of RE into energy supply systems are reasonably well understood. However, since integration issues tend to be site-specific, analyses of typical additional costs for RE integration options are limited and future research is required for use in scenario modelling. For example, it is not clear how the possible trend towards more decentralized energy supply systems might affect the future costs for developing further centralized heat and power supplies and the possible avoidance of constructing new infrastructure. [8.2]

Centralized energy systems, based mainly on fossil fuels, have evolved to provide reasonably cost-effective energy services to end users using

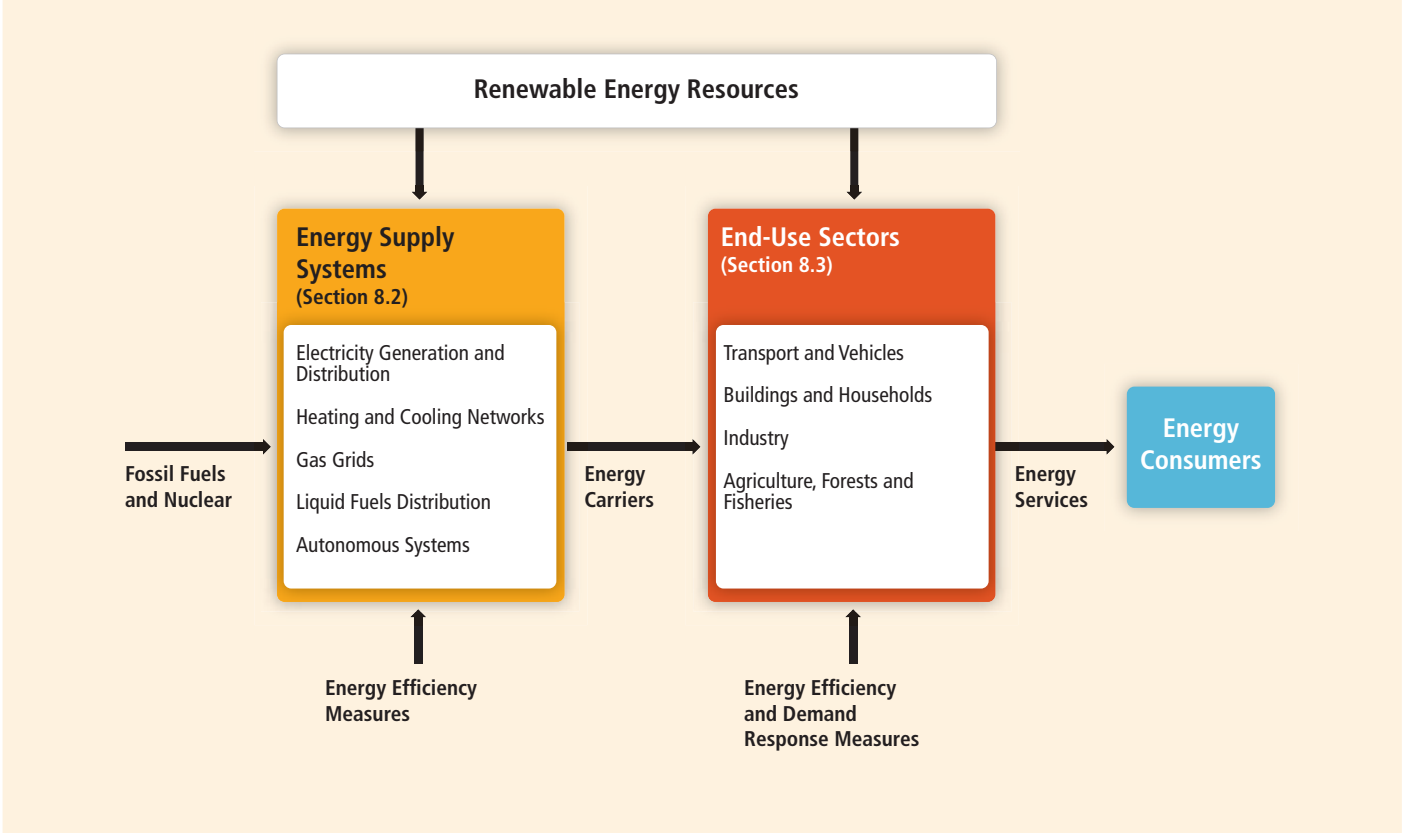


Figure TS.8.1 | Pathways for RE integration to provide energy services, either into energy supply systems or on-site for use by the end-use sectors. [Figure 8.1]

a range of energy carriers including solid, liquid and gaseous fuels, electricity, and heat. Increasing the deployment of RE technologies requires their integration into these existing systems by overcoming the associated technical, economic, environmental and social barriers. The advent of decentralized energy systems could open up new deployment opportunities. [8.1, 8.2]

In some regions, RE electricity systems could become the dominant future energy supply, especially if heating and transport demands are also to be met by electricity. This could be driven by parallel developments in electric vehicles, increased heating and cooling using electricity (including heat pumps), flexible demand response services (including the use of smart meters), and other innovative technologies. [8.1, 8.2.1.2, 8.2.2, 8.3.1–8.3.3]

The various energy systems differ markedly between countries and regions around the world and each is complex. As a result, a range of approaches are needed to encourage RE integration, whether centralized or decentralized. Prior to making any significant change in an energy supply system that involves increasing the integration of RE, a careful assessment of the RE resource availability; the suitability of existing technologies; institutional, economic and social constraints; the potential risks; and the need for related capacity building and skills development should be undertaken. [8.1, 8.2]

The majority of scenarios that stabilize atmospheric GHG concentrations around 450 ppm CO_2eq show that RE will exceed a 50% share of low-carbon primary energy by 2050. This transition can be illustrated by many scenarios, the single example of increasing market shares shown in Figure TS.8.2 being based on the IEA's World Energy Outlook 2010 '450 Policy Scenario'. To achieve such increased shares of primary and consumer energy from RE by 2035 would require the annual average incremental growth in primary RE to more than treble from today's level to around 4.0 EJ/yr. [8.1, 10.2, 10.2.2.4]

In order to gain greater RE deployment in each of the transport, building, industry and agriculture sectors, strategic elements need to be better understood, as do the social issues. Transition pathways for increasing the shares of each RE technology through integration depend on the specific sector, technology and region. Facilitating a smoother integration with energy supply systems and providing multiple benefits for energy end users should be the ultimate aims. [8.2, 8.3]

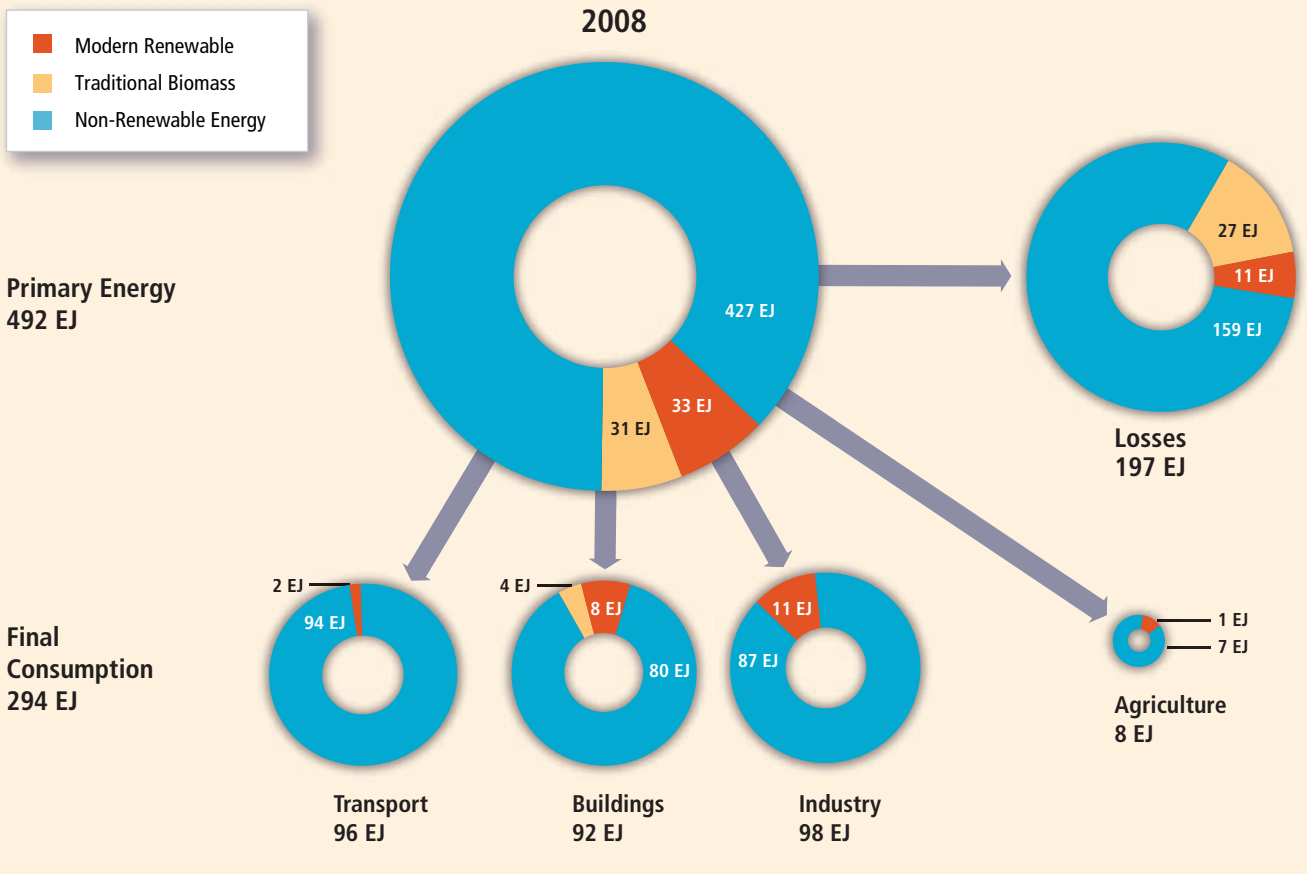
Several mature RE technologies have already been successfully integrated into a wide range of energy supply systems, mostly at relatively low shares but with some examples (including small- and large-scale hydropower, wind power, geothermal heat and power, first-generation biofuels and solar water heating systems) exceeding 30%. This was due mainly to their improved cost-competitiveness, an increase in support policies and growing public support due to the threats of an insecure energy supply and climate change. Exceptional examples are large-scale hydropower in Norway and hydro and geothermal power in Iceland approaching 100% of RE electricity, as has also been achieved by several small islands and towns. [8.2.1.3, 8.2.5.5, 11.2, 11.5]

Other less mature technologies require continuing investment in research, development, and demonstration (RD&D), infrastructure, capacity building and other supporting measures over the longer term. Such technologies include advanced biofuels, fuel cells, solar fuels, distributed power generation control systems, electric vehicles, solar absorption cooling and enhanced geothermal systems. [11.5, 11.6]

The current status of RE use varies for each end-use sector. There are also major regional variations in future pathways to enhance further integration by removal of barriers. For example, in the building sector, integrating RE technologies is vastly different for commercial high-rise buildings and apartments in mega-cities than for integration into small, modest village dwellings in developing countries that currently have limited access to energy services. [8.3.2]

Most energy supply systems can accommodate a greater share of RE than at present, particularly if the RE share is at relatively low levels (usually assumed to be below a 20% share of electricity, heat, pipeline gas blend or biofuel blend). To accommodate higher RE shares in the future, most energy supply systems will need to evolve and be adapted. In all cases, the maximum practical RE share will depend on the technologies involved, the RE resources available and the type and age of the present energy system. Further integration and increased rates of deployment can be encouraged by local, national and regional initiatives. The overall aim of Chapter 8 is to present the current knowledge on opportunities and challenges relating to RE integration for governments wishing to develop a coherent framework in preparation for future higher levels of RE penetration. Existing power supply systems, natural gas grids, heating/cooling schemes, petroleum-based transport fuel supply distribution networks and vehicles can all be adapted to accommodate greater supplies of RE than at present. RE technologies range from mature to those at the early concept demonstration stage. New technologies could enable increased RE uptake and their integration will depend upon improved cost-effectiveness, social acceptance, reliability and political support at national and local government levels in order to gain greater market shares. [8.1.2, 11.5]

Taking a holistic approach to the whole energy system may be a prerequisite to ensure efficient and flexible RE integration. This would include achieving mutual support between the different energy sectors, an intelligent forecasting and control strategy and coherent long-term planning. Together, these would enable the provision of electricity, heating, cooling and mobility to be more closely inter-linked. The optimum combination of technologies and social mechanisms to enable RE integration to reach high shares varies with the limitations of specific site conditions, characteristics of the available RE resources, and local energy demands. Exactly how present energy supply and demand systems can be adapted and developed to accommodate higher shares of RE, and the additional costs involved for their integration, depend on the specific circumstances, so


2008
Modern Renewable
Traditional Biomass
Non-Renewable Energy
Primary Energy
492 EJ
427 EJ
33 EJ
31 EJ
27 EJ
11 EJ
159 EJ
Losses
197 EJ
Final
Consumption
294 EJ
2 EJ
94 EJ
4 EJ
8 EJ
80 EJ
11 EJ
87 EJ
1 EJ
7 EJ
Transport
96 EJ
Buildings
92 EJ
Industry
98 EJ
Agriculture
8 EJ

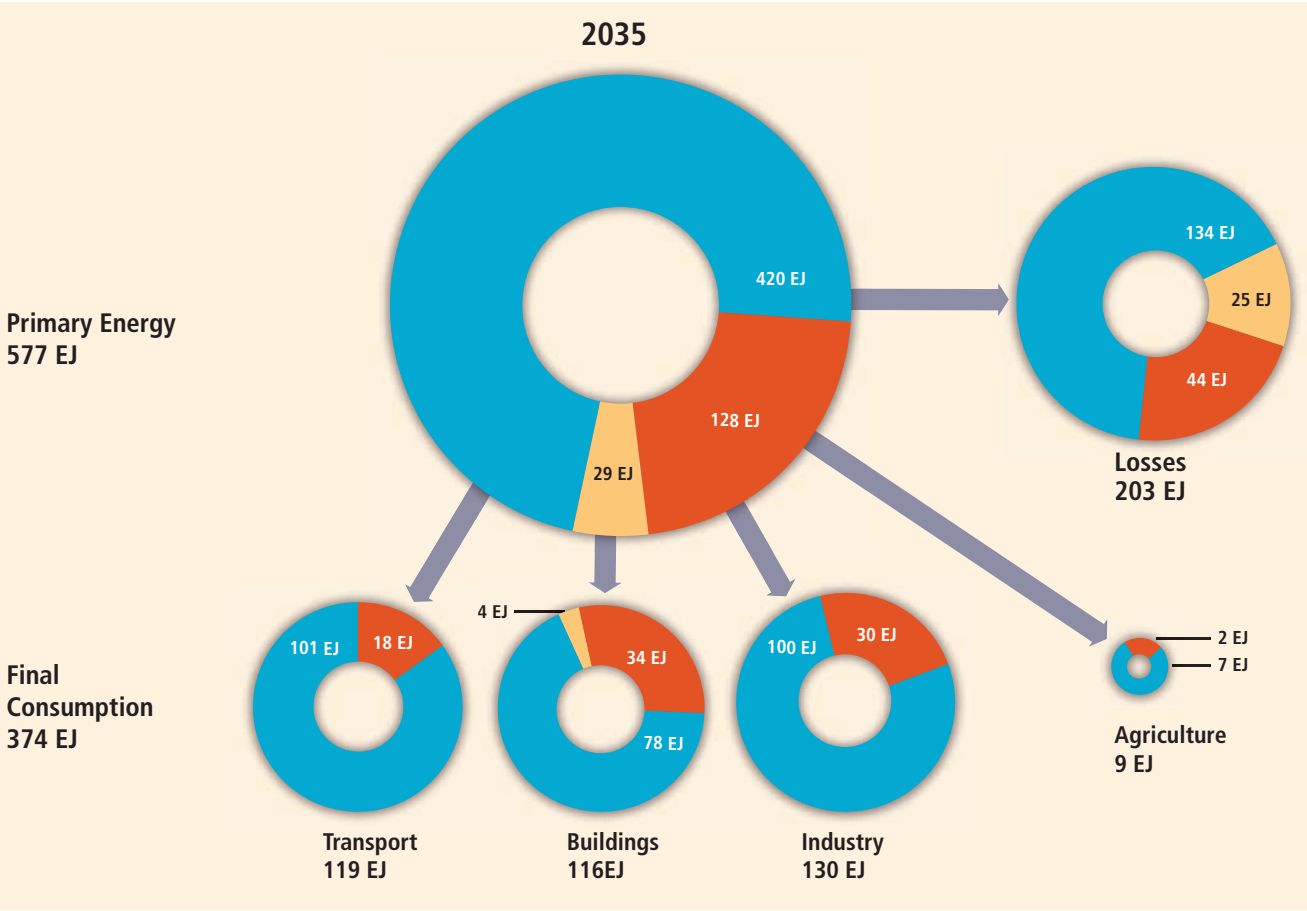

2035
Primary Energy
577 EJ
420 EJ
128 EJ
29 EJ
134 EJ
25 EJ
44 EJ
Losses
203 EJ
Final
Consumption
374 EJ
101 EJ
18 EJ
4 EJ
34 EJ
78 EJ
100 EJ
30 EJ
2 EJ
7 EJ
Transport
119 EJ
Buildings
116EJ
Industry
130 EJ
Agriculture
9 EJ

Figure TS.8.2 | (Preceding page) RE shares (red) of primary and final consumption energy in the transport, buildings (including traditional biomass), industry and agriculture sectors in 2008 and an indication of the projected increased RE shares needed by 2035 in order to be consistent with a 450 ppm CO_2eq stabilization level. [Figure 8.2]

Notes: Area of circles are approximately to scale. Energy system losses occur during the conversion, refining and distribution of primary energy sources to produce energy services for final consumption. 'Non-renewable' energy (blue) includes coal, oil, natural gas (with and without CCS by 2035) and nuclear power. This scenario example is based on data taken from the IEA World Energy Outlook 2010 but converted to direct equivalents. [Annex II.4] Energy efficiency improvements above the baseline are included in the 2035 projection. RE in the buildings sector includes traditional solid biomass fuels (yellow) for cooking and heating for 2.7 billion people in developing countries [2.2] along with some coal. By 2035, some traditional biomass has been partly replaced by modern bioenergy conversion systems. Excluding traditional biomass, the overall RE system efficiency (when converting from primary to consumer energy) remains around 66%.

further studies will be required. This is particularly the case for the electricity sector due to the wide variety of existing power generation systems and scales that vary with country and region. [8.2.1, 8.2.2, 8.3]

8.2 Integration of renewable energy into electrical power systems

Electrical power systems have been evolving since the end of the 19th century. Today, electrical power systems vary in scale and technological sophistication from the synchronized Eastern Interconnection in North America to small individual diesel-powered autonomous systems, with some systems, as in China, undergoing rapid expansion and transformation. Within these differences, however, electrical power systems are operated and planned with a common purpose of providing a reliable and cost-effective supply of electricity. Looking forward, electric power systems are expected to continue to expand in importance given that they supply modern energy, enable the transport of energy over long distances, and provide a potential pathway for delivering low-carbon energy. [8.2.1]

Electric power systems have several important characteristics that affect the challenges of integrating RE. The majority of electric power systems operate using alternating current (AC) whereby the majority of generation is synchronized and operated at a frequency of approximately either 50 or 60 Hz, depending on the region. The demand for electricity varies throughout the day, week and season, depending on the needs of electricity users. The aggregate variation in demand is matched by variation in schedules and dispatch instructions for generation in order to continuously maintain a balance between supply and demand. Generators and other power system assets are used to provide active power control to maintain the system frequency and reactive power control to maintain voltage within specified limits. Minute-to-minute variations in supply and demand are managed with automatic control of generation through services called regulation and load following, while changes over longer time scales of hours to days are managed by dispatching and scheduling generation (including turning generation on or off, which is also known as unit commitment). This continuous balancing is required irrespective of the mechanism used to achieve it. Some regions choose organized electricity markets in order to determine which generation units should be committed and/or how they should be dispatched. Even autonomous systems must employ methods to maintain a balance between generation and demand (via controllable generators, controllable loads, or storage resources like batteries). [8.2.1.1]

In addition to maintaining a balance between supply and demand, electric power systems must also transfer electricity between generation and demand through transmission and distribution networks with limited capacity. Ensuring availability of adequate generation and network capacity requires planning over multiple years. Planning electrical power systems incorporates the knowledge that individual components of the system, including generation and network components, will periodically fail (a contingency). A target degree of reliability can be met, however, by building adequate resources. One important metric used to determine the contribution of generation—fossil-fuel based or renewable—to meeting demand with a target level of reliability is called the capacity credit. [8.2.1.1]

Based on the features of electrical power systems, several RE characteristics are important for integrating RE into power systems. In particular, variability and predictability (or uncertainty) of RE is relevant for scheduling and dispatch in the electrical power system, the location of RE resources is a relevant indicator for impact on needs for electrical networks, and capacity factor, capacity credit and power plant characteristics are indicators relevant for comparison, for example, with thermal generation. [8.2.1.2]

Some RE electricity resources (particularly ocean, solar PV, wind) are variable and only partially dispatchable: generation from these resources can be reduced if needed, but maximum generation depends on availability of the RE resource (e.g., tidal currents, sun or wind). The capacity credit can be low if the generation is not well correlated with times of high demand. In addition, the variability and partial predictability of some RE increases the burden on dispatchable generation or other resources to ensure balance between supply and demand given deviations in RE. In many cases variability and partial predictability are somewhat mitigated by geographic diversity—changes and forecast errors will not always occur at the same time in the same direction. A general challenge for most RE, however, is that renewable resources are location specific, therefore concentrated renewably generated electricity may need to be transported over considerable distances and require network expansion. Dispatchable renewable sources (including hydropower, bioenergy, geothermal energy, and CSP with thermal storage) can in many cases offer extra flexibility for the system to integrate other renewable sources and often have a higher capacity credit. [8.2.1.2]

A very brief summary of the particular characteristics for a selection of the technologies is given in Table TS.8.1. [8.2.1.3]

Table TS.8.1 | Summary of integration characteristics for a selection of RE technologies. [Table 8.1]

Technology		Plant size range (MW)	Variability: Characteristic time scales for power system operation (Time scale)	Dispatchability (See legend)	Geographical diversity potential (See legend)	Predictability (See legend)	Capacity factor range %	Capacity credit range %	Active power, frequency control (See legend)	Voltage, reactive power control (See legend)
Bioenergy		0.1–100	Seasons (depending on biomass availability)	+++	+	++	50–90	Similar to thermal and CHP	++	++
Direct solar energy	PV	0.004–100 modular	Minutes to years	+	++	+	12–27	<25–75	+	+
	CSP with thermal storage[1]	50–250	Hours to years	++	+[2]	++	35–42	90	++	++
Geothermal energy		2–100	Years	+++	N/A	++	60–90	Similar to thermal	++	++
Hydro power	Run of river	0.1–1,500	Hours to years	++	+	++	20–95	0–90	++	++
	Reservoir	1–20,000	Days to years	+++	+	++	30–60	Similar to thermal	++	++
Ocean Energy	Tidal range	0.1–300	Hours to days	+	+	++	22.5–28.5	<10%	++	++
	Tidal current	1–200	Hours to days	+	+	++	19–60	10–20	+	++
	Wave	1–200	Minutes to years	+	++	+	22–31	16	+	+
Wind energy		5–300	Minutes to years	+	++	+	20–40 onshore, 30–45 offshore	5–40	+	++

Notes: 1. Assuming a CSP system with six hours of thermal storage in US Southwest. 2. In areas with direct-normal irradiance (DNI) >2,000 kWh/m^2/yr (7,200 MJ/m^2/yr).

Plant size: range of typical rated plant capacity.

Characteristic time scales: time scales where variability significant for power system integration occurs.

Dispatchability: degree of plant dispatchability: + low partial dispatchability, ++ partial dispatchability, +++ dispatchable.

Geographical diversity potential: degree to which siting of the technology may mitigate variability and improve predictability, without substantial need for additional network: +moderate potential, ++ high diversity potential.

Predictability: Accuracy to which plant output power can be predicted at relevant time scales to assist power system operation: + moderate prediction accuracy (typical <10% Root Mean Square (RMS) error of rated power day ahead), ++ high prediction accuracy.

Active power and frequency control: technology possibilities enabling plant to participate in active power control and frequency response during normal situations (steady state, dynamic) and during network fault situations (for example active power support during fault ride-through): + good possibilities, ++ full control possibilities.

Voltage and reactive power control: technology possibilities enabling plant to participate in voltage and reactive power control during normal situations (steady state, dynamic) and during network fault situations (for example reactive power support during fault ride-through): + good possibilities, ++ full control possibilities.

There is already significant experience with operating electrical power systems with a large share of renewable sources, in particular hydropower and geothermal power. Hydropower storage and strong interconnections help manage fluctuations in river flows. Balancing costs for variable generation are incurred when there are differences between the scheduled generation (according to forecasts) and the actual production. Variability and uncertainty increase balancing requirements. Overall, balancing is expected to become more difficult to achieve as partially dispatchable RE penetrations increase. Studies show clearly that combining different variable renewable sources, and resources from larger geographical areas, will be beneficial in smoothing the variability and decreasing overall uncertainty for the power systems. [8.2.1.3]

The key issue is the importance of *network infrastructure,* both to deliver power from the generation plant to the consumer as well as to enable larger regions to be balanced. Strengthening connections within an electrical power system and introducing additional interconnections to other systems can directly mitigate the impact of variable and uncertain RE sources. Network expansion is required for most RE, although the level is dependent on the resource and location relative to existing network infrastructure. Amongst other challenges will be expanding network infrastructure within the context of public opposition to overhead network infrastructure. In general, major changes will be required in the generation plant mix, the electrical power systems' infrastructure and operational procedures to make the transition to increased renewable generation while maintaining cost and environmental effectiveness. These changes will require major investments far enough in advance to maintain a reliable and secure electricity supply. [8.2.1.3]

In addition to improving network infrastructure, several other important integration options have been identified through operating experience or studies:

Increased generation flexibility: An increasing penetration of variable renewable sources implies a greater need to manage variability and uncertainty. Greater flexibility is required from the generation mix. Generation provides most of a power system's existing flexibility to cope with variability and uncertainty through ramping up or down and cycling as needed. Greater need for flexibility can imply either investment in new flexible generation or improvements to existing power plants to enable them to operate in a more flexible manner. [8.2.1.3]

Demand side measures: Although demand side measures have historically been implemented only to reduce average demand or demand during peak load periods, demand side measures may potentially contribute to meeting needs resulting from increased variable renewable generation. The development of advanced communications technology, with smart electricity meters linked to control centres, offers the potential to access much greater levels of flexibility from demand. Electricity users can be provided with incentives to modify and/or reduce their consumption by pricing electricity differently at different times, in particular with higher prices during higher demand periods. This reduction in demand during high demand periods can mitigate the impact of the low capacity credit of some types of variable generation. Furthermore, demand that can quickly be curtailed without notice during any time of the year can provide reserves rather than requiring generation resources to provide this reserve. Demand that can be scheduled to be met at anytime of the day or that responds to real-time electricity prices can participate in intra-day balancing thereby mitigating operational challenges that are expected to become increasingly difficult with variable generation. [8.2.1.3]

Electrical energy storage: By storing electrical energy when renewable output is high and the demand low, and generating when renewable output is low and the demand high, the curtailment of RE can be reduced, and the base-load units on the system will operate more efficiently. Storage can also reduce transmission congestion and may reduce the need for, or delay, transmission upgrades. Technologies such as batteries or flywheels that store smaller amounts of energy (minutes to hours) can in theory be used to provide power in the intra-hour timeframe to regulate the balance between supply and demand. [8.2.1.3]

Improved operational/market and planning methods: To help cope with the variability and uncertainty associated with variable generation sources, forecasts of their output can be combined with improved operational methods to determine both the required reserve to maintain the demand-generation balance, and also optimal generation scheduling. Making scheduling decisions closer to real time (i.e., shorter gate closure time in markets) and more frequently allows newer, more accurate information to be used in dispatching generating units. Moving to larger balancing areas, or shared balancing between areas, is also desirable with large amounts of variable generation, due to the aggregation benefits of multiple, dispersed renewable sources. [8.2.1.3]

In summary, RE can be integrated into all types of electrical power systems from large interconnected continental-scale systems to small autonomous systems. System characteristics including the network infrastructure, demand pattern and its geographic location, generation mix, control and communication capability combined with the location, geographical footprint, variability and predictability of the renewable resources determine the scale of the integration challenge. As the amounts of RE resources increase, additional electricity network infrastructure (transmission and/or distribution) will generally have to be constructed. Variable renewable sources, such as wind, can be more difficult to integrate than dispatchable renewable sources, such as bioenergy, and with increasing levels maintaining reliability becomes more challenging and costly. These challenges and costs can be minimized by deploying a portfolio of options including electrical network interconnection, the development of complementary flexible generation, larger balancing areas, sub-hourly markets, demand that can respond in relation to supply availability, storage technologies, and better forecasting, system operating and planning tools.

8.3 Integration of renewable energy into heating and cooling networks

A district heating (DH) or district cooling (DC) network allows multiple energy sources (Figure TS.8.3) to be connected to many energy consumers by pumping the energy carriers (hot or cold water and sometimes steam) through insulated underground pipelines. Centralized heat production can facilitate the use of low-cost and/or low-grade RE heat from geothermal or solar thermal sources or combustion of biomass (including refuse-derived fuels and waste by-products that are often unsuitable for use by individual heating systems). Waste heat from CHP generation and industrial processes can also be used. This flexibility produces competition among various heat sources, fuels and technologies. Centralized heat production can also facilitate the application of cost-effective measures that reduce local air pollution compared with having a multitude of small individual boilers. Being flexible in the sources of heat or cold utilized, district heating and cooling systems allow for the continuing uptake of several types of RE so that a gradual or rapid substitution of competing fossil fuels is usually feasible. [8.2.2]

Occupiers of buildings and industries connected to a network can benefit from a professionally managed central system, hence avoiding the need to operate and maintain individual heating/cooling equipment. Several high-latitude countries already have a district heating market penetration of 30 to 50%, with Iceland reaching 96% using its geothermal resources. World annual delivery of district heat has been estimated to be around 11 EJ though heat data are uncertain. [8.2.2.1]

DH schemes can provide electricity through CHP system designs and can also provide demand response options that can facilitate increased integration of RE, including by using RE electricity for heat pumps and electric boilers. Thermal storage systems can bridge the heat supply/demand gap resulting from variable, discontinuous or non-synchronized heating systems. For short-term storage (hours and days), the thermal capacity of the distribution network itself can be used. Thermal storage systems with storage periods up to several months at temperatures up to hundreds of degrees Celsius use a variety of materials and corresponding storage mechanisms that can have capacities up to several TJ. Combined production of heat, cold and electricity (tri-generation), as well as the possibility for diurnal and seasonal storage of heat and cold, mean that high overall system efficiency can be obtained and higher shares of RE achieved through increased integration. [8.2.2.2, 8.2.2.3]

Many commercial geothermal and biomass heat and CHP plants have been successfully integrated into DH systems without government support. Several large-scale solar thermal systems with collector areas

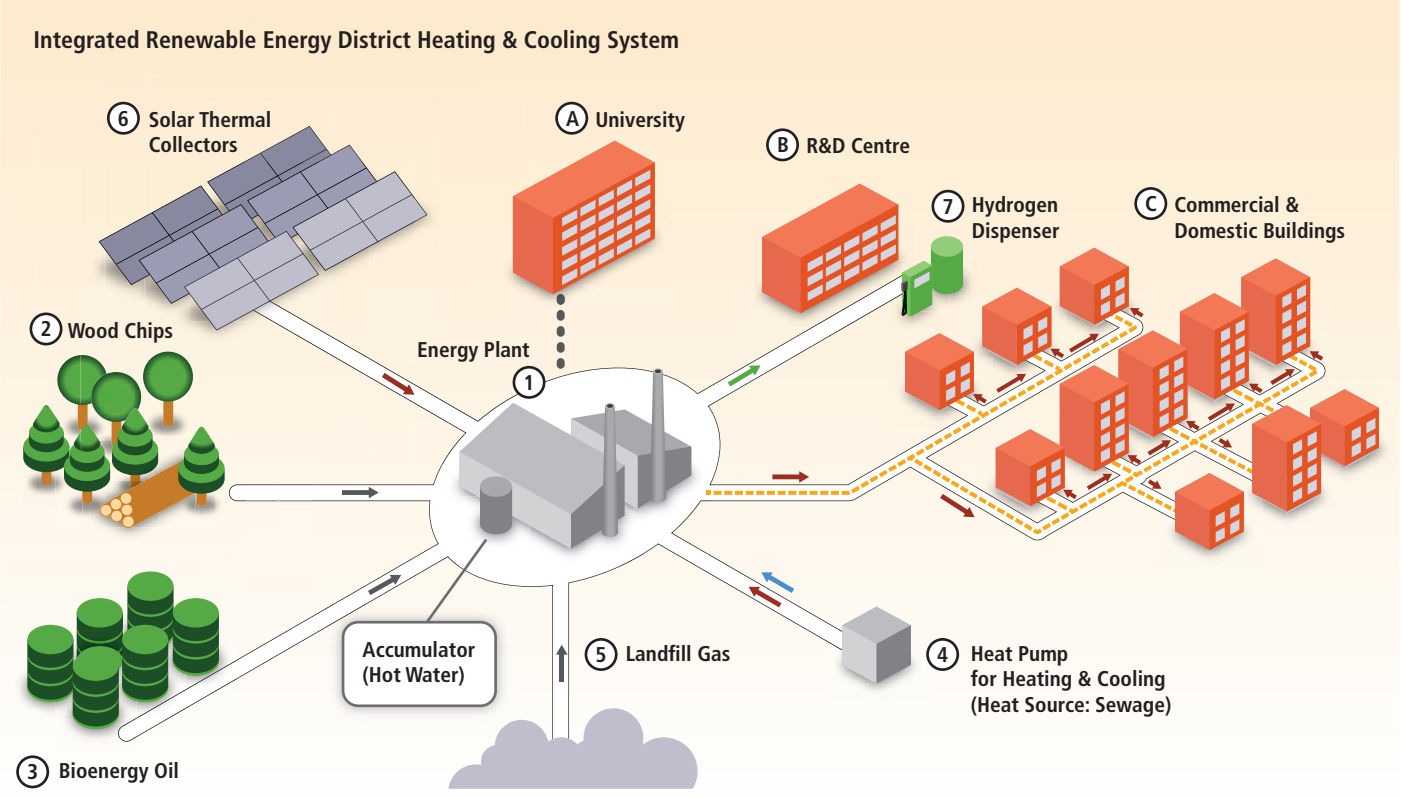


Figure TS.8.3 | An integrated RE-based energy plant in Lillestrøm, Norway, supplying the University, R&D Centre and a range of commercial and domestic buildings using a district heating and cooling system incorporating a range of RE heat sources, thermal storage and a hydrogen production and distribution system. (Total investment around USD$_{2005}$ 25 million and due for completion in 2011.) 1) Central energy system with 1,200 m^3 accumulator hot water storage tank; (2) 20 MW$_{th}$ wood burner system (with flue gas heat recovery); (3) 40 MW$_{th}$ bio-oil burner; (4) 4.5 MW$_{th}$ heat pump; (5) 1.5 MW$_{th}$ landfill gas burner and a 5 km pipeline; (6) 10,000 m^2 solar thermal collector system; and (7) RE-based hydrogen production (using water electrolysis and sorption-enhanced steam methane reforming of landfill gas) and vehicle dispensing system. [Figure 8.3]

of around 10,000 m^2 (Figure TS.8.3) have also been built in Denmark, Norway and elsewhere. The best mix of hot and cold sources, and heat transfer and storage technologies, depends strongly on local conditions, including user demand patterns. As a result, the heat energy supply mix varies widely between different systems. [3.5.3, 8.2.2]

Establishing or expanding a DH scheme involves high up-front capital costs for the piping network. Distribution costs alone can represent roughly half of the total cost but are subject to large variations depending on the heat demand density and the local conditions for building the insulated piping network. Increasing urbanization facilitates DH since network capital costs are lower for green-field sites and distribution losses per unit of heat delivered are lower in areas with higher heat demand densities. Heat distribution losses typically range from 5 to 30% but the extent to which high losses are considered a problem depends on the source and cost of the heat. [8.2.2.1, 8.2.2.3]

Expanding the use of deep geothermal and biomass CHP plants in DH systems can facilitate a higher share of RE sources, but to be economically viable this usually requires the overall system to have a large heat load. Some governments therefore support investments in DH networks as well as provide additional incentives for using RE in the system. [8.2.2.4]

Modern building designs and uses have tended to reduce their demand for additional heating whereas the global demand for cooling has tended to increase. The cooling demand to provide comfort has increased in some low-latitude regions where countries have become wealthier and in some higher latitudes where summers have become warmer. Cooling load reductions can be achieved by the use of passive cooling building design options or active RE solutions including solar absorption chillers. As for DH, the rate of uptake of energy efficiency to reduce cooling demand, deployment of new technologies, and the structure of the market, will determine the viability of developing a DC scheme. Modern DC systems, ranging from 5 to 300 MW_{th}, have been operating successfully for many years using natural aquifers, waterways, the sea or deep lakes as the sources of cold, classed as a form of RE. [8.2.2.4]

DH and DC schemes have typically been developed in situations where strong planning powers have existed, such as centrally planned economies, US university campuses, Western European countries with multi-utilities, and urban areas controlled by local municipalities.

8.4 Integration of renewable energy into gas grids

Over the past 50 years, large natural gas networks have been developed in several parts of the world. And more recently there has been increasing interest to 'green' them by integrating RE-based gases. Gaseous fuels from RE sources originate largely from biomass and can be produced either by anaerobic digestion to produce biogas (mainly methane and CO_2) or thermo-chemically to give synthesis (or producer) gas (mainly hydrogen and carbon monoxide). Biomethane, synthesis gas and, in the longer term, RE-based hydrogen can be injected into existing gas pipelines for distribution at the national, regional or local level. Differences in existing infrastructure, gas quality, and production and consumption levels can make planning difficult for increasing the RE share of gases by integration into an existing grid. [8.2.3, 8.2.3.1]

Biogas production is growing rapidly and several large gas companies are now making plans to upgrade large quantities for injection at the required quality into national or regional transmission gas pipelines. Most of the biomethane currently produced around the world is already distributed in local gas pipeline systems primarily dedicated for heating purposes. This can be a cheaper option per unit of energy delivered (Figure TS.8.4) than when transported by trucks (usually to filling stations for supplying gas-powered vehicles) depending on distance and the annual volume to be transported. [8.2.3.4]

Gas utilization can be highly efficient when combusted for heat; used to generate electricity by fuelling gas engines, gas boilers or gas turbines; or used in vehicles either compressed or converted to a range of liquid fuels using various processes. For example, biogas or landfill gas can be combusted onsite to produce heat and/or electricity; cleaned and upgraded to natural gas quality biomethane for injection into gas grids; or, after compressing or liquefying, distributed to vehicle filling stations for use in dedicated or dual gas-fuelled vehicles. [8.2.3.2–8.2.3.4]

Technical challenges relate to gas source, composition and quality. Only biogas and syngas of a specified quality can be injected into existing gas

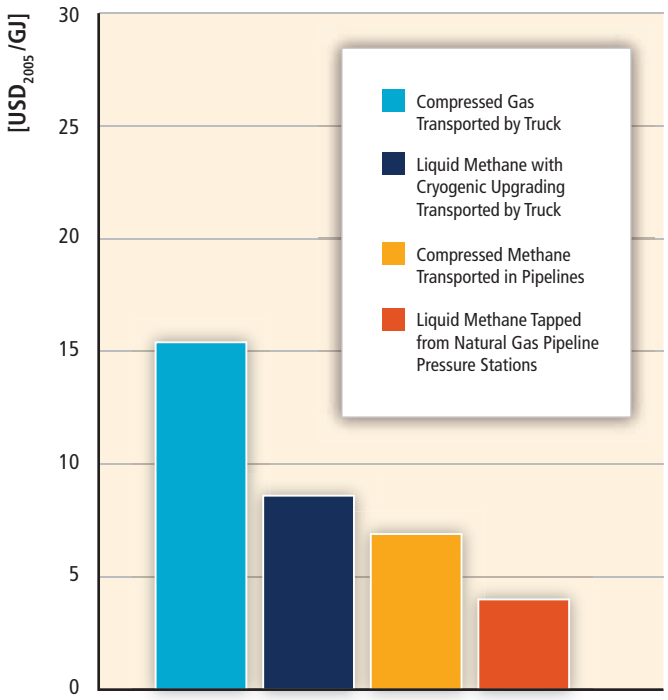


Figure TS.8.4 | Relative costs for distributing and dispensing biomethane (either compressed or liquefied) at the medium scale by truck or pipeline in Europe. [Figure 8.9]

grids so clean-up is a critical step to remove water, CO_2 (thereby increasing the heating value) and additional by-products from the gas stream. The cost of upgrading varies according to the scale of the facility and the process, which can consume around 3 to 6% of the energy content of the gas. RE gas systems are likely to require significant storage capacity to account for variability and seasonality of supply. The size and shape of storage facilities and the required quality of the gas will depend on the primary energy source of production and its end use. [8.2.3]

Hydrogen gas can be produced from RE sources by several routes including biomass gasification, the reformation of biomethane, or electrolysis of water. The potential RE resource base for hydrogen is therefore greater than for biogas or syngas. Future production of hydrogen from variable RE resources, such as wind or solar power by electrolysis, will depend significantly on the interaction with existing electricity systems and the degree of surplus capacity. In the short term, blending of hydrogen with natural gas (up to 20% by volume) and transporting it long distances in existing gas grids could be an option. In the longer term, the construction of pipelines for carrying pure hydrogen is possible, constructed from special steels to avoid embrittlement. The rate-limiting factors for deploying hydrogen are likely to be the capital and time involved in building a new hydrogen infrastructure and any additional cost for storage in order to accommodate variable RE sources. [8.2.3.2, 8.2.3.4]

In order to blend a RE gas into a gas grid, the gas source needs to be located near to the existing system to avoid high costs of additional pipeline construction. In the case of remote plant locations due to resource availability, it may be better to use the gas onsite where feasible to avoid the need for transmission and upgrading. [8.2.3.5]

8.5 Integration of renewable energy into liquid fuels

Most of the projected demand for liquid biofuels is for transport purposes, though industrial demand could emerge for bio-lubricants and bio-chemicals such as methanol. In addition, large amounts of traditional solid biomass could eventually be replaced by more convenient, safer and healthier liquid fuels such as RE-derived dimethyl ether (DME) or ethanol gels. [8.2.4]

Producing bioethanol and biodiesel fuels from various crops, usually used for food, is well understood (Figure TS.8.5). The biofuels produced can take advantage of existing infrastructure components already used for petroleum-based fuels including storage, blending, distribution and dispensing. However, sharing petroleum-product infrastructure (storage tanks, pipelines, trucks) with ethanol or blends can lead to problems from water absorption and equipment corrosion, so may require investment in specialized pipeline materials or linings. Decentralized biomass production, seasonality and remote agricultural locations away from existing oil refineries or fuel distribution centres, can impact the supply chain logistics and storage of biofuels. Technologies continue to evolve to produce biofuels from non-food feedstocks and biofuels that are more compatible with existing petroleum fuels and infrastructure. Quality control procedures need to be implemented to ensure that such biofuels meet all applicable product specifications. [8.2.4.1, 8.2.4.3, 8.2.4.4]

The use of blended fuels produced by replacing a portion (typically 5 to 25% but can be up to 100% substitution) of gasoline with ethanol,

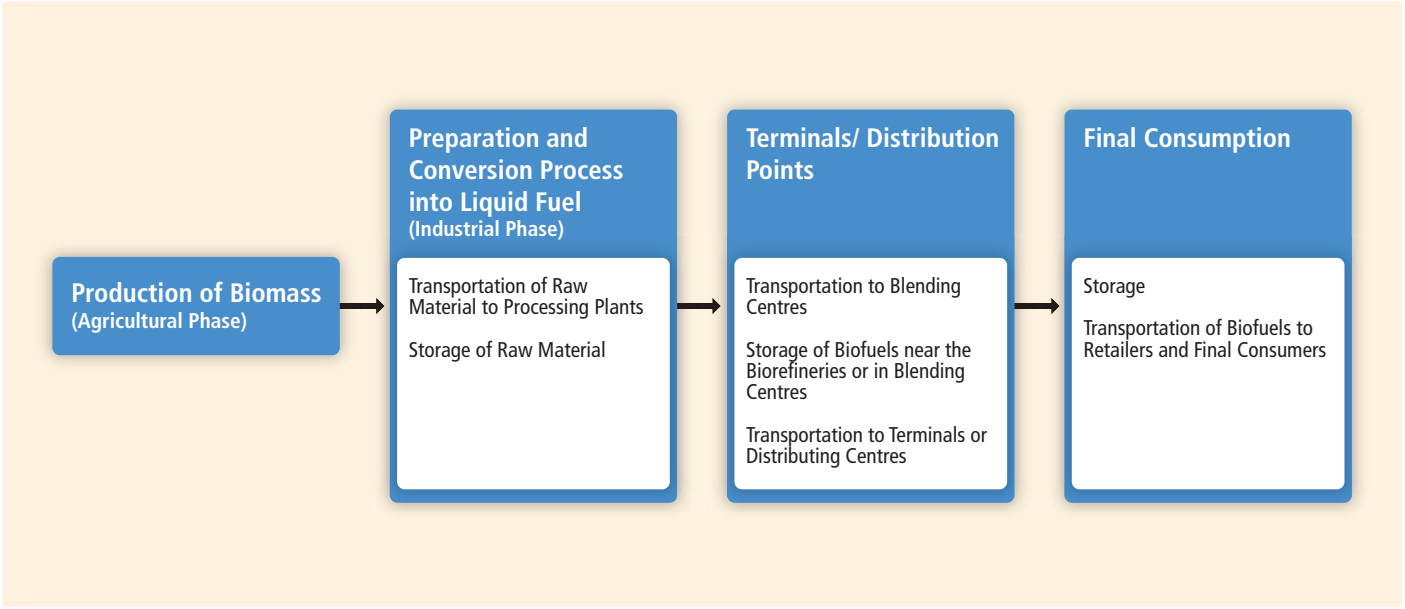


Figure TS.8.5 | The production, blending and distribution system for a range of liquid biofuels is similar regardless of the biomass feedstock. [Figure 8.11]

or diesel with biodiesel, requires investment in infrastructure including additional tanks and pumps at vehicle service stations. Although the cost of biofuel delivery is a small fraction of the overall cost, the logistics and capital requirements for widespread integration and expansion could present major hurdles if not well planned. Since ethanol has only around two-thirds the energy density (by volume) of gasoline, larger storage systems, more rail cars or vessels, and larger capacity pipelines are needed to store and transport the same amount of energy. This increases the fuel storage and delivery costs. Although pipelines would, in theory, be the most economical method of delivery, and pipeline shipments of ethanol have been successfully achieved, a number of technical and logistical challenges remain. Typically, current volumes of ethanol produced in an agricultural region to meet local demand, or for export, are usually too low to justify the related investment costs and operational challenges of constructing a dedicated pipeline. [8.2.4.3]

8.6 Integration of renewable energy into autonomous systems

Autonomous energy supply systems are typically small scale and are often located in off-grid remote areas, on small islands, or in individual buildings where the provision of commercial energy is not readily available through grids and networks. Several types of autonomous systems exist and can make use of either single energy carriers, for example, electricity, heat, or liquid, gaseous or solid fuels, or a combination of carriers. [8.2.5, 8.2.5.1]

In principle, RE integration issues for autonomous systems are similar to centralized systems, for example, for supply/demand balancing of electricity supply systems, selection of heating and cooling options, production of RE gases and liquid biofuel production for local use. However, unlike larger centralized supply systems, smaller autonomous systems often have fewer RE supply options that are readily available at a local scale. Additionally, some of the technical and institutional options for managing integration within larger networks become more difficult or even implausible for smaller autonomous systems, such as RE supply forecasting, probabilistic unit commitment procedures, stringent fuel quality standards, and the smoothing effects of geographical and technical diversity. [8.2.1–8.2.5]

RE integration solutions typically become more restricted as supply systems become smaller. Therefore greater reliance must be placed on those solutions that are readily available. Focusing on variable RE resources, because of restricted options for interconnection and operating and planning procedures, autonomous systems will naturally have a tendency to focus on energy storage options, various types of demand response, and highly flexible fossil fuel generation to help match supply and demand. RE supply options that better match local load profiles, or that are dispatchable, may be chosen over other lower-cost options that do not have as strong a match with load patterns or are variable. Managing RE integration within autonomous systems will, all else being equal, be more costly than in larger integrated networks because of the restricted set of options, but in most instances, such as on islands or in remote rural areas, there is no choice for the energy users. One implication is that autonomous electricity system users and designers can face difficult trade-offs between a desire for reliable and continuous supply and minimizing overall supply costs. [8.2.5]

The integration of RE conversion technologies, balancing options and end-use technologies in an autonomous energy system depend on the site-specific availability of RE resources and the local energy demand. These can vary with local climate and lifestyles. The balance between cost and reliability is critical when designing and deploying autonomous power systems, particularly for rural areas of developing economies because the additional cost of providing continuous and reliable supply may become higher for smaller autonomous systems. [8.2.5.2]

8.7 End-use sectors: Strategic elements for transition pathways

RE technology developments have continued to evolve, resulting in increased deployment in the transport, building, industry, and agriculture, forestry and fishery sectors. In order to achieve greater RE deployment in all sectors, both technical and non-technical issues should be addressed. Regional variations exist for each sector due to the current status of RE uptake, the wide range of energy system types, the related infrastructure currently in place, the different possible pathways to enhance increased RE integration, the transition issues yet to be overcome, and the future trends affected by variations in national and local ambitions and cultures. [8.3, 8.3.1]

8.7.1 Transport

Recent trends and projections show strong growth in transport demand, including the rapidly increasing number of vehicles worldwide. Meeting this demand, whilst achieving a low-carbon, secure energy supply, will require strong policy initiatives, rapid technological change, monetary incentives and/or the willingness of customers to pay additional costs. [8.3.1]

In 2008, the combustion of fossil fuels for transport consumed around 19% of global primary energy use, equivalent to 30% of total consumer energy and producing around 22% of GHG emissions, plus a significant share of local air-polluting emissions. Light duty vehicles (LDVs) accounted for over half of transport fuel consumption worldwide, with heavy duty vehicles (HDVs) accounting for 24%, aviation 11%, shipping 10% and rail 3%. Demand for mobility is growing rapidly with the number of motorized vehicles projected to triple by 2050 and with a similar growth in air travel. Maintaining a secure supply of energy is therefore a serious concern for the transport sector with about 94% of transport fuels presently coming from oil products that, for most countries, are imported. [8.3.1]

There are a number of possible fuel/vehicle pathways from the conversion of the primary energy source to an energy carrier (or fuel) through to the end use, whether in advanced internal combustion engine vehicles (ICEVs), electric battery vehicles (EVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) or hydrogen fuel cell vehicles (HFCVs) (Figure TS.8.6). [8.3.1.2]

Improving the efficiency of the transport sector, and decarbonizing it, have been identified as being critically important to achieving long-term, deep reductions in global GHG emissions. The approaches to reducing transport-related emissions include a reduction in travel demand, increased vehicle efficiency, shifting to more efficient modes of transport, and replacing petroleum-based fuels with alternative low- or near-zero-carbon fuels (including biofuels, electricity or hydrogen produced from low-carbon primary energy sources). Scenario studies strongly suggest that a combination of technologies will be needed to accomplish 50 to 80% reductions (compared to current rates) in GHG emissions by 2050 whilst meeting the growing transport energy demand (Figure TS.8.7). [8.3.1.1]

The current use of RE for transport is only a few percent of the total energy demand, mainly through electric rail and the blending of liquid biofuels with petroleum products. Millions of LDVs capable of running on high-biofuel blends are already in the world fleet and biofuel technology is commercially mature, as is the use of compressed biomethane in vehicles suitable for running on compressed natural gas. [8.2.3]

However, making a transition to new fuels and engine types is a complex process involving technology development, cost, infrastructure, consumer acceptance, and environmental and resource impacts. Transition issues vary for biofuels, hydrogen, and electric vehicles (Table TS.8.2) with no one option seen to be a clear 'winner' and all needing several decades to be deployed at a large scale. Biofuels are well proven, contributing around 2% of road transport fuels in 2008, but there are issues of sustainability. [2.5] Many hydrogen fuel cell vehicles have been demonstrated, but these are unlikely to be commercialized until at least 2015 to 2020 due to the barriers of fuel cell durability, cost, onboard hydrogen storage issues and hydrogen infrastructure availability. For EVs and PHEVs, the cost and relatively short life of present

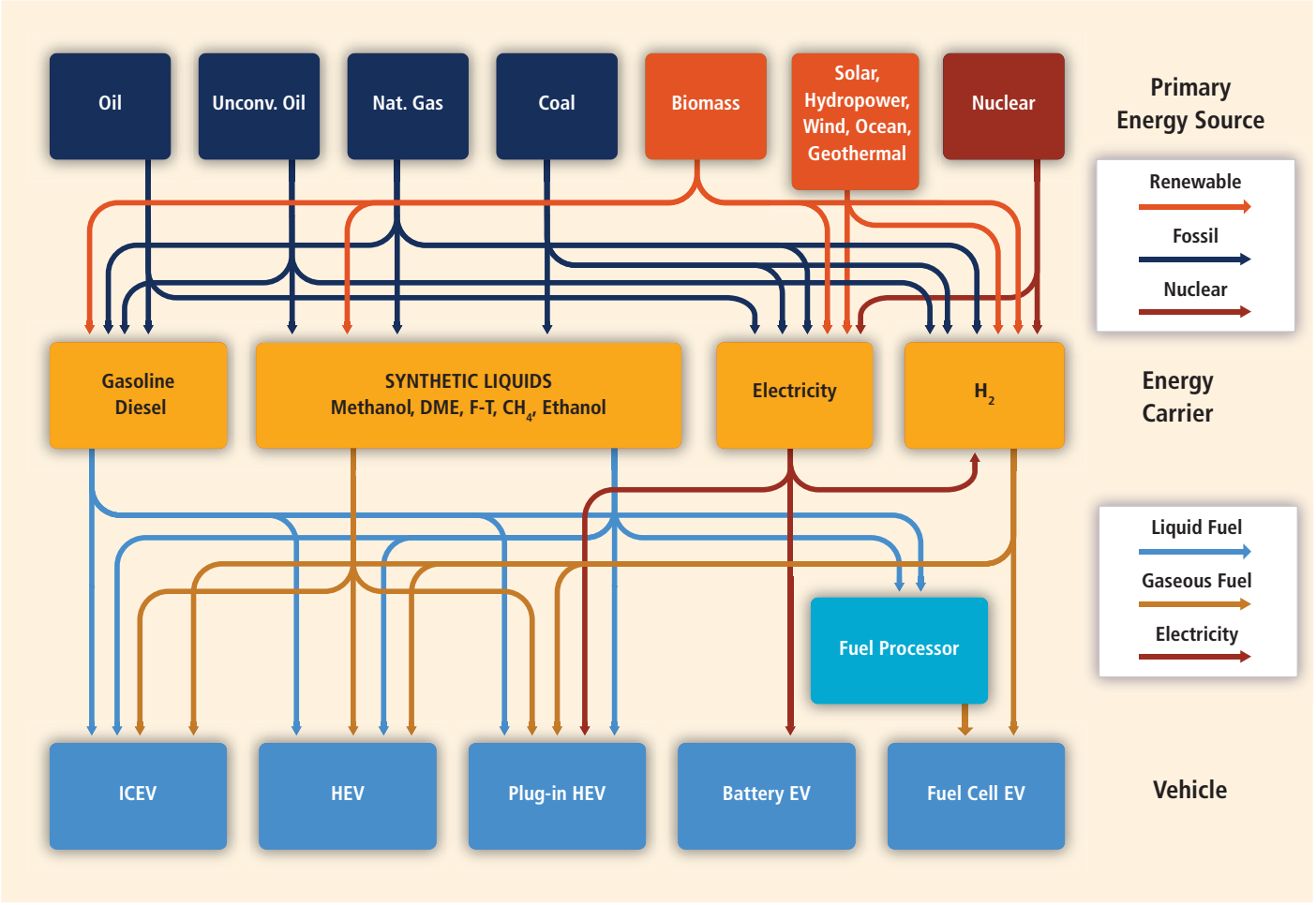


Figure TS.8.6 | A range of possible light duty vehicle fuel pathways, from primary energy sources (top), through energy carriers, to end-use vehicle drive train options (bottom) (with RE resources highlighted in green). [Figure 8.13]

Notes: F-T= Fischer-Tropsch process; DME = dimethyl ether; ICE = internal combustion engine; HEV = hybrid electric vehicle; EV = electric vehicle; 'unconventional oil' refers to oil sands, oil shale and other heavy crudes.

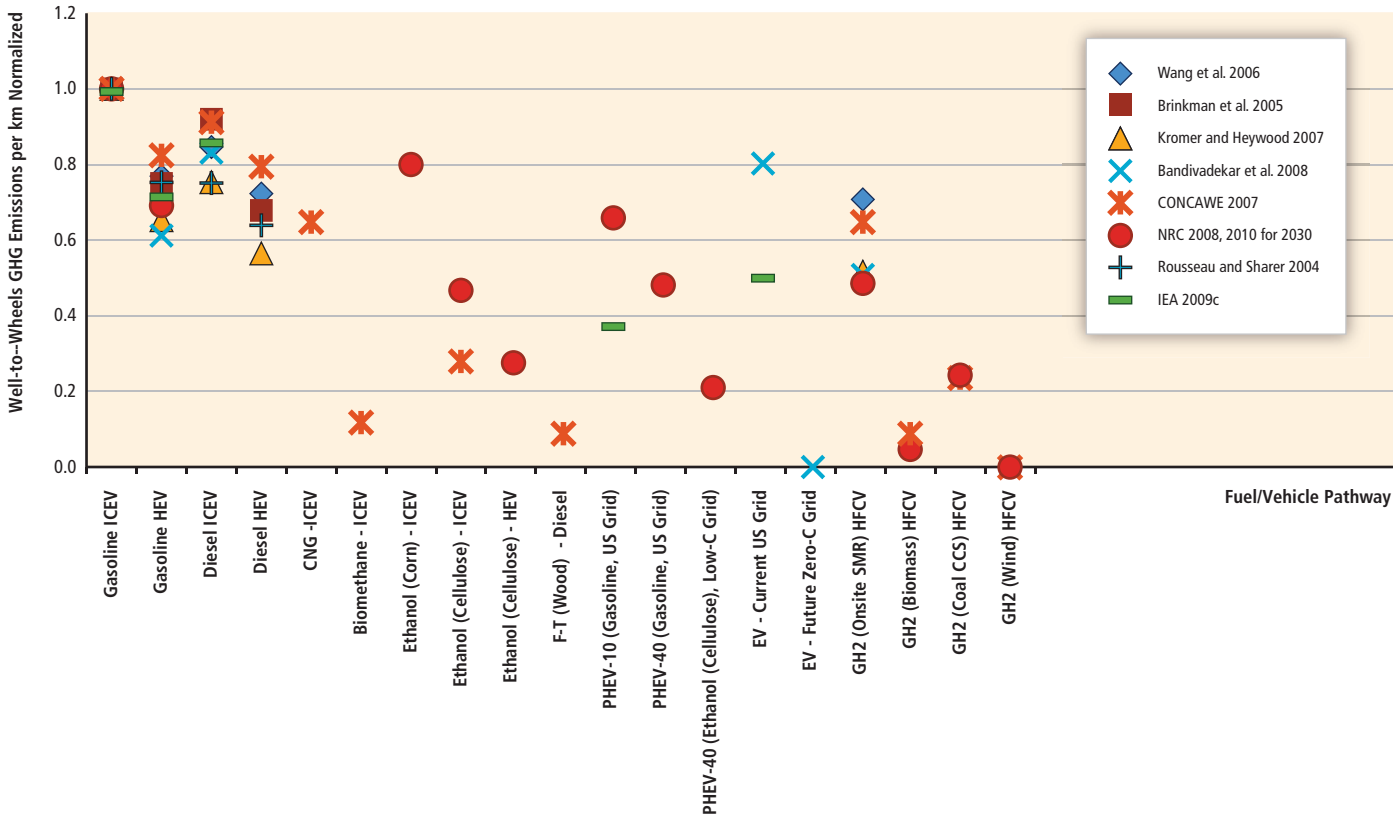


Figure TS.8.7 | Well-to-wheels (WTW) GHG emission reductions per kilometre travelled, with ranges shown taken from selected studies of alternative light duty fuel/vehicle pathways, normalized to the GHG emissions of a gasoline, internal combustion engine, light-duty vehicle. [Figure 8.17]

Notes: To allow for easier comparison among studies, WTW GHG emissions per km were normalized to emissions from a gasoline ICEV (such that 'Gasoline ICEV' = 1) taken from each study and ranging from 170 to 394 g CO_2/km. For all hydrogen pathways, hydrogen is stored onboard the vehicle as a compressed gas (GH2). CNG = compressed natural gas; SMR = steam methane reformer.

battery technologies, the limited vehicle range between recharging, and the time for recharging, can be barriers to consumer acceptance. EV and PHEV designs are undergoing rapid development, spurred by recent policy initiatives worldwide, and several companies have announced plans to commercialize them. One strategy could be to introduce PHEVs initially while developing and scaling up battery technologies. For hydrogen and electric vehicles, it may take several decades to implement a practical transport system by developing the necessary infrastructure at the large scale.

An advantage of *biofuels* is their relative compatibility with the existing liquid fuel infrastructure. They can be blended with petroleum products and most ICE vehicles can be run on blends, some even on up to 100% biofuel. They are similar to gasoline or diesel in terms of vehicle performance[14] and refuelling times, though some have limits on the concentrations that can be blended and they typically cannot be easily distributed using existing fuel pipelines without modifications. The sustainability of the available biomass resource is a serious issue for some biofuels. [2.5, 8.2.4, 8.3.1.2]

14 Performance in this instance excludes energy content. The energy content of biofuels is generally lower than their equivalent petroleum product.

Hydrogen has the potential to tap vast new energy resources to provide transport with zero or near-zero emissions. The technology for hydrogen from biomass gasification is being developed, and could become competitive beyond 2025. Hydrogen derived from RE sources by electrolysis has cost barriers rather than issues of technical feasibility or resource availability. Initially RE and other low-carbon technologies will likely be used to generate electricity, a development that could help enable near-zero-carbon hydrogen to be co-produced with electricity or heat in future energy complexes. Hydrogen is not yet widely distributed compared to electricity, natural gas, gasoline, diesel or biofuels but could be preferred in the future for large HDVs that have a long range and need relatively fast refuelling times. Bringing hydrogen to large numbers of vehicles would require building a new refuelling infrastructure that could take several decades to construct. The first steps to provide hydrogen to test fleets and demonstrate refuelling technologies in mini-networks have begun in several countries. [2.6.3.2, 8.3.1, 8.3.1.2]

For RE *electricity* to supply high numbers of EVs and PHEVs in future markets, several innovations must occur such as development of batteries and low-cost electricity supply available for recharging when the EVs need it. If using night-time, off-peak recharging, new capacity is less likely to be needed and in some locations there may be a good temporal match with

Table TS.8.2 | Transition issues for the use of biofuels, hydrogen and electricity as transport fuels for light duty vehicles. [Summarized from 8.3.1]

Technology Status	Biofuels	Hydrogen	Electricity
Existing and potential primary resources	Sugar, starch, oil crops; cellulosic crops; forest, agricultural and solid wastes; algae and other biological oils.	Fossil fuels; nuclear; all RE. Potential RE resource base is large but inefficiencies and costs of converting to H_2 can be an issue.	Fossil fuels, nuclear, all RE. Potential RE resource base is large.
Fuel production	First generation: ethanol from sugar and starch crops, biomethane, biodiesel. Advanced second-generation biofuels, e.g., from cellulosic biomass, bio-wastes, bio-oils, and algae after at least 2015.	Fossil H_2 commercial for large-scale industrial applications, but not competitive as transport fuel. Renewable H_2 generally more costly.	Commercial power readily available. RE electricity can be more costly, but preferred for transport due to low GHG emissions on a lifecycle basis.
Vehicles	Millions of flexi-fuel vehicles exist that use high shares of ethanol. Conventional ICEVs limited to low concentration blends of ethanol (<25%). Some commercial agricultural tractors and machinery can run on 100% biodiesel.	Demonstration HFCVs. Commercial HFCVs not until 2015 to 2020.	Demonstration PHEVs, Commercial PHEVs not until 2012 to 2015. Limited current use of EVs. Commercial EVs not until 2015 to 2020.
Costs[1] compared with gasoline ICE vehicles			
Incremental vehicle price compared to future gasoline ICEV (USD_{2005})	Similar price.	HFCV experience (by 2035) price increment >USD 5,300	Experience (by 2035) price increment: PHEVs >USD 5,900; EVs >USD 14,000
Fuel cost (USD_{2005}/km)	Fuel cost per km varies with biofuel type and level of agricultural subsidy. Biofuel can compete if price per unit of energy equates to gasoline/diesel price per unit of energy. Ethanol in Brazil competes without subsidies.	Target fuel cost at USD 3 to 4/kg for mature H_2 infrastructure—may prove optimistic. When used in HFCVs, competes with gasoline in HCEVs at USD 0.40 to 0.53/l. Assumes HFCV has twice fuel economy of gasoline ICEV. RE-derived H_2 around 1.5 to 3 times more expensive than other from sources.	Electricity cost per km, when the power is purchased at USD 0.10 to 0.30/kWh, competes with gasoline when purchased at USD 0.3 to 0.9/l (assuming the EV has fuel economy 3 times that of the gasoline ICEV).
Compatibility with existing infrastructure	Partly compatible with existing petroleum distribution system. Separate distribution and storage infrastructure may be needed for ethanol.	New H_2 infrastructure needed, as well as renewable H_2 production sources. Infrastructure deployment must be coordinated with vehicle market growth.	Widespread electric infrastructure in place. Need to add in-home and public recharger costs, RE generation sources, and upgrading of transmission and distribution (especially for fast chargers).
Consumer acceptance	Depends upon comparative fuel costs. Alcohol vehicles can have shorter range than gasoline. Potential cost impact on food crops. Land use and water issues can be factors.	Depends upon comparative vehicle and fuel costs. Public perception of safety. Poor public refuelling station availability in early markets.	High initial vehicle cost. High electricity cost of charging on-peak. Limited range unless PHEV. Modest to long recharging time, but home recharging possible. Significantly degraded performance in extreme cold winters or hot summers. Poor public refuelling station availability in early markets
GHG emissions	Depends on feedstock, pathway and land use issue[2]. Low for fuels from biomass residues including sugarcane. Near-term can be high for corn ethanol. Advanced second-generation biofuels likely to be lower.	Depends on H_2 production mix. Compared to future hybrid gasoline ICEVs, WTW GHG emissions for HFCVs using H_2 from natural gas can be slightly more or less depending on assumptions. WTW GHG emissions can approach zero for RE or nuclear pathways.	Depends on grid mix. Using coal-dominated grid mix, EVs and PHEVs have WTW GHG emissions similar or higher than gasoline HEV. With larger fraction of RE and low-carbon electricity, WTW emissions are lower.
Petroleum consumption	Low for blends	Very low	Very low
Environmental and sustainability issues			
Air pollution	Similar to gasoline. Additional issues for ethanol due to permeation of volatile organic compounds through fuel tank seals. Aldehyde emissions.	Zero emission vehicle	Zero emission vehicle.
Water use	More than gasoline depending on feedstock and crop irrigation needs.	Potentially low but depends on pathway as electrolysis and steam reformation depend on water.	Potentially very low but depends on pathway used for power generation.
Land use	Might compete with food and fibre production on cropland.	Depends on pathway.	Depends on pathway.
Materials use		Platinum in fuel cells. Neodymium and other rare earths in electric motors. Material recycling.	Lithium in batteries. Neodymium and other rare earths in electric motors. Material recycling.

Notes: 1. Costs quoted do not always include payback of incremental first vehicle costs. 2. Indirect land use-related GHG emissions linked to biofuels is not included.

wind or hydropower resources. Grid flexibility and/or energy storage may also be needed to balance vehicle recharging electricity demand with RE source availability. [8.2.1]

Other than LDVs, it is possible to introduce RE options and lower GHG emissions in the other transport sectors: HDVs, aviation, maritime and rail. The use of biofuels is key for increasing the share of RE in these sub-sectors but current designs of ICEs would probably need to be modified to operate on high-biofuel blends (above 80%). Aviation has perhaps less potential for fuel switching than the other sub-sectors due to safety needs and to minimize fuel weight and volume. However, various airlines and aircraft manufacturers have flown demonstration test flights using various biofuel blends, but significantly more processing is needed than for road fuels to ensure that stringent aviation fuel specifications are met, particularly at cold temperatures. For rail transport, as around 90% of the industry is powered by diesel fuel, greater electrification and the increased use of biodiesel are the two primary options for introducing RE. [8.3.1.5]

Given all these uncertainties and cost reduction challenges, it is important to maintain a portfolio approach over a long time line that includes behavioural changes (for example to reduce annual vehicle kilometres travelled or kilometres flown), more energy efficient vehicles, and a variety of low-carbon fuels. [8.3.1.5]

8.7.2 Buildings and households

The building sector provides shelter and a variety of energy services to support the livelihoods and well-being of people living in both developed and developing countries. In 2008, it accounted for approximately 120 EJ (about 37%) of total global final energy use (including between 30 and 45 EJ of primary energy from traditional biomass used for cooking and heating). The high share of total building energy demand for heating and cooling is usually met by fossil fuels (oil burners, gas heaters) and electricity (fans and air-conditioners). In many regions, these can be replaced economically by district heating and cooling (DHC) schemes or by the direct use of RE systems in buildings, such as modern biomass pellets and enclosed stoves, heat pumps (including ground source), solar thermal water and space heating, and solar sorption cooling systems. [2.2, 8.2.2, 8.3.2]

RE electricity generation technologies integrated into buildings (such as solar PV panels) provide the potential for buildings to become energy suppliers rather than energy consumers. Integration of RE into existing urban environments, combined with energy efficient appliances and 'green building' designs, are key to further deployment. For both household and commercial building sub-sectors, energy vectors and energy service delivery systems vary depending on the local characteristics and RE resources of a region, its wealth, and the average age of the current buildings and infrastructure impacting stock turnover. [8.3.2]

The features and conditions of energy demands in an existing or new building, and the prospects for RE integration, differ with location and between one building design and another. In both urban and rural settlements in developed countries, most buildings are connected to electricity, water and sewage distribution schemes. With a low building stock turnover rate of only around 1% per year in developed countries, future retrofitting of existing buildings will need to play a significant role in RE integration as well as energy efficiency improvements. Examples include installation of solar water heaters and ground source heat pumps and development or extensions of DHC systems that, being flexible on sources of heat or cold, allow for a transition to a greater share of RE over time. These can involve relatively high up-front investment costs and long payback periods, but these can possibly be offset by amended planning consents and regulations so they become more enabling, improved energy efficient designs, and the provision of economic incentives and financial arrangements. [8.2.2, 8.3.2.1]

Grid electricity supply is available in most urban areas of developing countries, although often the supply system has limited capacity and is unreliable. Increased integration of RE technologies using local RE resources could help ensure a secure energy supply and also improve energy access. In urban and rural settlements in developing countries, energy consumption patterns often include the unsustainable use of biomass and charcoal. The challenge is to reverse the increasing traditional biomass consumption patterns by providing improved access to modern energy carriers and services and increasing the share of RE through integration measures. The distributed nature of solar and other RE resources is beneficial for their integration into new and existing buildings however modest they might be, including dwellings in rural areas not connected to energy supply grids. [8.2.2.2, 8.2.5]

8.7.3 Industry

Manufacturing industries account for about 30% of global final energy use, although the share differs markedly between countries. The sector is highly diverse, but around 85% of industrial energy use is by the more energy-intensive 'heavy' industries including iron and steel, non-ferrous metals, chemicals and fertilizers, petroleum refining, mineral mining, and pulp and paper. [8.3.3.1]

There are no severe technical limits to increasing the direct and indirect use of RE in industry in the future. However, integration in the short term may be limited by factors such as land and space constraints or demands for high reliability and continuous operation. In addition to the integration of higher shares of RE, key measures to reduce industrial energy demands and/or GHG emissions include energy efficiency, recycling of materials, CCS for CO_2-emitting industries such as cement manufacturing, and the substitution of fossil fuel feedstocks. In addition, industry can provide demand-response facilities that are likely to

achieve greater prominence in future electricity systems that have a higher penetration of variable RE sources. [8.3.3.1]

The main opportunities for RE integration in industry include:

- Direct use of biomass-derived fuels and process residues for onsite production, and use of biofuels, heat and CHP; [2.4.3]
- Indirect use through increased use of RE-based electricity, including electro-thermal processes; [8.3.3]
- Indirect use through other purchased RE-based energy carriers including heat, liquid fuels, biogas, and, possibly to a greater degree in the future, hydrogen; [8.2.2–8.2.4]
- Direct use of solar thermal energy for process heat and steam demands although few examples exist to date; [3.3.2] and
- Direct use of geothermal resources for process heat and steam demands. [4.3.5]

Industry is not only a potential user of RE but also a potential supplier of bioenergy as a co-product. The current direct use of RE in industry is dominated by biomass produced in the pulp and paper, sugar and ethanol industries as process by-products and used for cogenerated heat and electricity, mainly onsite for the process but also sold offsite. Biomass is also an important fuel for many small and medium enterprises such as brick making, notably as charcoal in developing countries. [8.3.3.1]

Possible pathways for increased use of RE in energy-intensive industries vary between the different industrial sub-sectors. Biomass, for example, is technically able to replace fossil fuels in boilers, kilns and furnaces or to replace petrochemicals with bio-based chemicals and materials. However, due to the scale of many industrial operations, access to sufficient volumes of local biomass may be a constraint. Use of solar technologies can be constrained in some locations with low annual sunshine hours. The direct supply of hydropower to aluminium smelters is not unusual but, for many energy-intensive processes, the main option is indirect integration of RE through switching to RE electricity from the grid, or, in the future, to hydrogen. The broad range of options for producing low-carbon electricity, and its versatility of use, implies that electro-thermal processes could become more important in the future for replacing fossil fuels in a range of industrial processes. [8.3.3.2]

Less energy-intensive 'light' industries, including food processing, textiles, light manufacturing of appliances and electronics, automotive assembly plants, and saw-milling, although numerous, account for a smaller share of total energy use than do the heavy industries. Much of the energy demand by these 'light' industries reflects the energy use in commercial buildings for lighting, space heating, cooling, ventilation and office equipment. In general, light industries are more flexible and offer more readily accessible opportunities for the integration of RE than do energy-intensive industries. [8.3.3.3]

RE integration for process heat is practical at temperatures below around 400°C using the combustion of biomass (including charcoal) as well as solar thermal or direct geothermal energy. To meet process heat demand above 400°C, RE resources, with the exception of high-temperature solar, are less suitable (Figure TS.8.8). [8.3.3.3]

The potentials and costs for increasing the use of RE in industry are poorly understood due to the complexity and diversity of industry and the various geographical and local climatic conditions. Near-term opportunities for achieving higher RE shares could result from the increased utilization of process residues, CHP in biomass-based industries, and substitution of fossil fuels used for heating. Solar thermal technologies are promising with further development of collectors, thermal storage, back-up systems, process adaptation and integration under evaluation. RE integration using electricity generated from RE sources for electro-technologies may have the largest impact both in the near and long term. [8.3.3.2, 8.3.3.3]

Use of RE in industry has had difficulty in competing in the past in many regions due to relatively low fossil fuel prices together with low, or

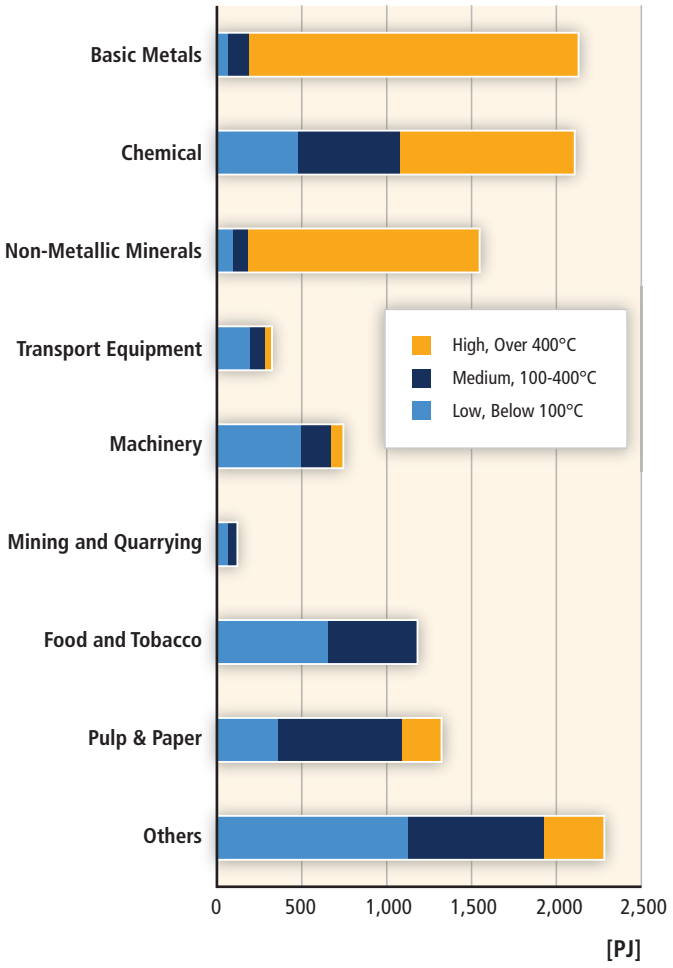


Figure TS.8.8 | Industrial heat demands for various temperature quality ranges by the heavy industrial and light manufacturing sub-sectors, based on an assessment within 32 European countries. [Figure 8.23]

non-existent, energy and carbon taxes. RE support policies in different countries tend to focus more on the transport and building sectors than on industry and consequently the potential for RE integration is relatively uncertain. Where support policies have been applied, successful RE deployment has resulted. [8.3.3.3]

8.7.4 Agriculture, forestry and fishing

Agriculture is a relatively low energy-consuming sector, utilizing only around 3% of total global consumer energy. The sector includes large corporate-owned farms and forests as well as subsistence farmers and fisher-folk in developing countries. The relatively high indirect energy use for the manufacture of fertilizers and machinery is included in the industry sector. Pumping water for irrigation usually accounts for the highest on-farm energy demand, along with diesel use for machinery and electricity for milking, refrigeration and fixed equipment. [8.3.4.1]

In many regions, land under cultivation could simultaneously be used for RE production. Multi-use of land for agriculture and energy purposes is becoming common, such as wind turbines constructed on grazing land; biogas plants used for treating animal manure with the nutrients recycled to the land; waterways used for small- and micro-hydropower systems; crop residues collected and combusted for heat and power; and energy crops grown and managed specifically to provide a biomass feedstock for liquid biofuels, heat and power generation (with co-products possibly used for feed and fibre). [2.6, 8.3.4.2, 8.3.4.3]

Since RE resources including wind, solar, crop residues and animal wastes are often abundant in rural areas, their capture and integration can enable the landowner or farm manager to utilize them locally for the farming operations. They can also earn additional revenue when energy carriers such as RE electricity or biogas are exported off the farm. [8.3.4]

Despite barriers to greater RE technology deployment including high capital costs, lack of available financing and remoteness from energy demand, it is likely that RE will be used to a greater degree by the global agricultural sector in the future to meet energy demands for primary production and post-harvest operations at both large and small scales. [8.3.4.1–8.3.4.2]

Integration strategies that could increase the deployment of RE in the primary sector will partly depend upon the local and regional RE resources, on-farm energy demand patterns, project financing opportunities and existing energy markets. [8.3.4.3]

9. Renewable Energy in the Context of Sustainable Development

9.1 Introduction

Sustainable development (SD) addresses concerns about relationships between human society and nature. Traditionally, SD has been framed in the three-pillar model—Economy, Ecology, and Society—allowing a schematic categorization of development goals, with the three pillars being interdependent and mutually reinforcing. Within another conceptual framework, SD can be oriented along a continuum between the two paradigms of weak sustainability and strong sustainability. The two paradigms differ in assumptions about the substitutability of natural and human-made capital. RE can contribute to the development goals of the three-pillar model and can be assessed in terms of both weak and strong SD, since RE utilization is defined as sustaining natural capital as long as the resource use does not reduce the potential for future harvest. [9.1]

9.2 Interactions between sustainable development and renewable energy

The relationship between RE and SD can be viewed as a hierarchy of goals and constraints that involve both global and regional or local considerations. Though the exact contribution of RE to SD has to be evaluated in a country-specific context, RE offers the opportunity to contribute to a number of important SD goals: (1) social and economic development; (2) energy access; (3) energy security; and (4) climate change mitigation and the reduction of environmental and health impacts. The mitigation of dangerous anthropogenic climate change is seen as one strong driving force behind the increased use of RE worldwide. [9.2, 9.2.1]

These goals can be linked to both the three-pillar model and the weak and strong SD paradigms. SD concepts provide useful frameworks for policymakers to assess the contribution of RE to SD and to formulate appropriate economic, social and environmental measures. [9.2.1]

The use of indicators can assist countries in monitoring progress made in energy subsystems consistent with sustainability principles, although there are many different ways to classify indicators of SD. The assessments carried out for the report and Chapter 9 are based on different methodological tools, including bottom-up indicators derived from attributional lifecycle assessments (LCA) or energy statistics, dynamic integrated modelling approaches, and qualitative analyses. [9.2.2]

Conventional economic growth metrics (GDP) as well as the conceptually broader Human Development Index (HDI) are analyzed to evaluate the contribution of RE to social and economic development. Potential employment opportunities, which serve as a motivation for some countries to support RE deployment, as well as critical financing questions for developing countries are also addressed. [9.2.2]

Access to modern energy services, whether from renewable or non-renewable sources, is closely correlated with measures of development, particularly for those countries at earlier development stages. Providing access to modern energy for the poorest members of society is crucial for the achievement of any single of the eight Millennium Development Goals. Concrete indicators used include per capita final energy consumption related to income, as well as breakdowns of electricity access (divided into rural and urban areas), and numbers for those parts of the population using coal or traditional biomass for cooking. [9.2.2]

Despite the lack of a commonly accepted definition, the term 'energy security' can best be understood as robustness against (sudden) disruptions of energy supply. Two broad themes can be identified that are relevant to energy security, whether for current systems or for the planning of future RE systems: availability and distribution of resources; and variability and reliability of energy supply. The indicators used to provide information about the energy security criterion of SD are the magnitude of reserves, the reserves-to-production ratio, the share of imports in total primary energy consumption, the share of energy imports in total imports, as well as the share of variable and unpredictable RE sources. [9.2.2]

To evaluate the overall burden from the energy system on the environment, and to identify potential trade-offs, a range of impacts and categories have to be taken into account. These include mass emissions to air (in particular GHGs) and water, and usage of water, energy and land per unit of energy generated and these must be evaluated across technologies. While recognizing that LCAs do not give the only possible answer as to the sustainability of a given technology, they are a particularly useful methodology for determining total system impacts of a given technology, which can serve as a basis for comparison. [9.2.2]

Scenario analyses provide insights into what extent integrated models take account of the four SD goals in different RE deployment pathways. Pathways are primarily understood as scenario results that attempt to address the complex interrelations among the different energy technologies at a global scale. Therefore, Chapter 9 mainly refers to global scenarios derived from integrated models that are also at the core of the analysis in Chapter 10. [9.2.2]

9.3 Social, environmental and economic impacts: Global and regional assessment

Countries at different levels of development have different incentives to advance RE. For developing countries, the most likely reasons to adopt RE technologies are providing access to energy, creating employment opportunities in the formal (i.e., legally regulated and taxable) economy, and reducing the costs of energy imports (or, in the case of fossil energy exporters, prolonging the lifetime of their natural resource base). For industrialized countries, the primary reasons to encourage RE include reducing carbon emissions to mitigate climate change, enhancing energy security, and actively promoting structural change in the economy, such that job losses in declining manufacturing sectors are softened by new employment opportunities related to RE. [9.3]

9.3.1 Social and economic development

Globally, per capita incomes are positively correlated with per capita energy use and economic growth can be identified as the most relevant factor behind increasing energy consumption in the last decades. However, there is no agreement on the direction of the causal relationship between energy use and increased macroeconomic output. [9.3.1.1]

As economic activity expands and diversifies, demands for more sophisticated and flexible energy sources arise: from a sectoral perspective, countries at an early stage of development consume the largest part of total primary energy in the residential (and to a lesser extent agricultural) sector; in emerging economies the manufacturing sector dominates, while in fully industrialized countries services and transport account for steadily increasing shares (see Figure TS.9.1). [9.3.1.1]

Despite the close correlation between GDP and energy use, a wide variety of energy use patterns across countries prevails: some have achieved high levels of per capita incomes with relatively low energy consumption. Others remain rather poor despite elevated levels of energy use, in particular countries abundantly endowed with fossil fuel resources, in which energy is often heavily subsidized. One hypothesis suggests that economic growth can largely be decoupled from energy use by steady declines in energy intensity. Further, it is often asserted that developing economies and economies in transition can 'leapfrog', that is, limit their energy use by adopting modern, highly efficient energy technologies. [9.3.1.1, Box 9.5]

Access to clean and reliable energy constitutes an important prerequisite for fundamental determinants of human development, such as health, education, gender equality and environmental safety. Using the HDI as a proxy indicator of development, countries that have achieved high HDI levels in general consume relatively large amounts of energy per capita and no country has achieved a high or even a medium HDI without significant access to non-traditional energy supplies. A certain minimum amount of energy is required to guarantee an acceptable standard of living (e.g., 42 GJ per capita), after which raising energy consumption yields only marginal improvements in the quality of life. [9.3.1.2]

Estimates of current net employment effects of RE differ due to disagreements regarding the use of the appropriate methodology. Still, there seems to be agreement about the positive long-term effects of RE

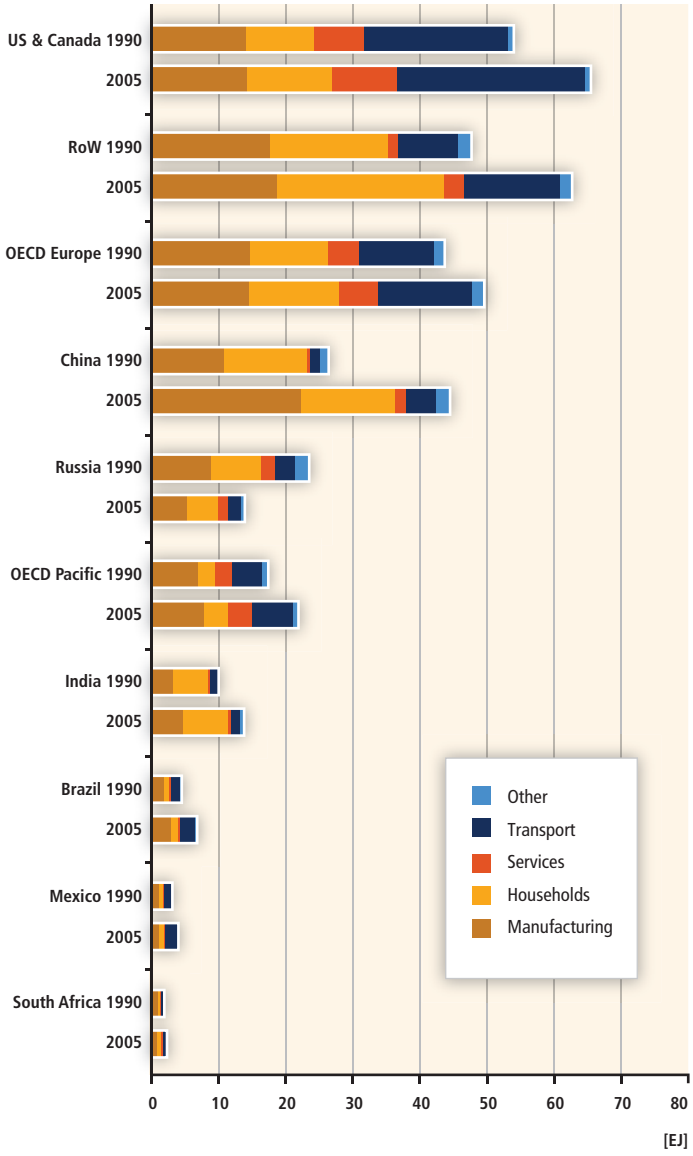


Figure TS.9.1 | Energy use (EJ) by economic sector. Note that the underlying data are calculated using the IEA physical content method, not the direct equivalent method.[1]

Notes: RoW = Rest of World. [Figure 9. 2] 1. Historical energy data have only been available for energy use by economic sector. For a conversion of the data using the direct equivalent method, the different energy carriers used by each economic sector would need to be known.

as an important contribution to job creation, which has been stressed in many national green-growth strategies. [9.3.1.3]

In general, the purely economic costs of RE exceed those of fossil fuel-based energy production in most instances. Especially for developing countries, the associated costs are a major factor determining the desirability of RE to meet increasing energy demand, and concerns have been voiced that increased energy prices might endanger industrializing countries' development prospects. Overall, cost considerations cannot be discussed independently of the burden-sharing regime adopted, that is, without specifying who assumes the costs for the benefits brought about from reduced GHG emissions, which can be characterized as a global public good. [9.3.1.4]

9.3.2 Energy access

Significant parts of the global population today have no or limited access to modern and clean energy services. From a sustainable development perspective, sustainable energy expansion needs to increase the availability of energy services to groups that currently have no or limited access to them: the poor (measured by wealth, income or more integrative indicators), those in rural areas and those without connections to the grid. [9.3.2]

Acknowledging the existing constraints regarding data availability and quality, 2009 estimates of the number of people without access to electricity are around 1.4 billion. The number of people relying on traditional biomass for cooking is around 2.7 billion, which causes significant health problems (notably indoor air pollution) and other social burdens (e.g., time spent gathering fuel) in the developing world. Given the strong correlation between household income and use of low quality fuels (Figure TS.9.2), a major challenge is to reverse the pattern of inefficient biomass consumption by changing the present, often unsustainable, use to more sustainable and efficient alternatives. [9.3.2]

By defining energy access as 'access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses', the incremental process of climbing the steps of the energy ladder is illustrated; even basic levels of access to modern energy services can provide substantial benefits to a community or household. [9.3.2]

In developing countries, decentralized grids based on RE have expanded and improved energy access; they are generally more competitive in rural areas with significant distances to the national grid and the low levels of rural electrification offer significant opportunities for RE-based mini-grid systems. In addition, non-electrical RE technologies offer opportunities for direct modernization of energy services, for example, using solar energy for water heating and crop drying, biofuels for transportation, biogas and modern biomass for heating, cooling, cooking and lighting, and wind for water pumping. While the specific role of RE in providing energy access in a more sustainable manner than other energy sources is not well understood, some of these technologies allow local communities to widen their energy choices; they stimulate economies, provide incentives for local entrepreneurial efforts and meet basic needs and services related to lighting and cooking, thus providing ancillary health and education benefits. [9.3.2]

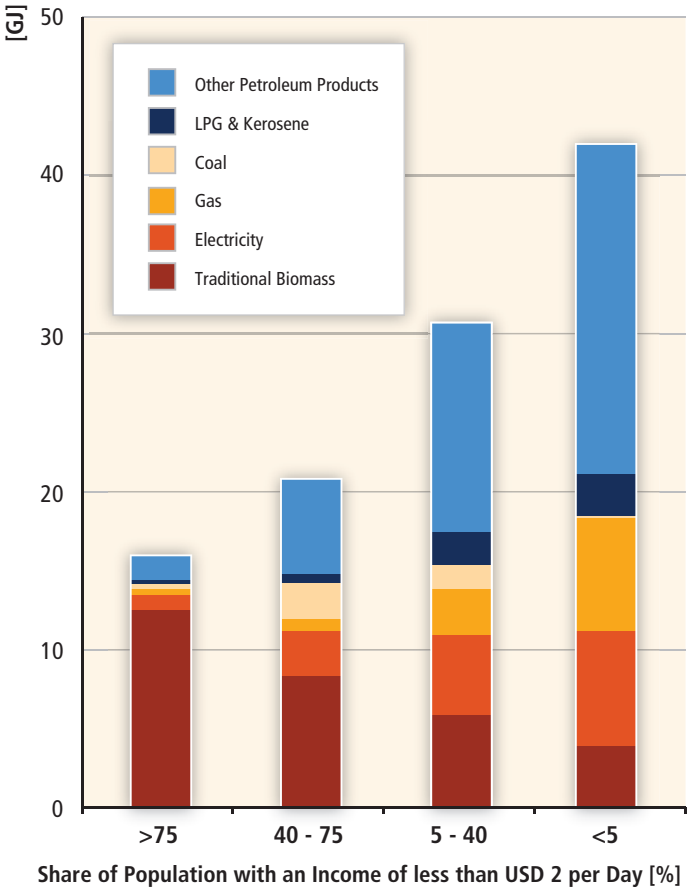


Figure TS.9.2 | The relationship between per capita final energy consumption and income in developing countries. Data refer to the most recent year available during the period 2000 to 2008. [Figure 9.5]

Note: LPG = liquid petroleum gas.

9.3.3 Energy security

The use of RE permits substitution away from increasingly scarce fossil fuel supplies; current estimates of the ratio of proven reserves to current production show that globally oil and natural gas would be exhausted in about four and six decades, respectively. [9.3.3.1]

As many renewable sources are localized and not internationally tradable, increasing their share in a country's energy portfolio diminishes the dependence on imports of fossil fuels, whose spatial distribution of reserves, production and exports is very uneven and highly concentrated in a few regions (Figure TS.9.3). As long as RE markets are not characterized by such geographically concentrated supply, this helps to diversify the portfolio of energy sources and to reduce the economy's vulnerability to price volatility. For oil-importing developing countries, increased uptake of RE technologies could be an avenue to redirect foreign exchange flows away from energy imports towards imports of goods that cannot be produced locally, such as high-tech capital goods. For example, Kenya and Senegal spend more than half of their export earnings for importing energy, while India spends over 45%. [9.3.3.1]

However, import dependencies can also occur in relation to the technologies needed for implementation of RE, with the secure access to required scarce inorganic mineral raw materials at reasonable prices constituting an upcoming challenge for all industries. [9.3.3.1]

The variable output profiles of some RE technologies often necessitate technical and institutional measures appropriate to local conditions to assure a constant and reliable energy supply. Reliable energy access is a particular challenge in developing countries and indicators for the reliability of infrastructure services show that in sub-Saharan Africa, almost 50% of firms maintain their own generation equipment. Many developing countries therefore specifically link energy access and security issues by broadening the definition of energy security to include stability and reliability of local supply. [9.3.3.2]

9.3.4 Climate change mitigation and reduction of environmental and health impacts

Sustainable development must ensure environmental quality and prevent undue environmental harm. No large-scale technology deployment comes without environmental trade-offs and a large body of literature is available that assesses various environmental impacts of the broad range of energy technologies (RE, fossil and nuclear) from a bottom-up perspective. [9.3.4]

Impacts on the climate through GHG emissions are generally well covered, and LCAs [Box 9.2] facilitate a quantitative comparison of 'cradle to grave' emissions across technologies. While a significant number of studies report on air pollutant emissions and operational water use, evidence is scarce for lifecycle emissions to water, land use, and health impacts other than those linked to air pollution. The assessment concentrates on those sectors which are best covered by the literature, such as electricity generation and transport fuels for GHG emissions. Heating and household energy are discussed only briefly, in particular with regards to air pollution and health. Impacts on biodiversity and ecosystems are mostly site-specific, difficult to quantify and are presented in a more qualitative manner. To account for burdens associated with accidents as opposed to normal operation, an overview of risks associated with energy technologies is provided. [9.3.4]

LCAs for electricity generation indicate that *GHG emissions from RE technologies* are, in general, considerably lower than those associated with fossil fuel options, and in a range of conditions, less than fossil fuels employing CCS. The maximum estimate for CSP, geothermal, hydropower, ocean and wind energy is less than or equal to 100 g CO_2eq/kWh, and median values for all RE range from 4 to 46 g CO_2eq/kWh. The upper quartile of the distribution of estimates for PV and biopower extend two to three times above the maximum for other RE technologies. However, GHG balances of bioenergy production have more uncertainties: excluding LUC, biopower could reduce GHG emissions compared to fossil fuelled systems and can lead to avoided GHG emissions from residues and wastes in landfill disposals and co-products; the combination of

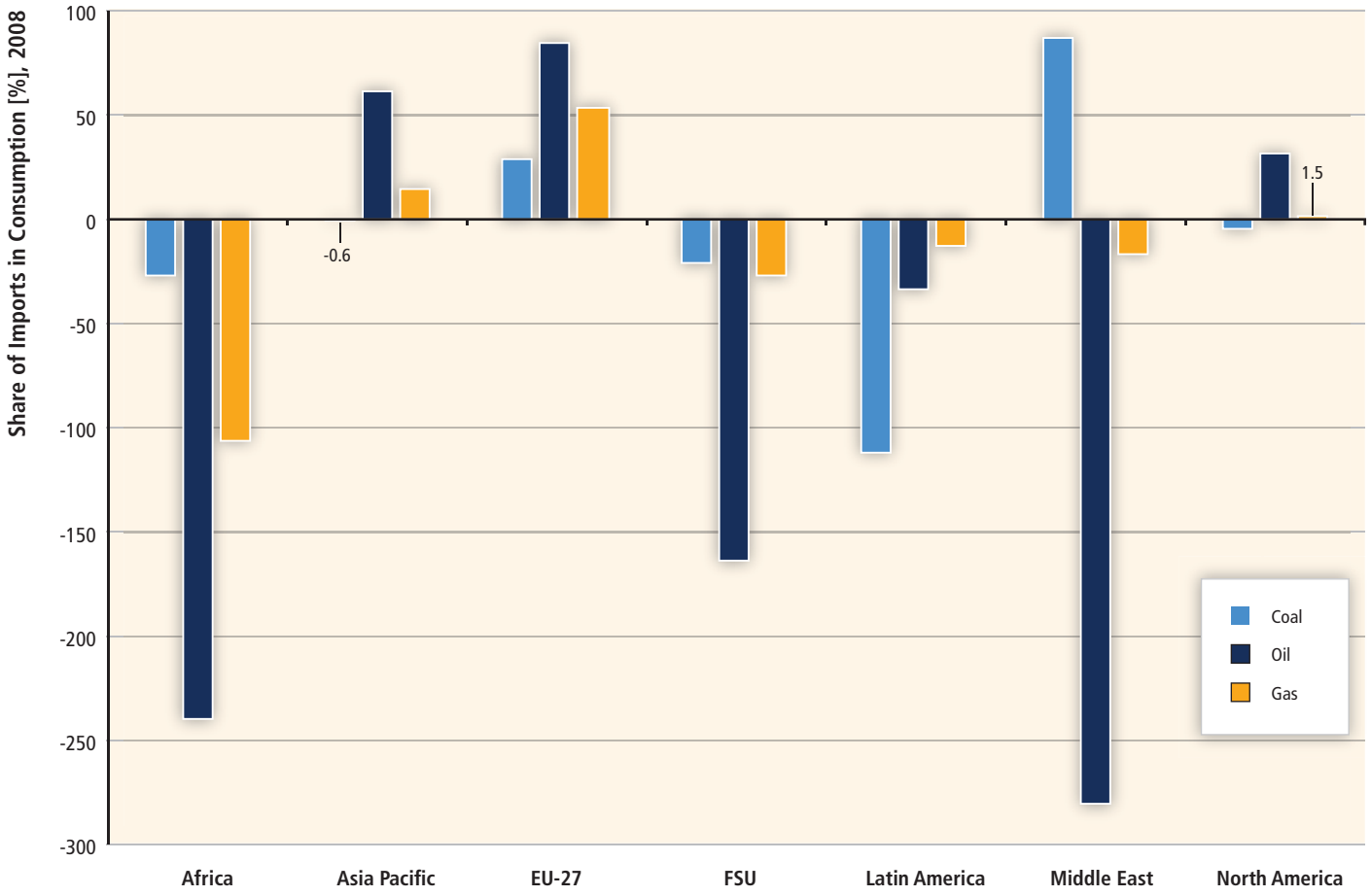


Figure TS.9.3 | Energy imports as the share of total primary energy consumption (%) for coal (hard coal and lignite), crude oil and natural gas for selected world regions in 2008. Negative values denote net exporters of energy carriers. [Figure 9.6]

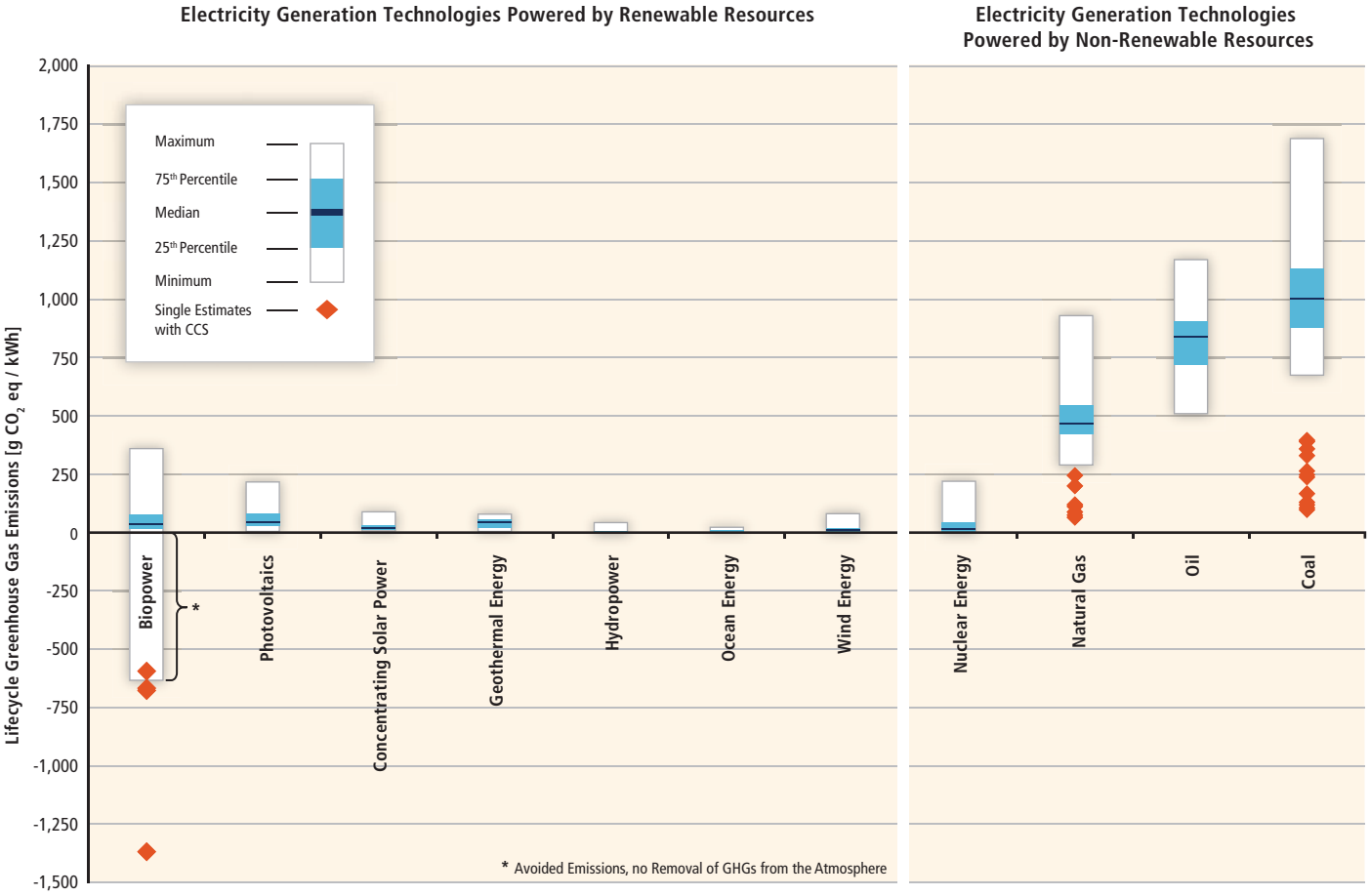
bioenergy with CCS may provide for further reductions (Figure TS.9.4). [9.3.4.1]

Accounting for differences in the quality of power produced, potential impacts to grid operation related to the addition of variable generation sources, and for direct or indirect LUC could reduce the GHG emissions benefit from switching to renewable electricity generation, but is not likely to negate the benefit. [9.3.4.1]

Measures such as the energy payback time, describing the energetic efficiency of technologies or fuels, have been declining rapidly for some RE technologies over recent years (e.g., wind and PV) due to technological advances and economies of scale. Fossil and nuclear power technologies are characterized by the continuous energy requirements for fuel extraction and processing, which might become increasingly important as qualities of conventional fuel supply decline and shares of unconventional fuels rise. [9.3.4.1]

For the assessment of *GHG emissions from transportation fuels*, selected petroleum fuels, first-generation biofuels (i.e., sugar- and starch-based ethanol, oilseed-based biodiesel and renewable diesel), and selected next-generation biofuels derived from lignocellulosic biomass (i.e., ethanol and Fischer-Tropsch diesel) are compared on a well-to-wheel basis. In this comparison, GHG emissions from LUC (direct and indirect) and other indirect effects (e.g., petroleum consumption rebound) have been excluded, but are separately considered below. Substituting biofuels for petroleum-based fuels has the potential to reduce lifecycle GHG emissions directly associated with the fuel supply chain. While first-generation biofuels result in relatively modest GHG mitigation potential (-19 to 77 g CO_2eq/MJ for first-generation biofuels versus 85 to 109 g CO_2eq/MJ for petroleum fuels), most next-generation biofuels (with lifecycle GHG emissions between -10 and 38 g CO_2eq/MJ) could provide greater climate benefits. Estimates of lifecycle GHG emissions are variable and uncertain for both biofuels and petroleum fuels, primarily due to assumptions about biophysical parameters, methodological issues and where and how the feedstocks are produced. [9.3.4.1]

Lifecycle *GHG emissions from LUC* are difficult to quantify, with land and biomass resource management practices strongly influencing any GHG emission reduction benefits and as such the sustainability of bioenergy. Changes to land use or management, brought about directly or indirectly by biomass production for use as fuels, power or heat, can lead to changes in terrestrial carbon stocks. Depending on the converted land's prior condition, this can either cause significant upfront emissions, requiring a time



	Biopower	Photovoltaics	Concentrating Solar Power	Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Nuclear Energy	Natural Gas	Oil	Coal
Count of Estimates	222(+4)	124	42	8	28	10	126	125	83(+7)	24	169(+12)
Count of References	52(+0)	26	13	6	11	5	49	32	36(+4)	10	50(+10)

Figure TS.9.4 | Estimates of lifecycle GHG emissions (g CO_2eq/kWh) for broad categories of electricity generation technologies, plus some technologies integrated with CCS. Land-use related net changes in carbon stocks (mainly applicable to biopower and hydropower from reservoirs) and land management impacts are excluded; negative estimates[1] for biopower are based on assumptions about avoided emissions from residues and wastes in landfill disposals and co-products. References and methods for the review are reported in Annex II. The number of estimates is greater than the number of references because many studies considered multiple scenarios. Numbers reported in parentheses pertain to additional references and estimates that evaluated technologies with CCS. Distributional information relates to estimates currently available in LCA literature, not necessarily to underlying theoretical or practical extrema, or the true central tendency when considering all deployment conditions. [Figure 9.8]

Note: 1. 'Negative estimates' within the terminology of lifecycle assessments presented in this report refer to avoided emissions. Unlike the case of bioenergy combined with CCS, avoided emissions do not remove GHGs from the atmosphere.

lag of decades to centuries before net savings are achieved, or improve the net uptake of carbon into soils and aboveground biomass. Assessments of the net GHG effects of bioenergy are made difficult by challenges in observation, measurement, and attribution of indirect LUC, which depends on the environmental, economic, social and policy context and is neither directly observable nor easily attributable to a single cause. Illustrative estimates of direct and indirect LUC-related GHG emissions induced by several first-generation biofuel pathways provide central tendencies (based on different reporting methods) for a 30-year timeframe: for ethanol (EU wheat, US maize, Brazilian sugarcane) 5 to 82 g CO_2eq/MJ and for diesel (soy and rapeseed) 35 to 63 g CO_2eq/MJ. [9.3.4.1]

Impacts from *local and regional air pollution* constitute another important assessment category, with air pollutants (including particulate matter (PM), nitrous oxides (NO_x), sulphur dioxide (SO_2) and non-methane volatile organic compounds (NMVOC)) having effects at the global [Box 9.4], regional and local scale. Compared to fossil-based power generation, non-combustion-based RE power generation technologies have the

potential to significantly reduce regional and local air pollution and associated health impacts (see this section below). For transportation fuels, however, the effect of switching to biofuels on tailpipe emissions is not yet clear. [9.3.4.2]

Local air pollutant emissions from fossil fuels and biomass combustion constitute the most important energy related impacts on *human health*. Ambient air pollution, as well as exposure to indoor air pollution from the combustion of coal and traditional biomass, has major health impacts and is recognized as one of the most important causes of morbidity and mortality worldwide, particularly for women and children in developing countries. In 2000, for example, comparative quantifications of health risks showed that more than 1.6 million deaths and over 38.5 million of disability-adjusted life-years (DALYs) were attributable to indoor smoke from solid fuels. Besides a fuel switch, mitigation options include improved cookstoves, ventilation and building design and behavioural changes. [9.3.4.3]

Impacts on *water* relate to operational and upstream water consumption of energy technologies and to water quality. These impacts are site specific and need to be considered with respect to local resources and needs. RE technologies like hydropower and some bioenergy systems, for example, are dependent on water availability and can either increase competition or mitigate water scarcity. In water-scarce areas, non-thermal RE technologies (e.g., wind and PV) can provide clean electricity without putting additional stress on water resources. Conventionally cooled thermal RE technologies (e.g., CSP, geothermal, biopower) can use more water during operation than non-RE technologies, yet dry cooling configurations can reduce this impact (Figure TS.9.5). Water use in upstream processes can be high for some energy technologies, particularly for fuel extraction and biomass feedstock production; including the latter, the current water footprint for electricity generation from biomass can be up to several hundred times greater than operational water consumption requirements for thermal power plants. Feedstock production, mining operations and fuel processing can also affect water quality. [9.3.4.4]

Most energy technologies have substantial *land requirements* when the whole supply chain is included. While the literature on lifecycle estimates for land use by energy technologies is scarce, the available evidence suggests that lifecycle land use by fossil energy chains can be comparable to or higher than land use by RE sources. For most RE sources, land use requirements are largest during the operational stage. An exception is the land intensity of bioenergy from dedicated feedstocks, which is significantly higher than for any other energy technology and shows substantial variations in energy yields per hectare for different feedstocks and climatic zones. A number of RE technologies (wind, wave and ocean) occupy large areas, but allow secondary uses such as farming, fishing and recreational activities. [9.3.4.5] Connected to land use are (site-specific) impacts on *ecosystems and biodiversity*. Occurring through various pathways, the most evident ones are through large-scale direct physical alteration of habitats and, more indirectly, habitat deterioration. [9.3.4.6]

The comparative assessment of *accident risks* is a pivotal aspect in a comprehensive evaluation of energy security aspects and sustainability performance associated with current and future energy systems. Risks of various energy technologies to society and the environment occur not only during the actual energy generation, but at all stages of energy chains. Accident risks of RE technologies are not negligible, but the technologies' often decentralized structure strongly limits the potential for disastrous consequences in terms of fatalities. While RE technologies overall exhibit low fatality rates, dams associated with some hydropower projects may create a specific risk depending on site-specific factors. [9.3.4.7]

9.4 Implication of sustainable development pathways for renewable energy

Following the more static analysis of the impacts of current and emerging RE systems on the four SD goals, the SD implications of possible future RE deployment pathways are assessed in a more dynamic manner and thus incorporate the intertemporal component of SD. Since the interaction of future RE and SD pathways cannot be anticipated by relying on a partial analysis of individual energy technologies, the discussion is based on results from the scenario literature that typically treats the portfolio of technological alternatives in the framework of a global or regional energy system. [9.4]

The vast majority of models used to generate the scenarios reviewed (see Chapter 10, Section 10.2) capture the interactions between different options for supplying, transforming and using energy. The models range from regional, energy-economic models to integrated assessment models (IAMs) and are here referred to as integrated models. Historically, these models have focused much more on the technological and macroeconomic aspects of energy transitions, and in the process have produced largely aggregated measures of technological penetration or energy generated by particular sources of supply. The value of these models in generating long-term scenarios and their potential to help understand the interrelation between SD and RE rests on their ability to consider interactions across a broad set of human activities over different regional and time scales. Integrated models continually undergo developments, some of which will be crucial for the representation of sustainability concerns in the future, for example, increasing their temporal and spatial resolution, allowing for a better representation of the distribution of wealth across the population and incorporating greater detail in human and physical Earth system characterization. [9.4]

The assessment focuses on what model-based analyses currently have to say with respect to SD pathways and the role of RE and evaluates how model-based analyses can be improved to provide a better understanding of sustainability issues in the future. [9.4]

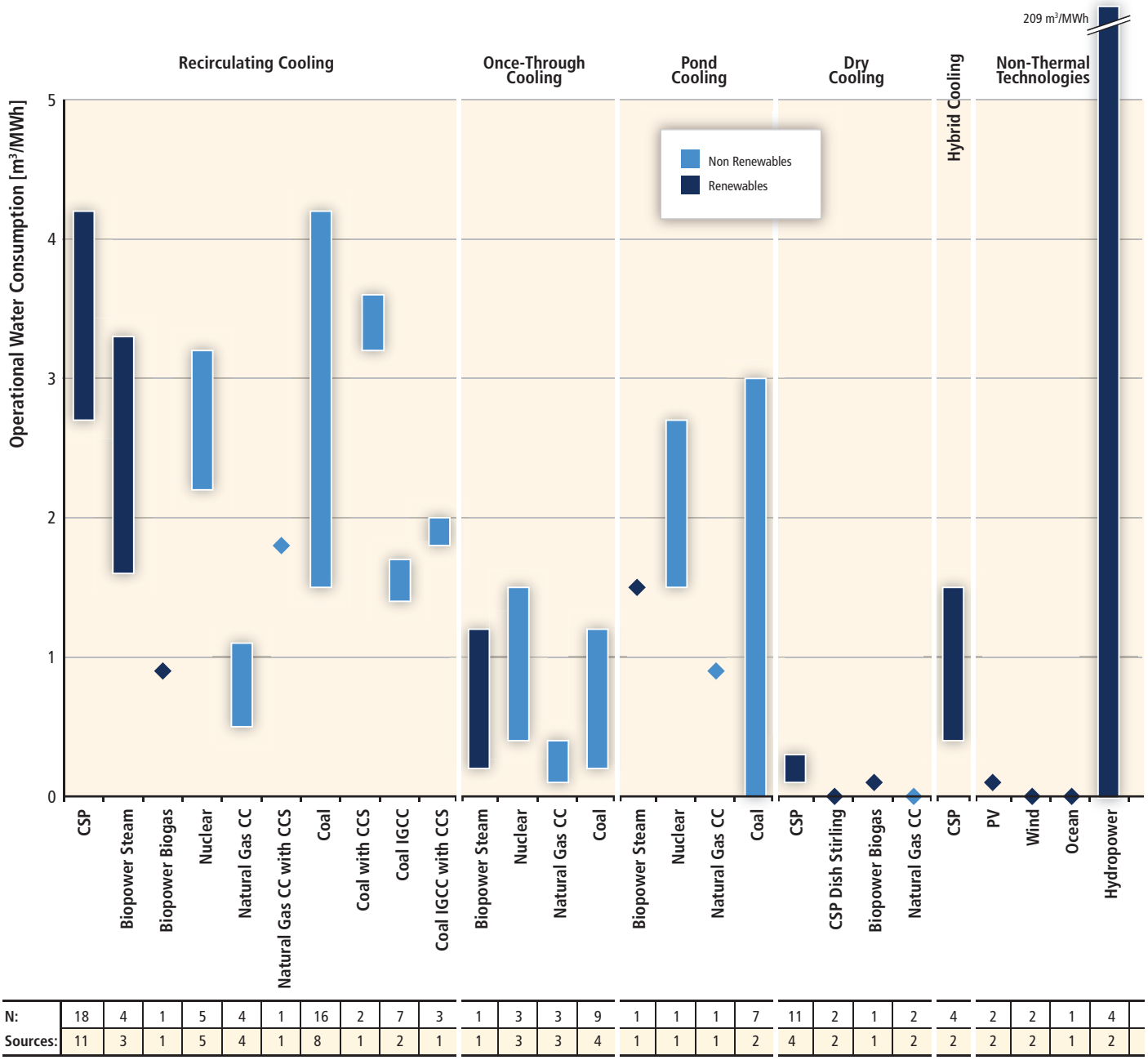


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Figure TS.9.5 | Ranges of rates of operational water consumption by thermal and non-thermal electricity-generating technologies based on a review of available literature (m³/MWh). Bars represent absolute ranges from available literature, diamonds single estimates; n represents the number of estimates reported in the sources. Methods and references used in this literature review are reported in Annex II. Note that upper values for hydropower result from a few studies measuring gross evaporation values, and may not be representative (see Box 5.2). [Figure 9.14]

Notes: CSP: concentrated solar power; CCS: carbon capture and storage; IGCC: integrated gasification combined cycle; CC: combined cycle; PV: photovoltaic.

9.4.1 Social and economic development

Integrated models usually have a strong macro-perspective and do not consider advanced welfare measures. [9.2.2, 9.3.1] Instead, they focus on economic growth, which in itself is an insufficient measure of sustainability, but can be used as an indicative welfare measure in the context of different stabilization pathways. Mitigation scenarios usually include a tentative strong sustainability constraint by putting an upper limit on future GHG emissions. This results in welfare losses (usually measured as GDP or consumption foregone) based on assumptions about the availability and costs of mitigation technologies. Limiting the availability of technological alternatives for constraining GHGs further increases welfare losses. Studies that specifically assess the implications of constraining RE for different GHG concentration stabilization levels

show that the wide availability of all RE technologies is essential in order to reach low stabilization levels and that the full availability of low-carbon technologies, including RE, is crucial for keeping mitigation costs at relatively low levels, even for less strict stabilization levels. [9.4.1]

With respect to regional effects, scenario analyses show that developing countries are likely to see most of the expansion in RE production. With the challenge to overcome high LCOEs of RE technologies still to be met, these results hint at the potential of developing countries to leap-frog the emission-intensive developing paths that developed countries have taken so far. Regional mitigation opportunities will, however, vary, depending on many factors including technology availability, but also population and economic growth. Costs will also depend on the allocation of tradable emission permits, both initially and over time, under a global climate mitigation regime. [9.4.1]

In general, scenario analyses point to the same links between RE, mitigation and economic growth in developed and developing countries, only the forces are generally larger in non-Annex I countries than in Annex I countries due to more rapid assumed economic growth and the consequently increasing mitigation burden over time. However, the modelling structures used to generate long-term global scenarios generally assume perfectly functioning economic markets and institutional infrastructures across all regions of the globe. They also discount the special circumstances that prevail in all countries, particularly in developing countries where these assumptions are particularly tenuous. These sorts of differences and the influence they might have on social and economic development among countries should be an area of active future research. [9.4.1]

9.4.2 Energy access

Integrated models thus far have often been based on developed country information and experience and assumed energy systems in other parts of the world and at different stages of development to behave likewise. Usually, models do not capture important and determinative dynamics in developing countries, such as fuel choices, behavioural heterogeneity and informal economies. This impedes an assessment of the interaction between RE and the future availability of energy services for different populations, including basic household level tasks, transportation, and energy for commerce, manufacturing and agriculture. However, some models have started to integrate factors such as potential supply shortages, informal economies and diverse income groups, and to increase the distributional resolution. [9.4.2]

Available scenario analyses are still characterized by large uncertainties. For India, results suggested that income distribution in a society is as important for increasing energy access as income growth. Also, increasing energy access is not necessarily beneficial for all aspects of SD, as a shift to modern energy away from, for example, traditional biomass could simply be a shift to fossil fuels. In general, available scenario analyses highlight the role of policies and finance for increased energy access, even though forced shifts to RE that would provide access to modern energy services could negatively affect household budgets. [9.4.2]

Further improvements in the distribution resolution and structural rigidity (inability of many models to capture social phenomena and structural changes that underlie peoples' utilization of energy technologies) are particularly challenging. An explicit representation of the energy consequences for the poorest, women, specific ethnic groups within countries, or those in specific geographical areas, tends to be outside the range of current global model output. In order to provide a more comprehensive view of the possible range of energy access options, future energy models should aim for a more explicit representation of relevant determinants (such as traditional fuels, modes of electrification, and income distribution) and link these to representations of alternative development pathways. [9.4.2]

9.4.3 Energy security

RE can influence energy security by mitigating concerns with respect to both availability and distribution of resources, as well as to the variability of energy sources. [9.2.2, 9.3.1] To the extent that RE deployment in mitigation scenarios reduces the overall risk of disruption by diversifying the energy portfolio, the energy system is less susceptible to (sudden) energy supply disruption. In scenarios, this role of RE will vary with the energy form. Solar, wind and ocean energy, which are closely associated with electricity production, have the potential to replace concentrated and increasingly scarce fossil fuels in the buildings and the industry sector. With appropriate carbon mitigation policies in place, electricity generation can be relatively easily decarbonized. In contrast, the demand for liquid fuels in the transport sector remains inelastic if no technological breakthrough can be achieved. While bioenergy could play an important role, this will depend on the availability of CCS that could divert its use to power generation with CCS—resulting in negative net carbon emissions for the system and smoothing the overall mitigation efforts significantly. [9.4.1, 9.4.3]

Against this background, energy security concerns raised in the past that related to oil supply disruptions are likely to remain relevant in the future. For developing countries the issue will become even more important, as their share in global total oil consumption increases in all assessed scenarios (Figure TS.9.6b). As long as technological alternatives for oil, for example, biofuels and/or the electrification of the transportation sector, do not play a dominant role in scenario analyses,

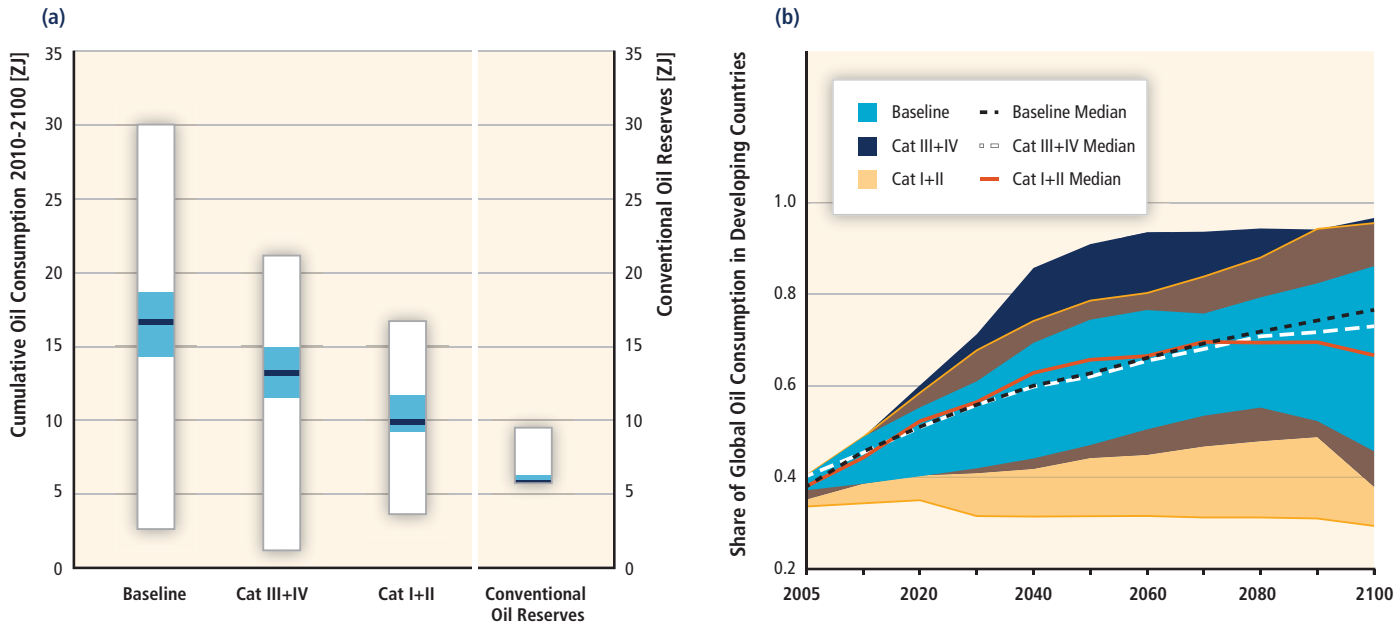


Figure TS.9.6 | (a) Conventional oil reserves compared to projected cumulative oil consumption (ZJ) from 2010 to 2100 in scenarios assessed in Chapter 10 for different scenario categories: baseline scenarios, Category III and IV scenarios and low stabilization (Category I+II) scenarios. The thick dark blue line corresponds to the median, the light blue bar corresponds to the inter-quartile range (25th to 75th percentile) and the white surrounding bar corresponds to the total range across all reviewed scenarios. The last column shows the range of proven recoverable conventional oil reserves (light blue bar) and estimated additional reserves (white surrounding bar). (b) Range of share of global oil consumed in non-Annex I countries for different scenario categories over time, based on scenarios assessed in Chapter 10. [Figure 9.18]

most mitigation scenarios do not see dramatic differences between the baseline and policy scenarios with respect to cumulative oil consumption (Figure TS.9.6a). [9.4.3]

An increased market for bioenergy could raise additional energy security concerns in the future if it was characterized by a small number of sellers and thus showed parallels to today's oil market. In such an environment, the risk that food prices could be linked to volatile bioenergy markets would have to be mitigated to impede severe impacts on SD as high and volatile food prices would clearly hurt the poor. [9.4.3]

The introduction of variable RE technologies also adds new concerns, such as vulnerability to extreme natural events or international price fluctuations, which are not yet satisfactorily addressed by large integrated models. Additional efforts to increase system reliability are likely to add costs and involve balancing needs (such as holding stocks of energy), the development of complementary flexible generation, strengthening network infrastructure and interconnections, energy storage technologies and modified institutional arrangements including regulatory and market mechanisms [7.5, 8.2.1, 9.4.3]

Energy security considerations today usually focus on the most prominent energy security issues in recent memory. However, energy security aspects of the future might go well beyond these issues, for example, in relation to critical material inputs for RE technologies. These broader concerns as well as options for addressing them, for example, recycling, are largely absent from future scenarios of mitigation and RE. [9.4.3]

9.4.4 Climate change mitigation and environmental and health impacts in scenarios of the future

Replacing fossil fuels with RE or other low-carbon technologies can significantly contribute to the reduction of NO_x and SO_2 emissions. Several models have included explicit representation of factors, such as sulphate pollution, that are linked to environmental or health impacts. Some scenario results show that climate policy can help drive improvements in local air pollution (i.e., PM), but air pollution reduction policies alone do not necessarily drive reductions in GHG emissions. Another implication of some potential energy trajectories is the possible diversion of land to support biofuel production. Scenario results have pointed at the possibility that, if not accompanied by other policy measures, climate policy could drive widespread deforestation, with land use being shifted to bioenergy crops with possibly adverse SD implications, including GHG emissions. [9.4.4]

Unfortunately, existing scenario literature does not explicitly treat the many non-emissions related elements of sustainable energy development, such as water use, the impacts of energy choices on household-level services, or indoor air quality. This can be partly explained by models being designed to look at fairly large world regions without income or geographic distributional detail. For a broad assessment of environmental impacts at the regional and local level, models would need to look at smaller scales of geographical impacts, which is currently a matter of ongoing research. Finally, many models do not explicitly allow for incorporation of LCA results of the technological alternatives. What these

impacts are, whether and how to compare them across categories, and whether they might be incorporated into future scenarios would constitute useful areas for future research. [9.4.4]

9.5 Barriers and opportunities for renewable energy in the context of sustainable development

Pursuing a renewable energy deployment strategy in the context of SD implies that most environmental, social and economic effects are taken explicitly into account. Integrated planning, policy and implementation processes can support this by anticipating and overcoming potential barriers to and exploiting opportunities of RE deployment. [9.5]

Barriers that are particularly pertinent in a sustainable development context and that may either impede RE deployment or result in trade-offs with SD criteria relate to socio-cultural, information and awareness, market-related and economic barriers. [9.5.1]

Socio-cultural barriers or concerns have different origins and are intrinsically linked to societal and personal values and norms. Such values and norms affect the perception and acceptance of RE technologies and the potential impacts of their deployment by individuals, groups and societies. From a sustainable development perspective, barriers may arise from inadequate attention to such socio-cultural concerns, which include barriers related to behaviour; natural habitats and natural and human heritage sites, including impacts on biodiversity and ecosystems; landscape aesthetics; and water/land use and water/land use rights, as well as their availability for competing uses. [9.5.1.1]

Public awareness and acceptance is an important element in the need to rapidly and significantly scale up RE deployment to help meet climate change mitigation goals. Large-scale implementation can only be undertaken successfully with the understanding and support of the public. This may require dedicated communication efforts related to the achievements and the opportunities associated with wider-scale applications. At the same time, however, public participation in planning decisions as well as fairness and equity considerations in the distribution of the benefits and costs of RE deployment play an equally important role and cannot be side-stepped. [9.5.1.1]

In developing countries, limited technical and business skills and the absence of technical support systems are particularly apparent in the energy sector, where awareness of and information dissemination regarding available and appropriate RE options among potential consumers is a key determinant of uptake and market creation. This gap in awareness is often perceived as the single most important factor affecting the deployment of RE and development of small and medium enterprises that contribute to economic growth. Also, there is a need to focus on the capacity of private actors to develop, implement and deploy RE technologies, which includes increasing technical and business capability at the micro or firm level. [9.5.1.2]

Attitudes towards RE in addition to rationality are driven by emotions and psychological issues. To be successful, RE deployment and information and awareness efforts and strategies need to take this explicitly into account. [9.5.1.2]

To assess the economics of RE in the context of SD, social costs and benefits need to be explicitly considered. RE should be assessed against quantifiable criteria targeted at cost effectiveness, regional appropriateness, and environmental and distributional consequences. Grid size and technologies are key determinants of the *economic viability* of RE and of the competitiveness of RE compared to non-renewable energy. Appropriate RE technologies that are economically viable are often found to be available for expanding rural off-grid energy access, in particular smaller off-grid and mini-grid applications. [9.5.1.3]

In cases where deployment of RE is viable from an economic perspective, other economic and financial barriers may affect its deployment. High upfront costs of investments, including high installation and grid connection costs, are examples of frequently identified barriers to RE deployment. In developing countries, policy and entrepreneurial support systems are needed along with RE deployment to stimulate economic growth and SD and catalyze rural and peri-urban cash economies. Lack of adequate resource potential data directly affects uncertainty regarding resource availability, which may translate into higher risk premiums for investors and project developers. The internalization of environmental and social externalities frequently results in changes in the ranking of various energy sources and technologies, with important lessons for SD objectives and strategies. [9.5.1.3]

Strategies for SD at international, national and local levels as well as in private and nongovernmental spheres of society can help overcome barriers and create opportunities for RE deployment by integrating RE and SD policies and practices. [9.5.2]

Integrating RE policy into national and local SD strategies (explicitly recognized at the 2002 World Summit on Sustainable Development) provides a framework for countries to select effective SD and RE strategies and to align those with international policy measures. To that end, national strategies should include the removal of existing financial mechanisms that work against SD. For example, the removal of fossil fuel subsidies may have the potential to open up opportunities for more extensive use or even market entry of RE, but any subsidy reform towards the use of RE technologies needs to address the specific needs of the poor and demands a case-specific analysis. [9.5.2.1]

The CDM established under the Kyoto Protocol is a practical example of a mechanism for SD that internalizes environmental and social externalities. However, there are no international standards for

sustainability assessments (including comparable SD indicators) to counter weaknesses in the existing system regarding sustainability approval. As input to the negotiations for a post-2012 climate regime, many suggestions have been made about how to reform the CDM to better achieve new and improved mechanisms for SD. [9.5.2.1]

Opportunities for RE to play a role in national strategies for SD can be approached by integrating SD and RE goals into development policies and by development of sectoral strategies for RE that contribute to goals for green growth and low-carbon and sustainable development including leapfrogging. [9.5.2.1]

At the local level, SD initiatives by cities, local governments, and private and nongovernmental organizations can be drivers of change and contribute to overcome local resistance to RE installations. [9.5.2.2]

9.6 Synthesis, knowledge gaps and future research needs

RE can contribute to SD and the four goals assessed to varying degrees. While benefits with respect to reduced environmental and health impacts may appear more clear-cut, the exact contribution to, for example, social and economic development is more ambiguous. Also, countries may prioritize the four SD goals according to their level of development. To some extent, however, these SD goals are also strongly interlinked. Climate change mitigation constitutes in itself a necessary prerequisite for successful social and economic development in many developing countries. [9.6.6]

Following this logic, climate change mitigation can be assessed under the strong SD paradigm, if mitigation goals are imposed as constraints on future development pathways. If climate change mitigation is balanced against economic growth or other socioeconomic criteria, the problem is framed within the paradigm of weak SD allowing for trade-offs between these goals and using cost-benefit type analyses to provide guidance in their prioritization. [9.6.6]

However, the existence of uncertainty and ignorance as inherent components of any development pathway, as well as the existence of associated and possibly 'unacceptably high' opportunity costs, will make continued adjustments crucial. In the future, integrated models may be in a favourable position to better link the weak and strong SD paradigms for decision-making processes. Within well-defined guardrails, integrated models could explore scenarios for different mitigation pathways, taking account of the remaining SD goals by including important and relevant bottom-up indicators. According to model type, these alternative development pathways might be optimized for socially beneficial outcomes. Equally, however, the incorporation of GHG emission-related LCA data will be crucial for a clear definition of appropriate GHG concentration stabilization levels in the first place. [9.6.6]

In order to improve the knowledge regarding the interrelations between SD and RE and to find answers to the question of effective, economically efficient and socially acceptable transformations of the energy system, it is necessary to develop a closer integration of insights from social, natural and economic sciences (e.g., through risk analysis approaches), reflecting the different dimensions of sustainability (especially intertemporal, spatial, and intergenerational). So far, the knowledge base is often limited to very narrow views from specific branches of research, which do not fully account for the complexity of the issue. [9.7]

10. Mitigation Potential and Costs

10.1 Introduction

Future GHG emission estimates are highly dependent on the evolution of many variables, including, among others, economic growth, population growth, energy demand, energy resources and the future costs and performance of energy supply and end-use technologies. Mitigation and other non-mitigation policy structures in the future will also influence deployment of mitigation technologies and therefore GHG emissions and the ability to meet climate goals. Not only must all these different forces be considered simultaneously when exploring the role of RE in climate mitigation [see Figure 1.14], it is not possible to know today with any certainty how these different key forces might evolve decades into the future. [10.1]

Questions about the role that RE sources are likely to play in the future, and how they might contribute to GHG mitigation pathways, need to be explored within this broader context. Chapter 10 provides such an exploration through the review of 164 existing medium- to long-term scenarios from large-scale, integrated models. The comprehensive review explores the range of global RE deployment levels emerging in recent published scenarios and identifies many of the key forces that drive the variation among scenarios (note that the chapter relies exclusively on existing published scenarios and does not create any new scenarios). It does so both at the scale of RE as a whole and also in the context of individual RE technologies. The review highlights the importance of interactions and competition with other technologies as well as the evolution of energy demand more generally. [10.2]

This large-scale review is complemented with a more detailed discussion of future RE deployment, using 4 of the 164 scenarios as illustrative examples. The chosen scenarios span a range of different future expectations about RE characteristics, are based on different methodologies and cover different GHG concentration stabilization levels. This approach provides a next level of detail for exploring the role of RE in climate change mitigation, distinguishing between different applications (electricity generation, heating and cooling, transport) and regions. [10.3]

As the resulting role of RE is significantly determined by cost factors, a more general discussion about cost curves and cost aspects is then provided. This discussion starts with an assessment of the strengths and shortcomings of supply curves for RE and GHG mitigation, and then reviews the existing literature on regional RE supply curves, as well as abatement cost curves, as they pertain to mitigation using RE sources. [10.4]

Costs of RE commercialization and deployment are then addressed. The chapter reviews present RE technology costs, as well as expectations about how these costs might evolve into the future. To allow an assessment of future market volumes and investment needs, based on the results of the four illustrative scenarios investments in RE are discussed in particular with respect to what might be required if ambitious climate protection goals are to be achieved. [10.5]

Standard economic measures do not cover the full set of costs. Therefore, social and environmental costs and benefits of increased deployment of RE in relation to climate change mitigation and SD are synthesized and discussed. [10.6]

10.2 Synthesis of mitigation scenarios for different renewable energy strategies

An increasing number of integrated scenario analyses that are able to provide relevant insights into the potential contribution of RE to future energy supplies and climate change mitigation has become available. To provide a broad context for understanding the role of RE in mitigation and the influence of RE on the costs of mitigation, 164 recent medium- to long-term scenarios from 16 global energy-economic and integrated assessment models were reviewed. The scenarios were collected through an open call. The scenarios cover a large range of CO_2 concentrations (350 to 1,050 ppm atmospheric CO_2 concentration by 2100), representing both mitigation and baseline scenarios. [10.2.2.1]

Although these scenarios represent some of the most recent and sophisticated thinking regarding climate mitigation and the role of RE in climate mitigation in the medium- to long-term, they, as with any analysis looking decades into the future, must be interpreted carefully. All of the scenarios were developed using quantitative modelling, but there is enormous variation in the detail and structure of the models used to construct the scenarios. In addition, the scenarios do not represent a random sample of possible scenarios that could be used for formal uncertainty analysis. Some modelling groups provided more scenarios than others. In scenario ensemble analyses based on collecting scenarios from different studies, such as the review here, there is an inevitable tension between the fact that the scenarios are not truly a random sample and the sense that the variation in the scenarios does still provide real and often clear insights into our knowledge about the future, or lack thereof. [10.2.1.2, 10.2.2.1]

A fundamental question relating to the role of RE in climate mitigation is how closely RE deployment levels are correlated with long-term atmospheric CO_2 concentration or related climate goals. The scenarios indicate that although there is a strong correlation between fossil and industrial CO_2 emissions pathways and long-term CO_2 concentration goals across the scenarios, the relationship between RE deployment and CO_2 concentration goals is far less robust (Figure TS.10.1). RE deployment generally increases with the stringency of the CO_2 concentration goal, but there is enormous variation among RE deployment levels for any given CO_2 concentration goal. For example, in scenarios that stabilize the atmospheric CO_2 concentration at a level of less than 440 ppm (Categories I and II), the median RE deployment levels are 139 EJ/yr in 2030 and 248 EJ/yr in 2050, with the highest levels reaching 252 EJ/yr in 2030 and up to 428 EJ/yr in 2050. These levels are considerably higher than the corresponding RE deployment levels in baseline scenarios, although it has to be acknowledged that the range of RE deployment in each of the CO_2 stabilization categories is wide. [10.2.2.2]

At the same time, it is also important to note that despite the variation, the absolute magnitudes of RE deployment are dramatically higher than those of today in the vast majority of the scenarios. In 2008, global renewable primary energy supply in direct equivalent stood at roughly 64 EJ/yr. The majority of this, about 30 EJ/yr, was traditional biomass. In contrast, by 2030, many scenarios indicate a doubling of RE deployment or more compared to today, and this is accompanied in most scenarios by a reduction in traditional biomass, implying substantial growth in non-traditional RE sources. By 2050, RE deployment levels in most scenarios are higher than 100 EJ/yr (median at 173 EJ/yr), reach 200 EJ/yr in many of the scenarios and more than 400 EJ/yr in some cases. Given that traditional biomass use decreases in most scenarios, the scenarios represent an increase in RE production (excluding traditional biomass) of anywhere from roughly three- to more than ten-fold. More than half of the scenarios show a contribution of RE in excess of a 17% share of primary energy supply in 2030, rising to more than 27% in 2050. The scenarios with the highest RE shares reach approximately 43% in 2030 and 77% in 2050. Deployments after 2050 are even larger. This is an extraordinary expansion in energy production from RE. [10.2.2.2]

Indeed, RE deployment is quite large in many of the baseline scenarios with no assumed GHG concentration stabilization level. By 2030, RE deployment levels of up to about 120 EJ/yr are projected, with many baseline scenarios reaching more than 100 EJ/yr in 2050 and in some cases up to 250 EJ/yr. These large RE baseline deployments result from a range of underlying scenario assumptions, for example, the assumption that energy consumption will continue to grow substantially throughout the century, assumptions about the ability of RE to contribute to increased energy access, assumptions about the availability of fossil resources, and other assumptions (e.g., improved costs and performance of RE technologies) that would render RE technologies economically increasingly competitive in many applications even absent climate policy. [10.2.2.2]

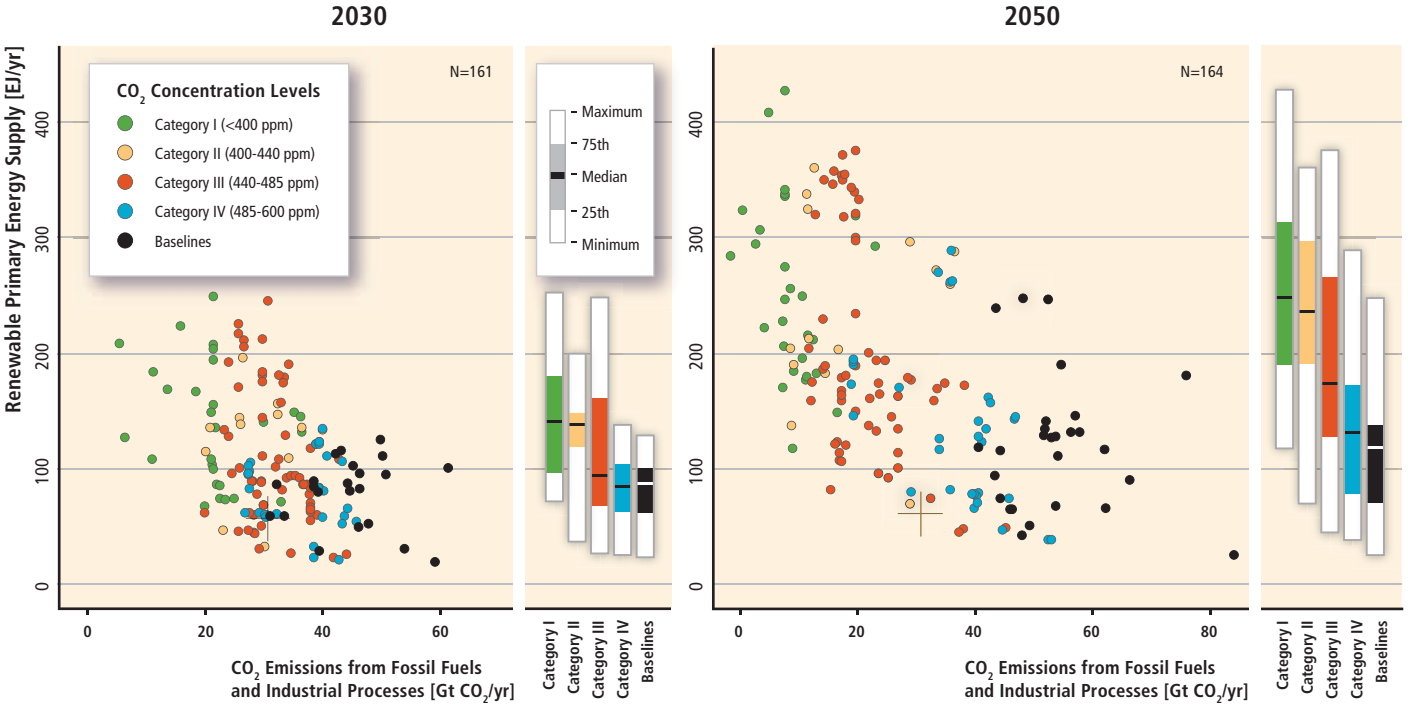


Figure TS.10.1 | Global RE primary energy supply (direct equivalent) from 164 long-term scenarios as a function of fossil and industrial CO_2 emissions in 2030 and 2050. Colour coding is based on categories of atmospheric CO_2 concentration level in 2100. The panels to the right of the scatterplots show the deployment levels of RE in each of the atmospheric CO_2 concentration categories. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. The blue crossed-lines show the relationship in 2007. Pearson's correlation coefficients for the two data sets are -0.40 (2030) and -0.55 (2050). For data reporting reasons, only 161 scenarios are included in the 2030 results shown here, as opposed to the full set of 164 scenarios. RE deployment levels below those of today are a result both of model output as well as differences in the reporting of traditional biomass. [Figure 10.2]

The uncertainty in RE's role in climate mitigation results from uncertainty regarding a number of important forces that influence the deployment of RE. Two important factors are energy demand growth and the competition with other options to reduce CO_2 emissions (primarily nuclear energy and fossil energy with CCS). Meeting long-term climate goals requires a reduction in the CO_2 emissions from energy and other anthropogenic sources. For any given climate goal, this reduction is relatively well defined; there is a tight relationship between fossil and industrial CO_2 emissions and the deployment of freely emitting fossil energy across the scenarios (Figure TS.10.2). The demand for low-carbon energy (including RE, nuclear energy and fossil energy with CCS) is simply the difference between total primary energy demand and the production of freely-emitting fossil energy; that is, whatever energy cannot be supplied by freely-emitting fossil energy because of climate constraints must be supplied either by low-carbon energy or by measures that reduce energy consumption. However, scenarios indicate enormous uncertainty about energy demand growth, particularly many decades into the future. This variation is generally much larger than the effect of mitigation on energy consumption. Hence, there is substantial variability in low-carbon energy for any given CO_2 concentration goal due to variability in energy demand (Figure TS.10.2). [10.2.2.3]

The competition between RE, nuclear energy, and fossil energy with CCS then adds another layer of variability in the relationship between RE deployment and the CO_2 concentration goal. The cost, performance and availability of the competing supply side options—nuclear energy and fossil energy with CCS—is also uncertain. If the option to deploy these other supply-side mitigation technologies is constrained—because of cost and performance, but also potentially due to environmental, social or national security barriers—then, all things being equal, RE deployment levels will be higher (Figure TS.10.3). [10.2.2.4]

There is also great variation in the deployment characteristics of individual RE technologies. The absolute scales of deployments vary considerably among technologies and also deployment magnitudes are characterized by greater variation for some technologies relative to others (Figures TS.10.4 and TS.10.5). Further, the time scale of deployment varies across different RE sources, in large part representing differences in deployment levels today and (often) associated assumptions about relative technological maturity. [10.2.2.5]

The scenarios generally indicate that RE deployment is larger in non-Annex I countries over time than in the Annex I countries. Virtually all scenarios include the assumption that economic and energy demand growth will be larger at some point in the future in the non-Annex I countries than in the Annex I countries. The result is that the non-Annex I countries account for an increasingly large proportion of CO_2 emissions in baseline, or no-policy, cases and must therefore make larger emissions reductions over time (Figure TS.10.4). [10.2.2.5]

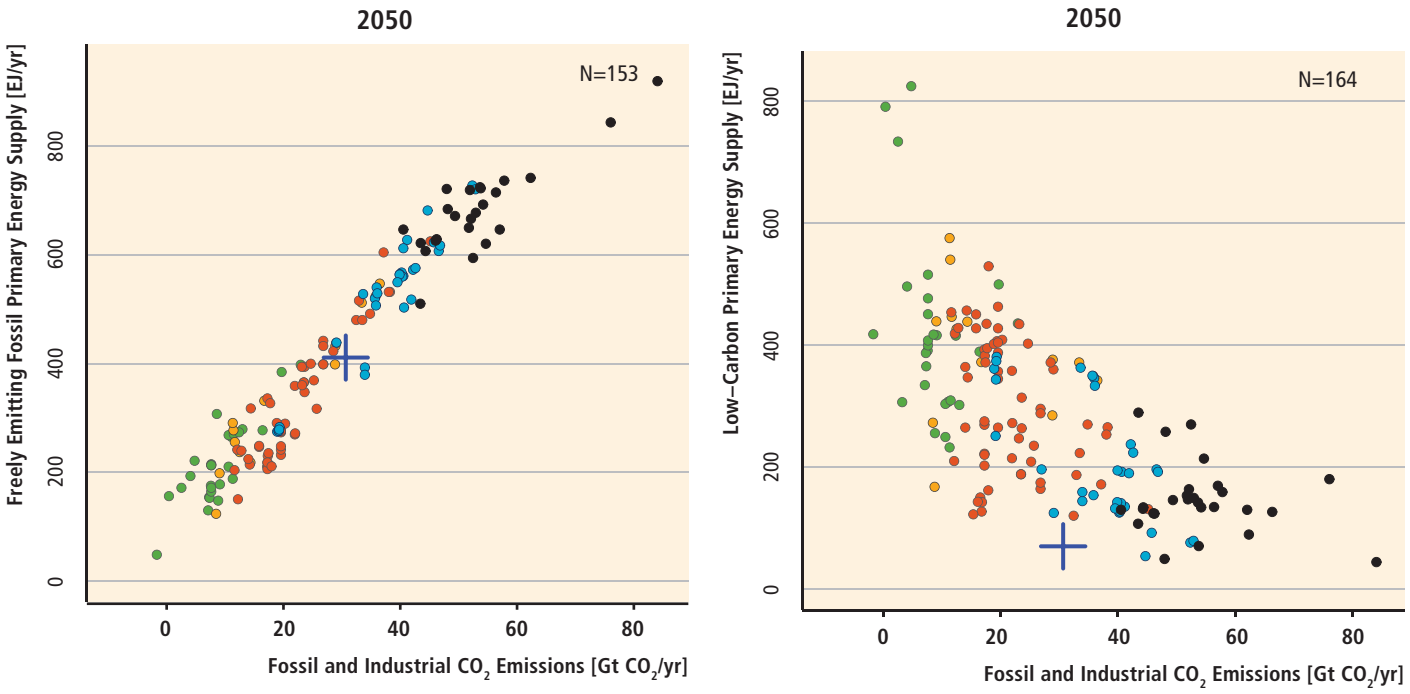


Figure TS.10.2 | Global freely emitting fossil fuel (left panel; direct equivalent) and low-carbon primary energy supply (right panel; direct equivalent) in 164 long-term scenarios in 2050 as a function of fossil and industrial CO_2 emissions. Low-carbon energy refers to energy from RE, fossil energy with CCS, and nuclear energy. Colour coding is based on categories of atmospheric CO_2 concentration level in 2100. The blue crossed lines show the relationship in 2007. Pearson's correlation coefficients for the two data sets are 0.97 (freely emitting fossil) and -0.68 (low-carbon energy). For data reporting reasons, only 153 scenarios and 161 scenarios are included in the freely-emitting fossil and low-carbon primary energy results shown here, respectively, as opposed to the full set of 164 scenarios. [Figure 10.4, right panel, Figure 10.5, right panel]

Another fundamental question regarding RE and mitigation is the relationship between RE and mitigation costs. A number of studies have pursued scenario sensitivities that assume constraints on the deployment of individual mitigation options, including RE as well as nuclear energy and fossil energy with CCS (Figures TS.10.6 and TS.10.7). These studies indicate that mitigation costs are higher when options, including RE, are not available. Indeed, the cost penalty for limits on RE is often at least of the same order of magnitude as the cost penalty for limits on nuclear energy and fossil energy with CCS. The studies also indicate that more aggressive concentration goals may not be possible when RE options, or other low-carbon options, are not available. At the same time, when taking into account the wide range of assumptions across the full range of scenarios explored in this assessment, the scenarios demonstrate no meaningful link between measures of cost (e.g., carbon prices) and absolute RE deployment levels. This variation is a reflection of the fact that large-scale integrated models used to generate scenarios are characterized by a wide range of carbon prices and mitigation costs based on both parameter assumptions and model structure. To summarize, while there is an agreement in the literature that mitigation costs will increase if the deployment of RE technologies is constrained and that more ambitious concentration stabilization levels may not be reachable, there is little agreement on the precise magnitude of the cost increase. [10.2.2.6]

10.3 Assessment of representative mitigation scenarios for different renewable energy strategies

An in-depth analysis of 4 selected illustrative scenarios from the larger set of 164 scenarios allowed a more detailed look at the possible contribution of specific RE technologies in different regions and sectors. The IEA's World Energy Outlook (IEA WEO 2009) was selected as an example of a baseline scenario, while the other scenarios set clear GHG concentration stabilization levels. The chosen mitigation scenarios are ReMIND-RECIPE from the Potsdam Institute, MiniCAM EMF 22 from the Energy Modelling Forum Study 22 and the Energy [R] evolution scenario from the German Aerospace Centre, Greenpeace International and EREC (ER 2010). The scenarios work as illustrative examples, but they are not representative in a strict sense. However they represent four different future paths based on different methodologies and a wide range of underlying assumptions. Particularly, they stand for different RE deployment paths reaching from a typical

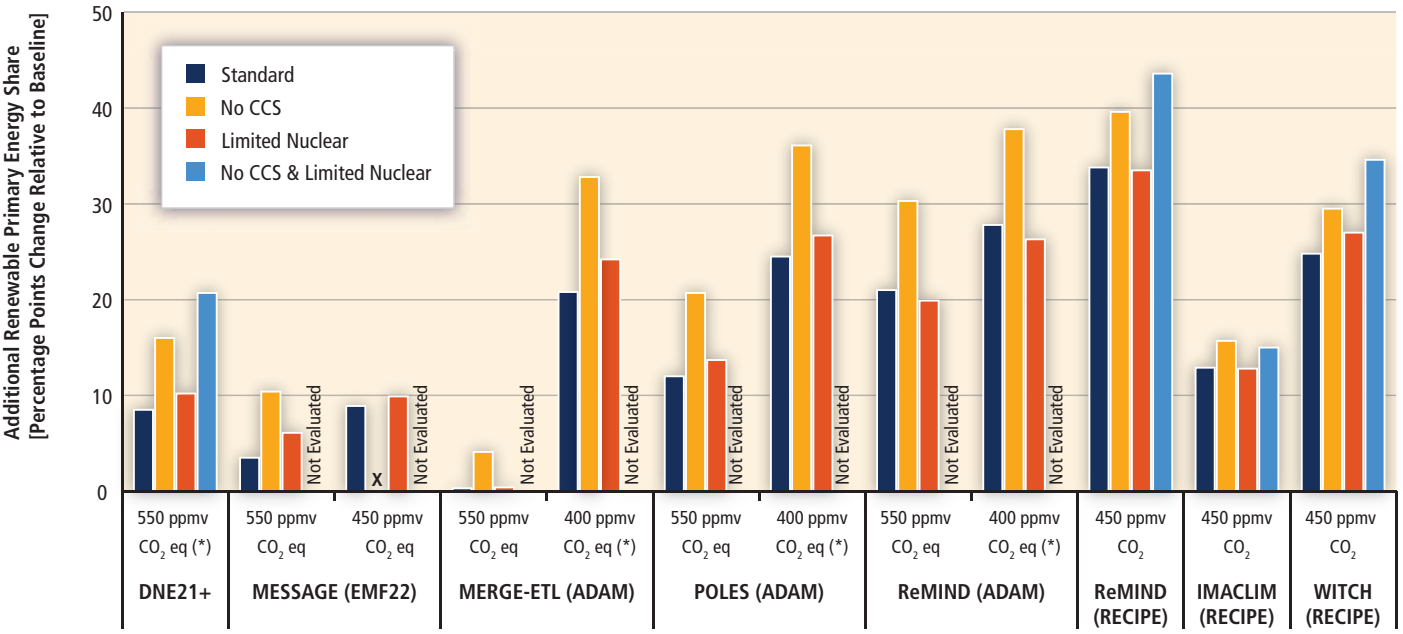


Figure TS.10.3 | Increase in global renewable primary energy share (direct equivalent) in 2050 in selected constrained technology scenarios compared to the respective baseline scenarios. The 'X' indicates that the respective concentration level for the scenario was not achieved. The definition of 'lim Nuclear' and 'no CCS' cases varies across models. The DNE21+, MERGE-ETL and POLES scenarios represent nuclear phase-outs at different speeds; the MESSAGE scenarios limit the deployment to 2010; and the ReMIND, IMACLIM and WITCH scenarios limit nuclear energy to the contribution in the respective baseline scenarios, which can still imply a significant expansion compared to current deployment levels. The REMIND (ADAM) 400 ppmv no CCS scenario refers to a scenario in which cumulative CO_2 storage is constrained to 120 Gt CO_2. The MERGE-ETL 400 ppmv no CCS case allows cumulative CO_2 storage of about 720 Gt CO_2. The POLES 400 ppmv CO_2eq no CCS scenario was infeasible and therefore the respective concentration level of the scenario shown here was relaxed by approximately 50 ppm CO_2. The DNE21+ scenario is approximated at 550 ppmv CO_2eq based on the emissions pathway through 2050. [Figure 10.6]

baseline perspective to a scenario that follows an optimistic application path for RE assuming that amongst others driven by specific policies the current high dynamic (increase rates) in the sector can be maintained. [10.3.1]

Figure TS.10.8 provides an overview of the resulting primary energy production by source for the four selected scenarios for 2020, 2030 and 2050 and compares the numbers with the range of the global primary energy supply. Using the direct equivalent methodology as done here, in 2050 bioenergy has the highest market share in all selected scenarios, followed by solar energy. The total RE share in the primary energy mix by 2050 has a substantial variation across all four scenarios. With 15% by 2050—more or less about today's level (12.9% in 2008)—the IEA WEO 2009 projects the lowest primary RE share, while the ER 2010 with 77% marks the upper level. The MiniCam EMF 22 expects that 31% and ReMIND-RECIPE that 48% of the world's primary energy demand will be provided by RE in 2050. The wide ranges of RE shares are a function of different assumptions for technology cost and performance data, availability of other mitigation technologies (e.g., CCS, nuclear power), infrastructure or integration constraints, non-economic barriers (e.g., sustainability aspects), specific policies and future energy demand projections. [10.3.1.4]

In addition, although deployment of the different technologies significantly increases over time, the resulting contribution of RE in the scenarios for most technologies in the different regions of the world is much lower than their corresponding technical potentials (Figure TS.10.9). The overall total global RE deployment by 2050 in all analyzed scenarios represents less than 3% of the available technical RE potential. On a regional level, the maximum deployment share out of the overall technical potential for RE in 2050 was found for China, with a total of 18% (ER 2010), followed by OECD Europe with 15% (ER 2010) and India with 13% (MiniCam EMF 22). Two regions have deployment rates of around 6% of the regional available technical RE potential by 2050: 7% in Developing Asia (MiniCam EMF 22) and 6% in OECD North America (ER 2010). The remaining five regions use less than 5% of the available technical potential for RE. [10.3.2.1]

Based on the resulting RE deployment for the selected four illustrative scenarios, the corresponding GHG mitigation potential has been calculated. For each sector, emission factors have been specified, addressing the kind of electricity generation or heat supply that RE displaces. As the substituted energy form depends on the overall system behaviour, this cannot be done exactly without conducting new and consistent scenario analysis or complex power plant dispatching analysis. Therefore, the calculation is necessarily based on simplified assumptions and can only be seen as indicative. Generally, attribution of precise mitigation potentials to RE should be viewed with caution. [10.3.3]

Very often RE applications are supposed to fully substitute for the existing mix of fossil fuel use, but in reality that may not be true as RE can compete, for instance, with nuclear energy or within the RE portfolio itself. To cover the uncertainties even partly for the specification of the emission factor, three different cases have been distinguished

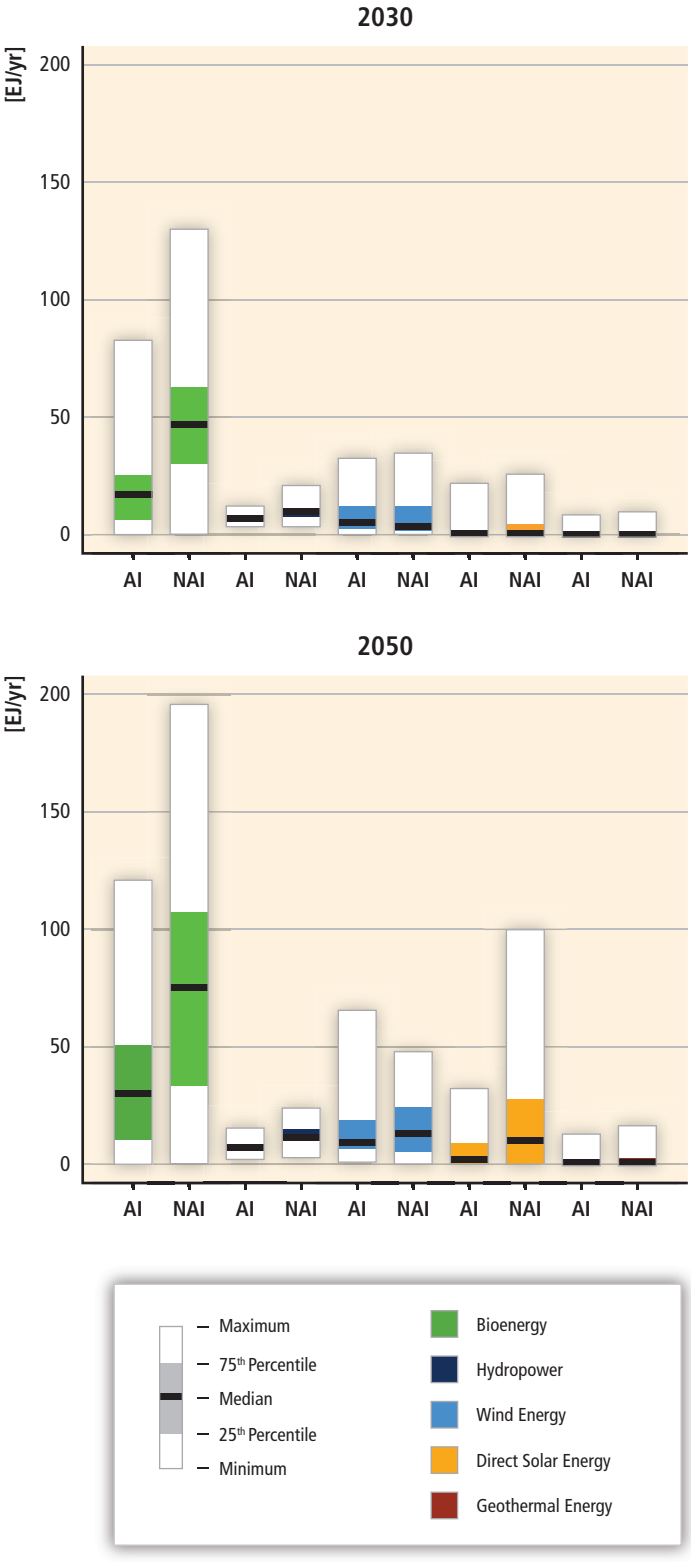


Figure TS.10.4 | Global RE primary energy supply (direct equivalent) by source in Annex I (AI) and Non-Annex I (NAI) countries in 164 long-term scenarios by 2030 and 2050. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. Depending on the source, the number of scenarios underlying these figures varies between 122 and 164. Although instructive for interpreting the information, it is important to note that the 164 scenarios are not explicitly a random sample meant for formal statistical analysis. (One reason that bioenergy supply appears larger than supplies from other sources is that the direct equivalent method is used to represent primary energy in this figure. Bioenergy is accounted for prior to conversion to fuels such as ethanol or electricity. The other technologies produce primarily (but not entirely) electricity, and they are accounted for based on the electricity produced. If primary equivalents were used, based on the substitution method, rather than direct equivalents, then energy production from non-biomass RE would be of the order of three times larger than shown here.) Ocean energy is not presented here as only very few scenarios consider this RE technology. [Figure 10.8]

(upper case: specific average CO_2 emissions of the fossil generation mix under the baseline scenario; medium case: specific average CO_2 emissions of the overall generation mix under the baseline scenario; and lower case: specific average CO_2 emissions of the generation mix of the particular analyzed scenario). Biofuels and other RE options for transport are excluded from the calculation due to limited data availability.

Additionally, to reflect the embedded GHG emissions from bioenergy used for direct heating, only half of the theoretical CO_2 savings have been considered in the calculation. Given the high uncertainties and variability of embedded GHG emissions, this is necessarily once more a simplified assumption. [10.3.3]

Figure TS.10.10 shows cumulative CO_2 reduction potentials from RE sources up to 2020, 2030 and 2050 resulting from the four scenarios reviewed here in detail. The analyzed scenarios outline a cumulative reduction potential (2010 to 2050) in the medium-case approach of between 244 Gt CO_2 (IEA WEO 2009) under the baseline conditions, 297 Gt CO_2 (MiniCam EMF 22), 482 Gt CO_2 (ER 2010) and 490 Gt CO_2 (ReMIND-RECIPE scenario). The full range across all calculated cases and scenarios is cumulative CO_2 savings of 218 Gt CO_2 (IEA WEO 2009) to 561 Gt CO_2 (ReMIND-RECIPE) compared to about 1,530 Gt CO_2 cumulative fossil and industrial CO_2 emissions in the WEO 2009 Reference scenario during the same period. However, these numbers exclude CO_2 savings for RE use in the transport sector (including biofuels and electric vehicles). The overall CO_2 mitigation potential can therefore be higher. [10.3.3]

10.4 Regional cost curves for mitigation with renewable energy sources

The concept of supply curves of carbon abatement, energy, or conserved energy all rest on the same foundation. They are curves consisting typically of discrete steps, each step relating the marginal cost of the abatement measure/energy generation technology or measure to conserve energy to its potential; these steps are ranked according to their cost. Graphically, the steps start at the lowest cost on the left with the next highest cost added to the right and so on, making an upward sloping left-to-right marginal cost curve. As a result, a curve is obtained that can be interpreted similarly to the concept of supply curves in traditional economics. [10.4.2.1]

The concept of energy conservation supply curves is often used, but it has common and specific limitations. The most often cited limitations in

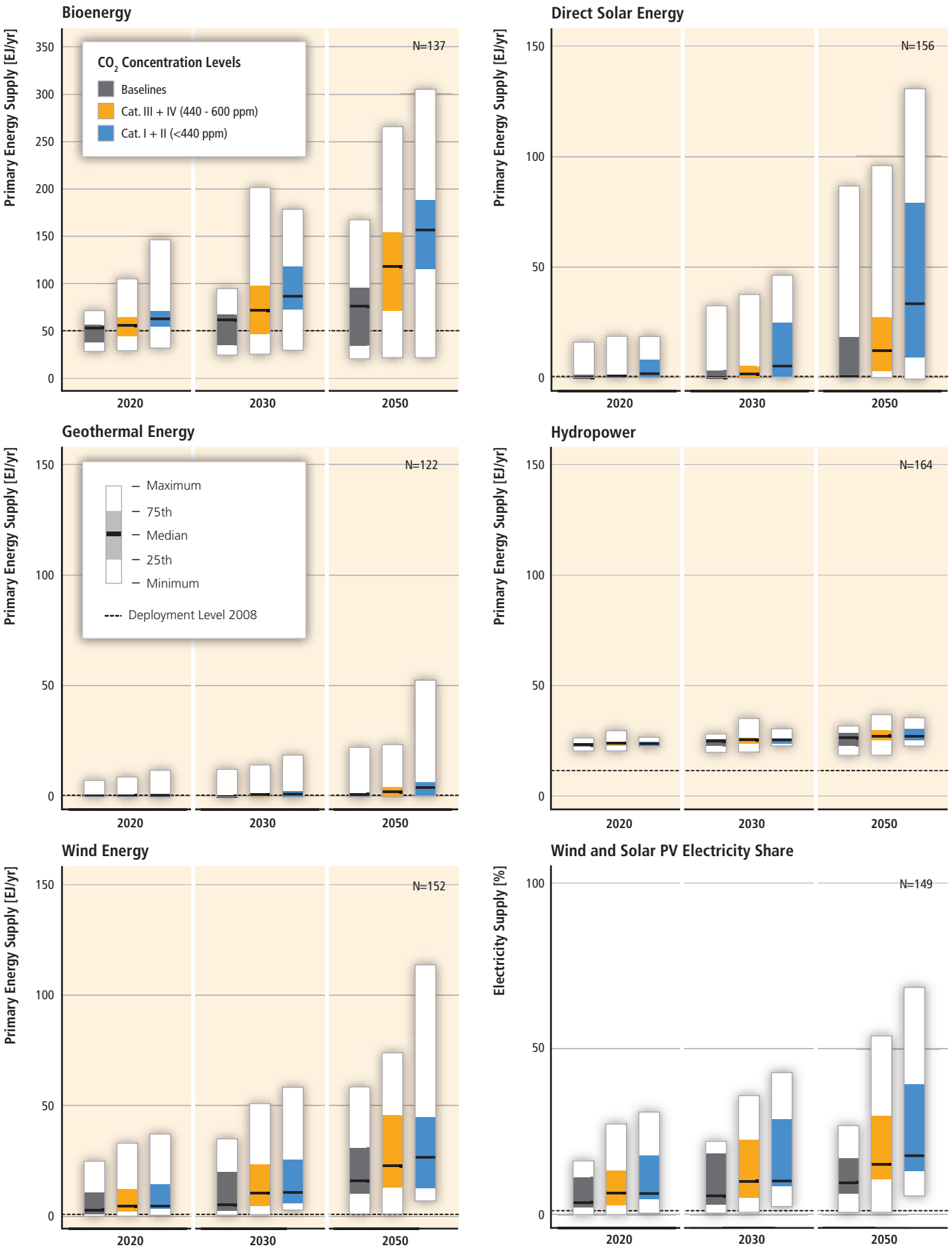

Bioenergy
Primary Energy Supply [EJ/yr]
N=137
CO_2 Concentration Levels
Baselines
Cat. III + IV (440 - 600 ppm)
Cat. I + II (<440 ppm)
Direct Solar Energy
N=156
Geothermal Energy
N=122
Maximum
75th
Median
25th
Minimum
Deployment Level 2008
Hydropower
N=164
Wind Energy
N=152
Wind and Solar PV Electricity Share
Electricity Supply [%]
N=149
2020
2030
2050

Figure TS.10.5 | (Preceding page) Global primary energy supply (direct equivalent) of biomass, wind, solar, hydro, and geothermal energy in 164 long-term scenarios in 2020, 2030 and 2050, and grouped by different categories of atmospheric CO_2 concentration level in 2100. The thick black line corresponds to the median, the coloured box corresponds to the inter-quartile range (25th to 75th percentile) and the ends of the white surrounding bars correspond to the total range across all reviewed scenarios. [Figure 10.9]

Notes: For data reporting reasons, the number of scenarios included in each of the panels shown here varies considerably. The number of scenarios underlying the individual panels, as opposed to the full set of 164 scenarios, is indicated in the right upper corner of each panel. One reason that bioenergy supply appears larger than supplies from other sources is that the direct equivalent method is used to represent primary energy in this figure. Bioenergy is accounted for prior to conversion to fuels such as biofuels, electricity and heat. The other technologies produce primarily (but not entirely) electricity and heat, and they are accounted for based on this secondary energy produced. If primary equivalents based on the substitution method were used rather than direct equivalent accounting, then energy production from non-biomass RE would be of the order of two to three times larger than shown here. Ocean energy is not presented here as scenarios so far seldom consider this RE technology. Finally, categories V and above are not included and Category IV is extended to 600 ppm from 570 ppm, because all stabilization scenarios lie below 600 ppm CO_2 in 2100, and because the lowest baselines scenarios reach concentration levels of slightly more than 600 ppm by 2100.

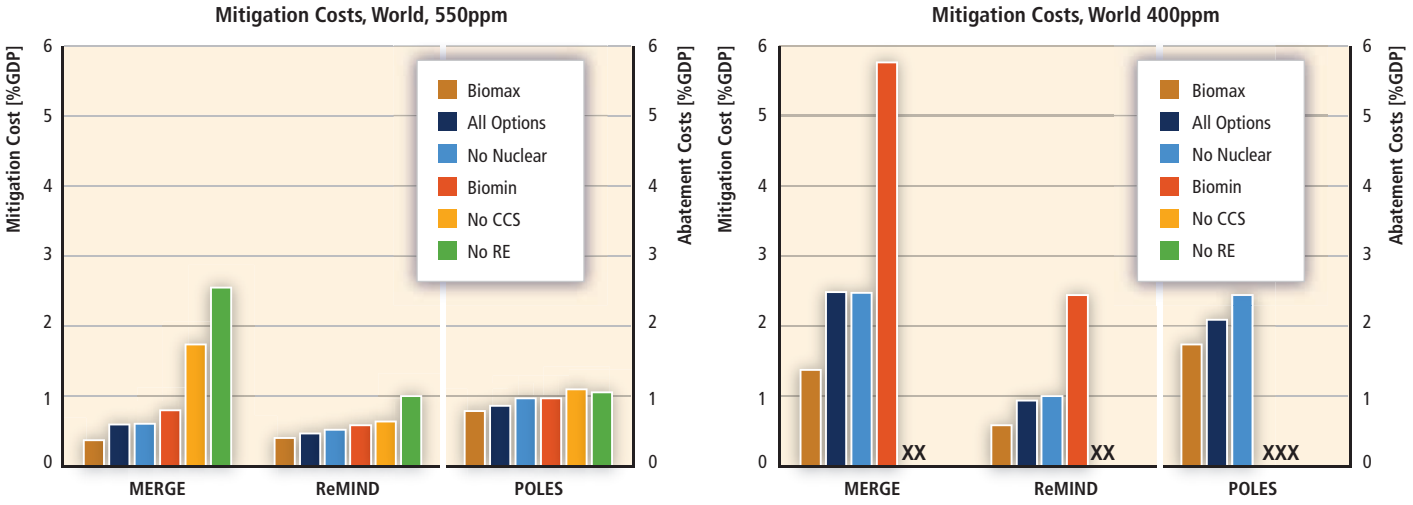


Figure TS.10.6 | Global mitigation costs (measured in terms of consumption loss) from the ADAM project under varying assumptions regarding technology availability for long-term stabilization levels of 550 and 400 ppmv CO_2eq. 'All options' refers to the standard technology portfolio assumptions in the different models, while 'biomax' and 'biomin' assume double and half the standard biomass potential of 200 EJ respectively. 'noccs' excludes CCS from the mitigation portfolio and 'nonuke' and 'norenew' constrain the deployment levels of nuclear and RE to the baseline level, which still potentially means a considerable expansion compared to today. The 'X' in the right panel indicates non-attainability of the 400 ppmv CO_2eq level in the case of limited technology options. [Figure 10.11]

this context are: controversy among scientists about potentials at negative costs; simplification of reality as actors also base their decisions on other criteria than those reflected in the curves; economic and technological uncertainty inherent to predicting the future, including energy price developments and discount rates; further uncertainty due to strong aggregation; high sensitivity relative to baseline assumptions and the entire future generation and transmission portfolio; consideration of individual measures separately, ignoring interdependencies between measures applied together or in different order; and, for carbon abatement curves, high sensitivity to (uncertain) emission factor assumptions. [10.4.2.1]

Having these criticisms in mind, it is also worth noting that it is very difficult to compare data and findings from RE abatement cost and supply curves, as very few studies have used a comprehensive and consistent approach that details their methodologies. Many of the regional and country studies provide less than 10% abatement of the baseline CO_2 emissions over the medium term at abatement costs under approximately USD_{2005} 100/t CO_2. The resulting low-cost abatement potentials are quite low compared to the reported mitigation potentials of many of the scenarios reviewed here. [10.4.3.2]

10.5 Cost of commercialization and deployment

Some RE technologies are broadly competitive with current market energy prices. Many of the other RE technologies can provide competitive energy services in certain circumstances, for example, in regions with favourable resource conditions or that lack the infrastructure for other low-cost energy supplies. In most regions of the world, however, policy measures are still required to ensure rapid deployment of many RE sources. [2.7, 3.8, 4.6, 5.8, 6.7, 7.8, 10.5.1, Figure TS.1.9]

Figures TS.10.11 and TS.10.12 provide additional data on levelized costs of energy (LCOE), also called levelized unit costs or levelized generation costs, for selected renewable power technologies and for renewable heating technologies, respectively. Figure TS.10.13 shows the levelized

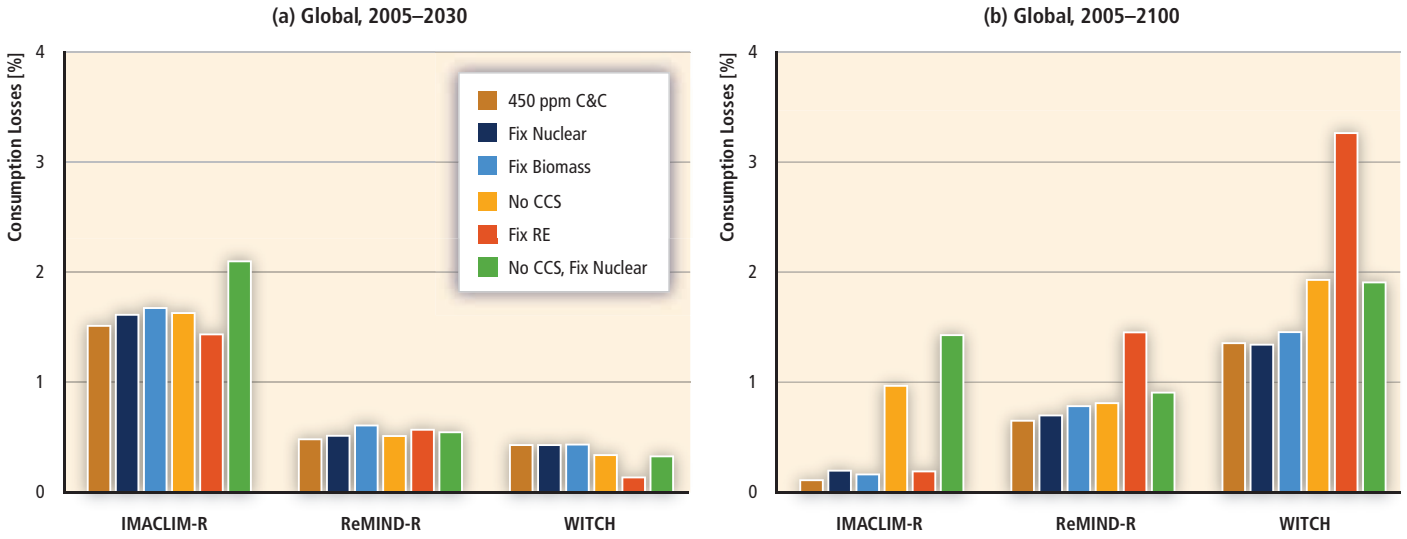


Figure TS.10.7 | Mitigation costs from the RECIPE project under varying assumptions regarding technology availability for a long-term stabilization level of 450 ppmv CO_2. Option values of technologies in terms of consumption losses for scenarios in which the option indicated is foregone (CCS) or limited to baseline levels (all other technologies) for the periods a) 2005 to 2030 and b) 2005 to 2100. Option values are calculated as differences in consumption losses for a scenario in which the use of certain technologies is limited with respect to the baseline scenario. Note that for WITCH, the generic backstop technology was assumed to be unavailable in the 'fix RE' scenario. [Figure 10.12]

cost of transport fuels (LCOF). LCOEs capture the full costs (i.e., investment costs, O&M costs, fuel costs and decommissioning costs) of an energy conversion installation and allocate these costs over the energy output during its lifetime, although not taking into account subsidies or policy incentives. As some RE technologies (e.g., PV, CSP and wind energy) are characterized by high shares of investment costs relative to variable costs, the applied discount rate has a prominent influence on the LCOE of these technologies (see Figures TS.10.11, TS.10.12 and TS.10.13). [10.5.1] The LCOEs are based on literature reviews and represent the most current cost data available. The respective ranges are rather broad as the levelized cost of identical technologies can vary across the globe depending on the RE resource base and local costs of investment, financing and O&M. Comparison between different technologies should not be based solely on the cost data provided in Figures TS 1.9,

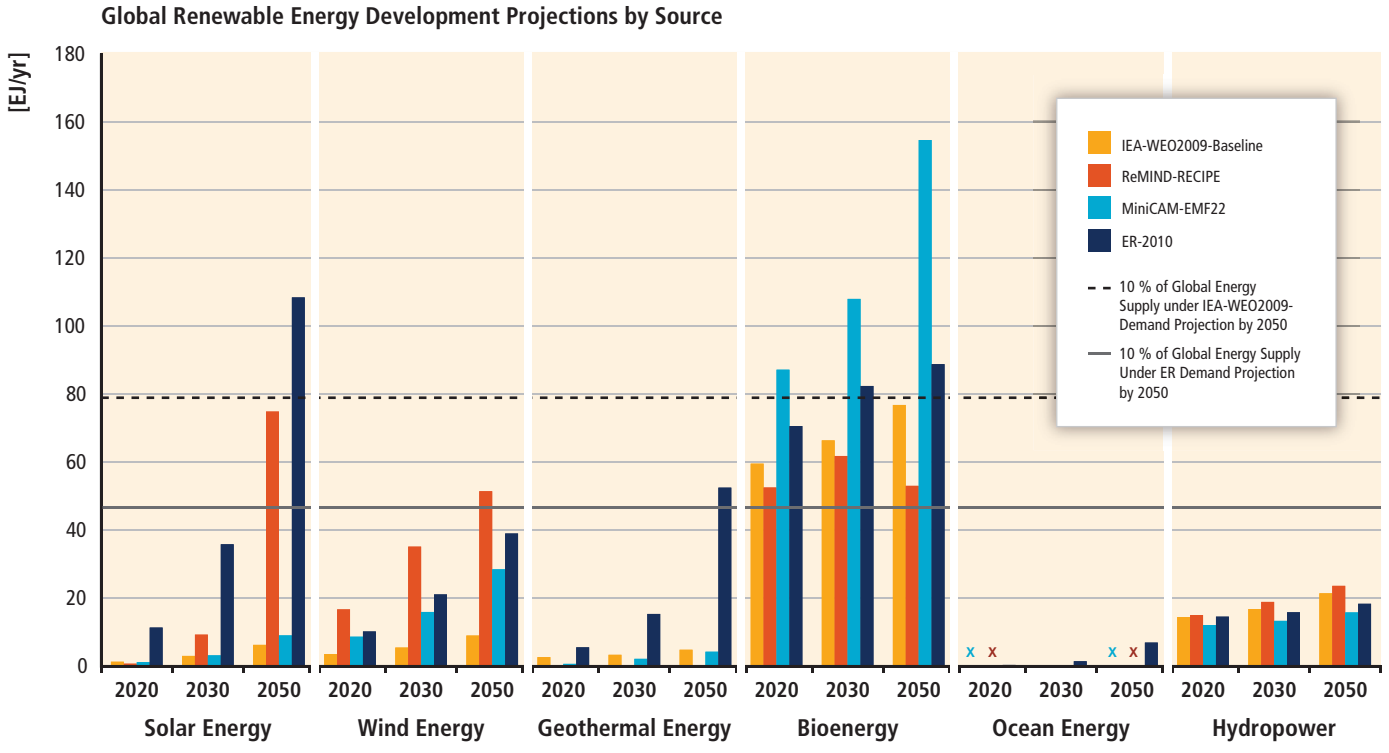
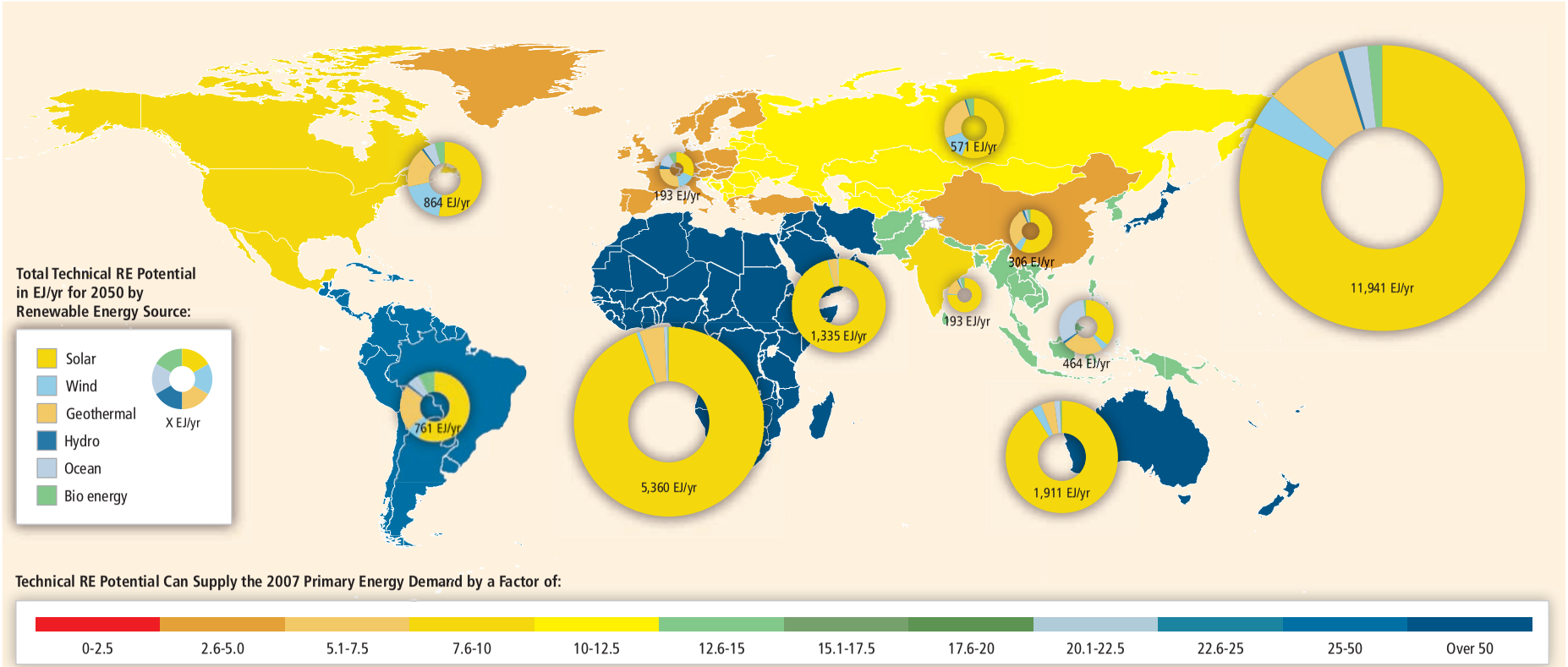


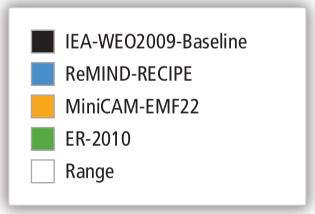
Figure TS.10.8 | Global RE development projections by source and global primary RE shares by source for a set of four illustrative scenarios. [Figure 10.14]

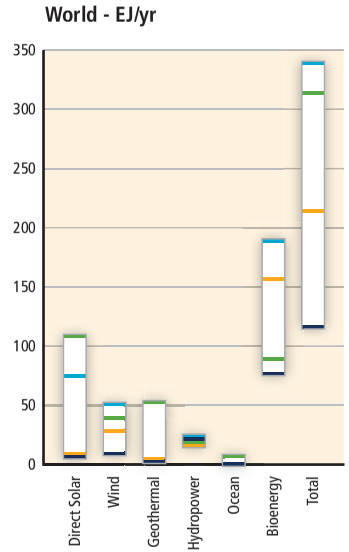


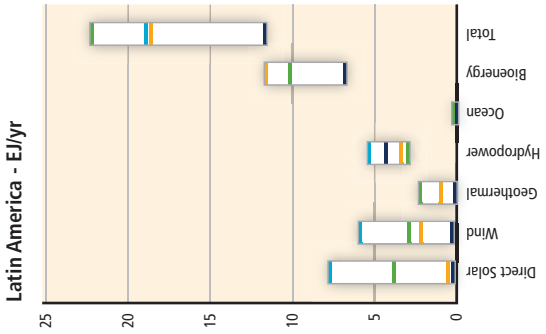
RE potential analysis: Technical RE potentials reported here represent total worldwide and regional potentials based on a review of studies published before 2009 by Krewitt et al. (2009). They do not deduct any potential that is already being utilized for energy production. Due to methodological differences and accounting methods among studies, strict comparability of these estimates across technologies and regions, as well as to primary energy demand, is not possible. Technical RE potential analyses published after 2009 show higher results in some cases but are not included in this figure. However, some RE technologies may compete for land which could lower the overall RE potential.

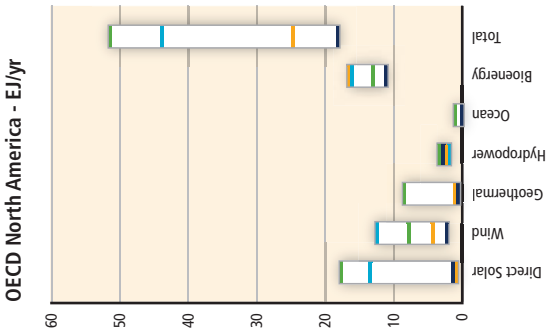
Scenario data: IEA WEO 2009 Reference Scenario (International Energy Agency (IEA), 2009; Teske et al., 2010), ReMIND-RECIPE 450ppm Stabilization Scenario (Luderer et al., 2009), MiniCAM EMF22 1st-best 2.6 W/2 Overshoot Scenario (Calvin et al., 2009), Advanced Energy
[R]evolution 2010 (Teske et al., 2010)

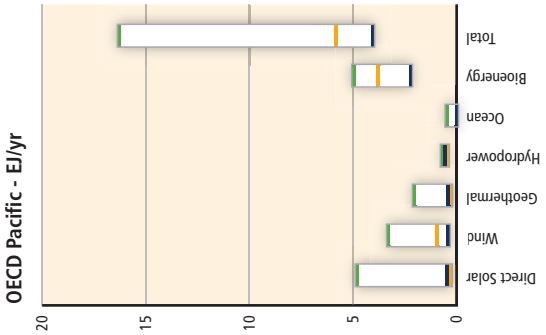
Range graphs: Level of RE Deployment in 2050 by Scenario and Renewable Energy, in EJ/yr:

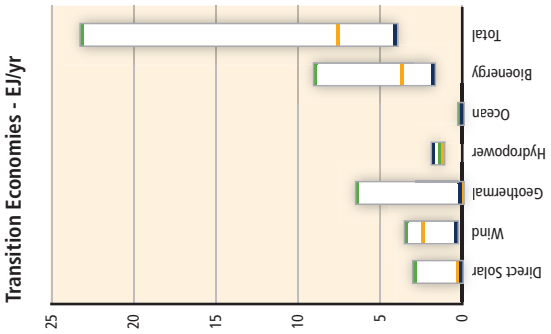


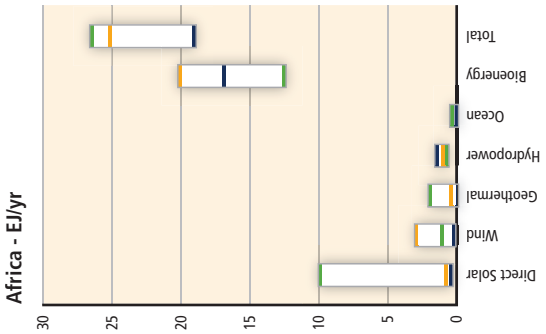


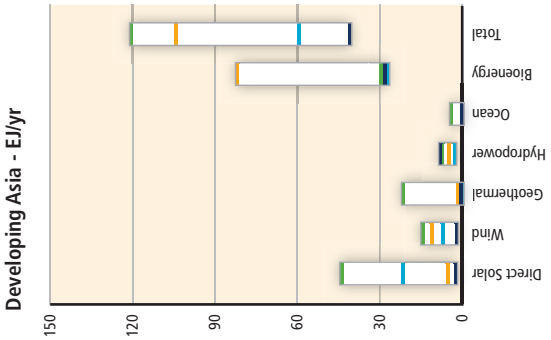

Latin America - EJ/yr
0
5
10
15
20
25
Direct Solar
Wind
Geothermal
Hydropower
Ocean
Bioenergy
Total

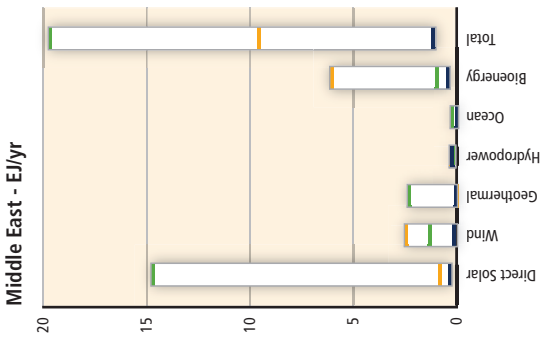

OECD North America - EJ/yr
0
10
20
30
40
50
60
Direct Solar
Wind
Geothermal
Hydropower
Ocean
Bioenergy
Total


OECD Pacific - EJ/yr
0
5
10
15
20
Direct Solar
Wind
Geothermal
Hydropower
Ocean
Bioenergy
Total


Transition Economies - EJ/yr
0
5
10
15
20
25
Direct Solar
Wind
Geothermal
Hydropower
Ocean
Bioenergy
Total


Africa - EJ/yr
0
5
10
15
20
25
30
Direct Solar
Wind
Geothermal
Hydropower
Ocean
Bioenergy
Total


Developing Asia - EJ/yr
0
30
60
90
120
150
Direct Solar
Wind
Geothermal
Hydropower
Ocean
Bioenergy
Total


Middle East - EJ/yr
0
5
10
15
20
Direct Solar
Wind
Geothermal
Hydropower
Ocean
Bioenergy
Total

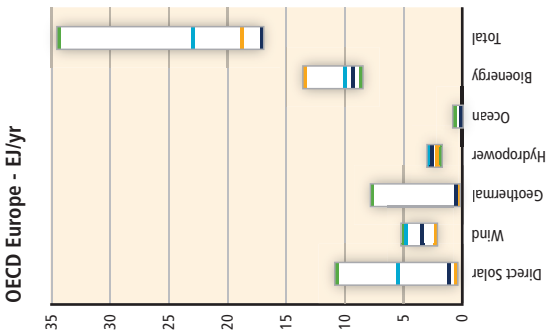

OECD Europe - EJ/yr
0
5
10
15
20
25
30
35
Direct Solar
Wind
Geothermal
Hydropower
Ocean
Bioenergy
Total

Figure TS.10.9 | (Preceding pages) Regional breakdown of RE deployment in 2050 for an illustrative set of four scenarios and comparison of the potential deployment to the corresponding technical potential for different technologies. The selected four illustrative scenarios are a part of the comprehensive survey of 164 scenarios. They represent a span from a reference scenario (IEA WEO 2009) without specific GHG concentration stabilization levels to three scenarios representing different CO_2 concentration categories, one of them (REMind-RECIPE) Category III (440 to 485 ppm) and two of them (MiniCam EMF 22 and ER 2010 Category I (<400 ppm). Of the latter, MiniCam EMF 22 includes nuclear energy and CCS as mitigation options and allows overshoot to get to the concentration level, while ER 2010 follows an optimistic application path for RE. Transition economies are countries that changed from a former centrally planned economy to a free market system. [Figure 10.19]

TS 10.11, TS.10.12 and TS.10.13; instead site, project and/or investor-specific conditions should be taken into account. The technology chapters [2.7, 3.8, 4.7, 5.8, 6.7, 7.8] provide useful sensitivities in this respect. [10.5.1]

The cost ranges provided here do not reflect costs of integration (Chapter 8), external costs or benefits (Chapter 9) or costs of policies (Chapter 11). Given suitable conditions, the lower ends of the ranges indicate that some RE technologies already can compete with traditional forms at current energy market prices in many regions of the world. [10.5.1]

The supply cost curves presented [10.4.4, Figures 10.23, 10.25, 10.26, and 10.27] provide additional information about the available resource base (given as a function of the LCOE associated with harvesting it). The supply cost curves discussed [10.3.2.1, Figures 10.15–10.17], in contrast, illustrate the amount of RE that is harnessed (once again as a function of the associated LCOE) in different regions once specific trajectories for the expansion of RE are followed. In addition, it must be emphasized that most of the supply cost curves refer to future points in time (e.g., 2030 or 2050), whereas the LCOE given in the cost sections of the technology chapters as well as those shown in Figures TS.10.11, TS.10.12, and TS.10.13 (and in Annex III) refer to current costs. [10.5.1]

Significant advances in RE technologies and associated cost reductions have been demonstrated over the last decades, though the contribution and mutual interaction of different drivers (e.g., learning by searching, learning by doing, learning by using, learning by interacting, upsizing of technologies, and economies of scale) is not always understood in detail. [2.7, 3.8, 7.8, 10.5.2]

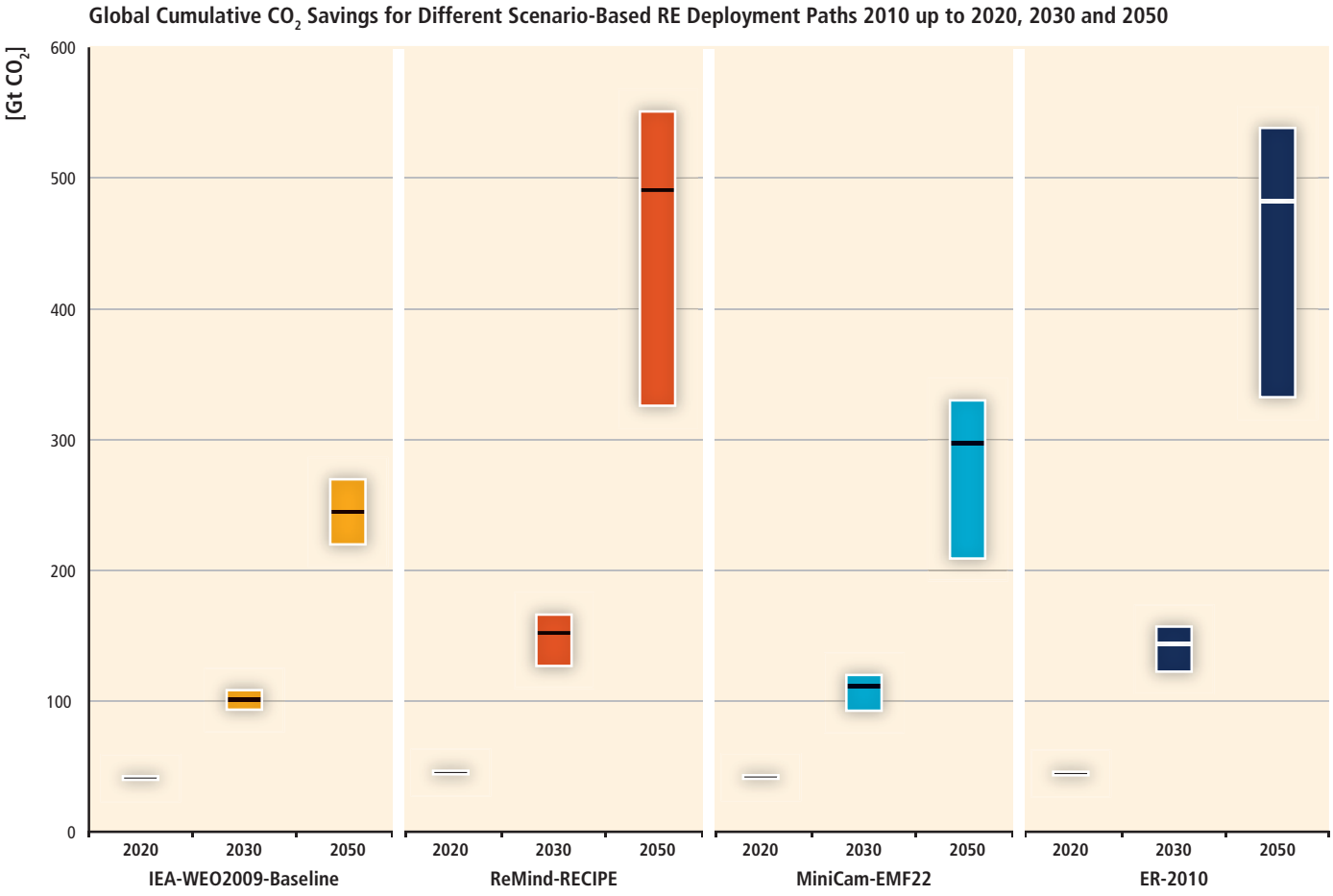


Figure TS.10.10 | Global cumulative CO_2 savings between 2010 and 2050 for four illustrative scenarios. The presented ranges mark the high uncertainties regarding the substituted conventional energy source. While the upper limit assumes a full substitution of high-carbon fossil fuels, the lower limit considers specific CO_2 emissions of the analyzed scenario itself. The line in the middle was calculated assuming that RE displaces the specific energy mix of a reference scenario. [Figure 10.22]

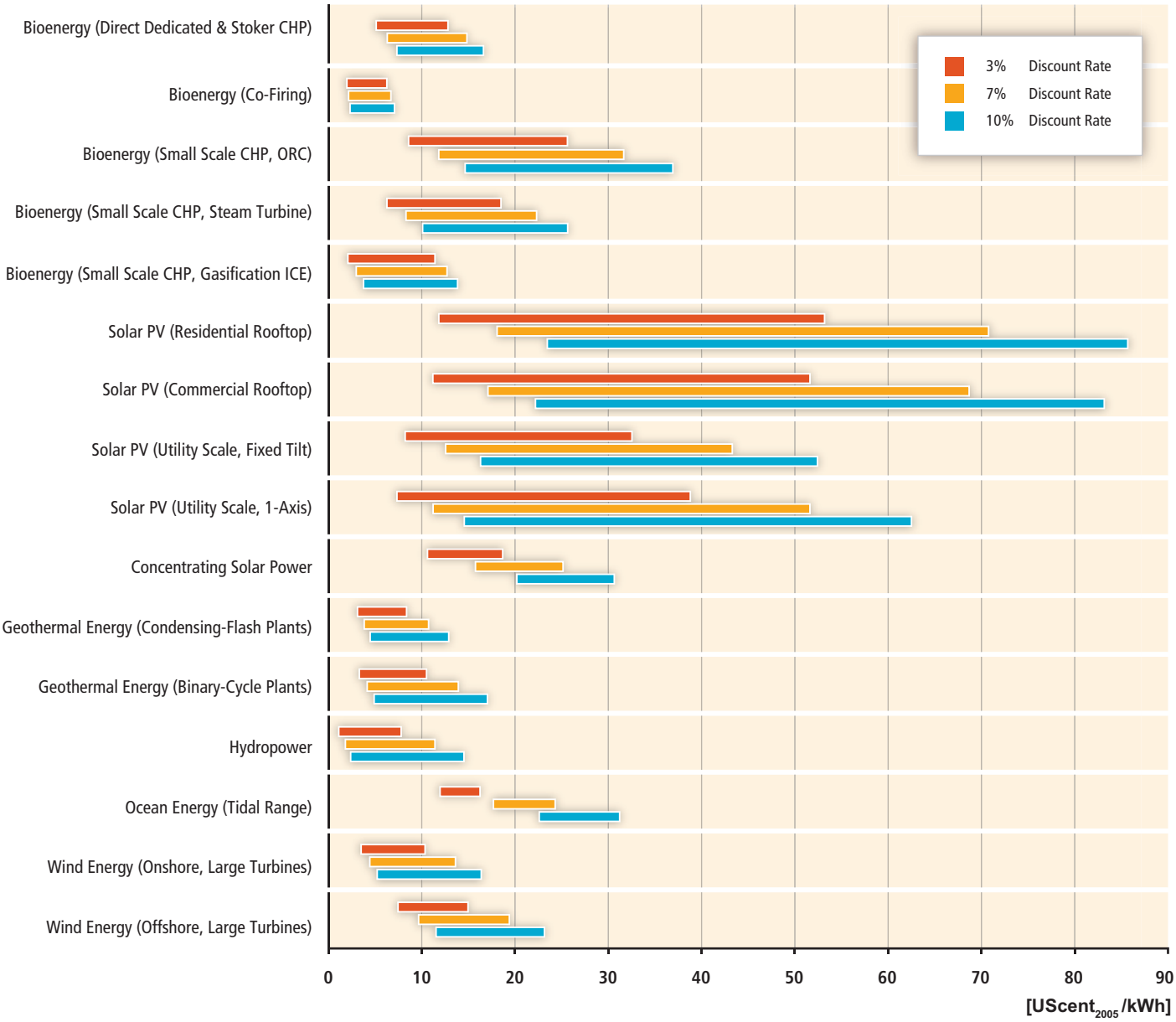


Figure TS.10.11 | Levelized cost of electricity for commercially available RE technologies at 3, 7 and 10% discount rates. The levelized cost of electricity estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost range is based on the low ends of the ranges of investment, operations and maintenance (O&M), and (if applicable) feedstock cost and the high ends of the ranges of capacity factors and lifetimes as well as (if applicable) the high ends of the ranges of conversion efficiencies and by-product revenue. The higher bound of the levelized cost range is accordingly based on the high end of the ranges of investment, O&M and (if applicable) feedstock costs and the low end of the ranges of capacity factors and lifetimes as well as (if applicable) the low ends of the ranges of conversion efficiencies and by-product revenue. Note that conversion efficiencies, by-product revenue and lifetimes were in some cases set to standard or average values. For data and supplementary information see Annex III. (CHP: combined heat and power; ORC: organic Rankine cycle, ICE: internal combustion engine.) [Figure 10.29]

From an empirical point of view, the resulting cost decrease can be described by experience (or 'learning') curves. For a doubling of the (cumulative) installed capacity, many technologies showed a more or less constant percentage decrease in the specific investment costs (or in the levelized costs or unit price, depending on the selected cost indicator). The numerical value describing this improvement is called the learning rate (LR). A summary of observed learning rates is provided in Table TS.10.1. [10.5.2]

Any efforts to assess future costs by extrapolating historic experience curves must take into account the uncertainty of learning rates as well as caveats and knowledge gaps discussed. [10.5.6, 7.8.4.1] As a supplementary approach, expert elicitations could be used to gather additional information about future cost reduction potentials, which might be contrasted with the assessments gained by using learning rates. Furthermore, engineering model analyses to identify technology improvement potentials could also provide additional information for developing cost projections. [2.6, 3.7, 4.6, 6.6, 7.7, 10.5.2]

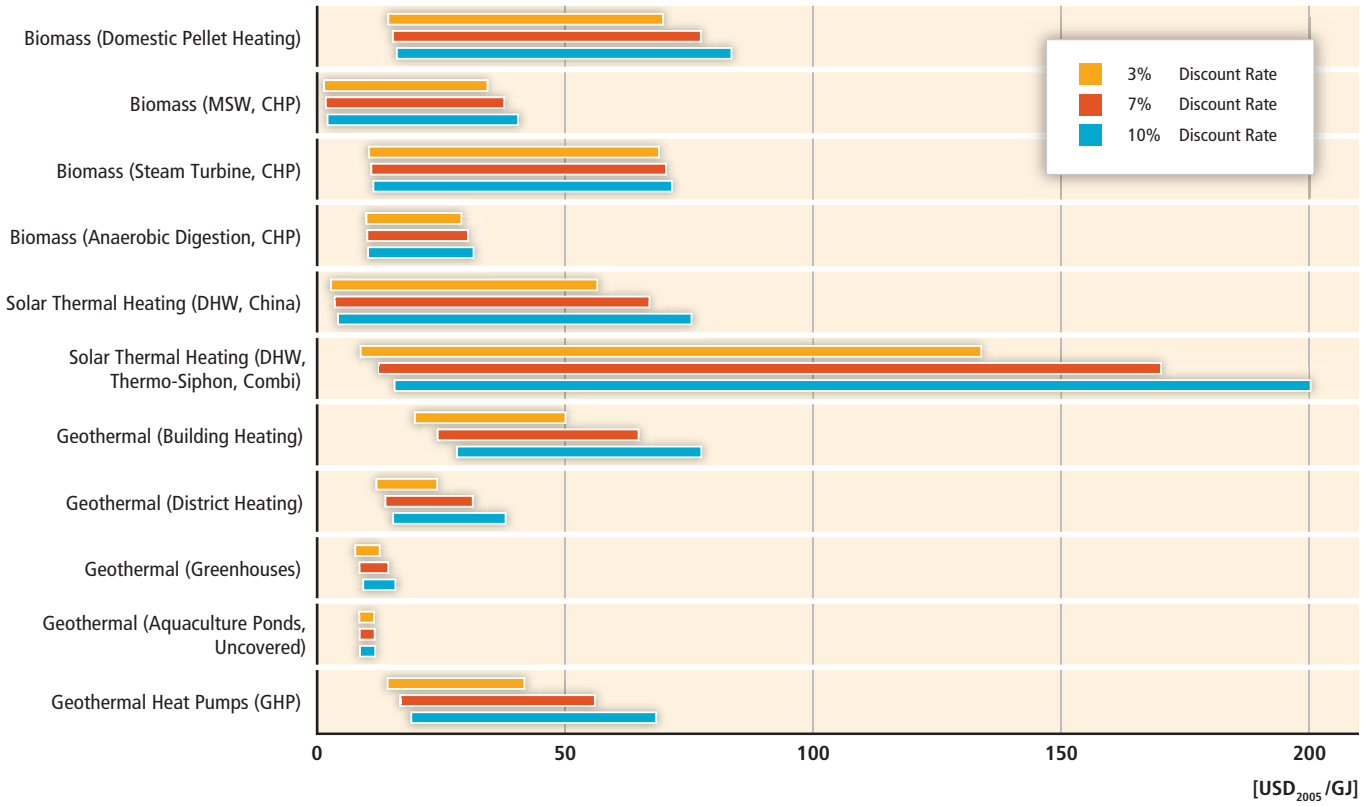


Figure TS.10.12 | Levelized cost of heat (LCOH) for commercially available RE technologies at 3, 7 and 10% discount rates. The LCOH estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost range is based on the low ends of the ranges of investment, operations and maintenance (O&M), and (if applicable) feedstock cost and the high ends of the ranges of capacity factors and lifetimes as well as (if applicable) the high ends of the ranges of conversion efficiencies and by-product revenue. The higher bound of the levelized cost range is accordingly based on the high end of the ranges of investment, O&M and (if applicable) feedstock costs and the low end of the ranges of capacity factors and lifetimes as well as (if applicable) the low ends of the ranges of conversion efficiencies and by-product revenue. Note that capacity factors and lifetimes were in some cases set to standard or average values. For data and supplementary information see Annex III. (MSW: municipal solid waste; DHW: domestic hot water.) [Figure 10.30]

Important potential technological advances and associated cost reductions, for instance, are expected in (but are not limited to) the following application fields: next-generation biofuels and biorefineries; advanced PV and CSP technologies and manufacturing processes; enhanced geothermal systems; multiple emerging ocean technologies; and foundation and turbine designs for offshore wind energy. Further cost reductions for hydropower are likely to be less significant than some of the other RE technologies, but R&D opportunities exist to make hydropower projects technically feasible in a wider range of natural conditions and to improve the technical performance of new and existing projects. [2.6, 3.7, 4.6, 5.3, 5.7, 5.8, 6.6, 7.7]

An answer to the question whether or not upfront investments in a specific innovative technology are justified cannot be given as long as the technology is treated in isolation. In a first attempt to clarify this issue and, especially, to investigate the mutual competition of prospective climate protection technologies, integrated assessment modellers have started to model technological learning in an endogenous way. The results obtained from these modelling comparison exercises indicate that—in the context of stringent climate goals—upfront investments in learning technologies can be justified in many cases. [10.5.3.]

However, as the different scenarios considered in Figure TS.10.14 and other studies clearly show, considerable uncertainty surrounds the exact volume and timing of these investments. [10.5.4]

The four illustrative scenarios that were analyzed in detail in Section 10.3 span a range of cumulative global decadal investments (in the power generation sector) ranging from USD_{2005} 1,360 to 5,100 billion (for the decade 2011 to 2020) and from USD_{2005} 1,490 to 7,180 billion (for the decade 2021 to 2030). These numbers allow the assessment of future market volumes and resulting investment opportunities. The lower values refer to the IEA World Energy Outlook 2009 Reference Scenario and the higher ones to a scenario that seeks to stabilize atmospheric CO_2 (only) concentration at 450 ppm. The average annual investments in the reference scenario are slightly lower than the respective investments reported for 2009. Between 2011and 2020, the higher values of the annual averages of the RE power generation sector investment approximately correspond to a three-fold increase in the current global investments in this field. For the next decade (2021 to 2030), a five-fold increase is projected. Even the upper level of the annual investments is smaller than 1% of the world's GDP. Additionally, increasing the installed capacity of

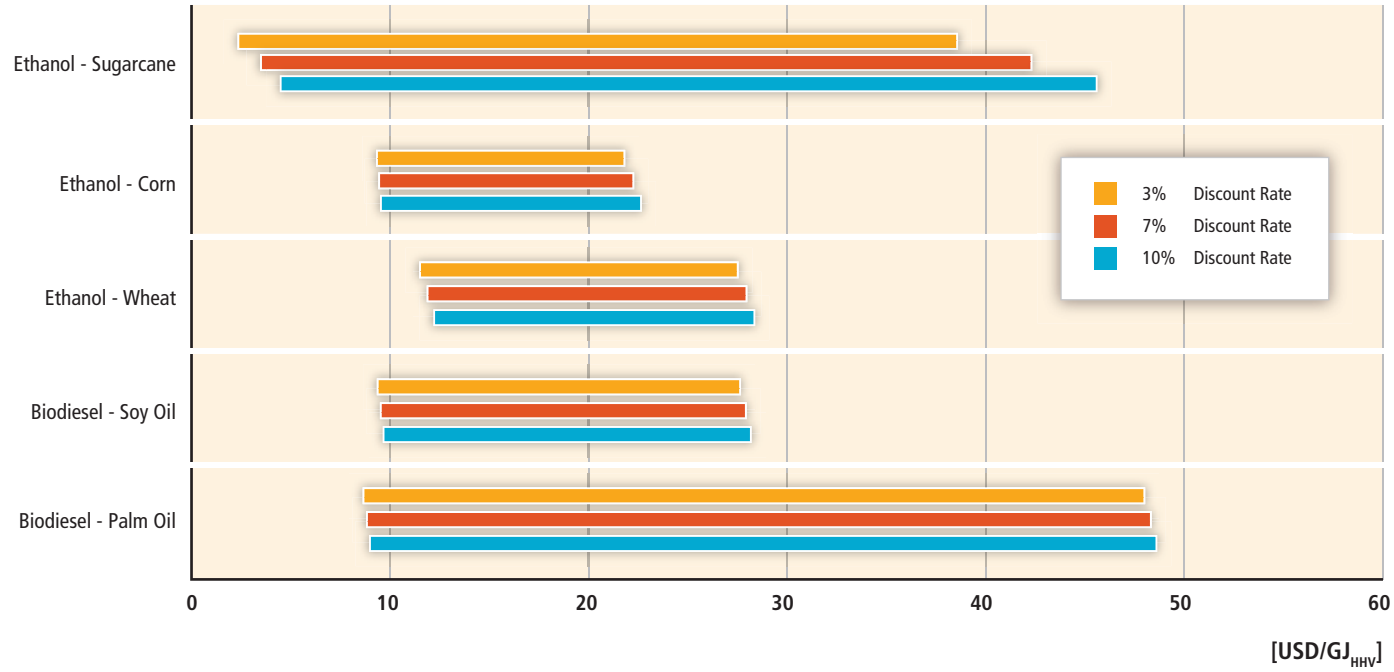


Figure TS.10.13 | Levelized cost of fuels (LCOF) for commercially available biomass conversion technologies at 3, 7 and 10% discount rates. LCOF estimates for all technologies are based on input data summarized in Annex III and the methodology outlined in Annex II. The lower bound of the levelized cost range is based on the low ends of the ranges of investment, O&M and feedstock cost. The higher bound of the levelized cost range is accordingly based on the high end of the ranges of investment, O&M and feedstock costs. Note that conversion efficiencies, by-product revenue, capacity factors and lifetimes were set to average values. For data and supplementary information see Annex III. (HHV: higher heating value.) [Figure 10.31]

RE power plants will reduce the amount of fossil and nuclear fuels that otherwise would be needed in order to meet a given electricity demand. [10.5.4]

10.6 Social and environmental costs and benefits

Energy extraction, conversion and use cause significant environmental impacts and external costs. Although replacing fossil fuel-based energy with RE often can reduce GHG emissions and also to some extent other environmental impacts and external costs, RE technologies can also have environmental impacts and external costs themselves, depending on the energy source and technology. These impacts and costs should be considered if a comprehensive cost assessment is required. [10.6.2]

Figure TS.10.15 shows the large uncertainty ranges of two dominant external cost components, namely climate- and health-related external costs. Small-scale biomass fired CHP plants cause relatively high external costs due to health effects via particulate emissions. Offshore wind energy seems to cause the smallest external cost. External cost estimates for nuclear power are not reported here because the character and assessment of external costs and risk from release of radionuclides due to low-probability accidents or due to leakages from waste repositories in a distant future are very different, for example, from climate change and air pollution, which are practically unavoidable. Those external impacts related to nuclear power can be, however, considered by discussion and judgment in the society. Accident risks in terms of fatalities due to various energy production chains (e.g., coal, oil, gas and hydro) are generally higher in non-OECD countries than in OECD countries. [10.6.3, 9.3.4.7]

As only external costs of individual technologies are shown in Figure TS.10.15, benefits can be derived when assuming that one technology replaces another one. RE sources and the technologies using them for electricity generation have mostly lower external costs per produced electricity than fossil fuel-based technologies. However, case-specific considerations are needed as there can also be exceptions. [10.6.3]

There are, however, considerable uncertainties in the assessment and valuation of external impacts of energy sources. The assessment of physical, biological and health damages includes considerable uncertainty and the estimates are based typically on calculational models, the results of which are often difficult to validate. The damages or changes seldom have market values that could be used in cost estimation, thus indirect information or other approaches must be used for damage valuation. Further, many of the damages will take place far in the future or in societies very different from those benefiting from the use of the considered energy production, which complicates the

Table TS.10.1 | Observed learning rates for various energy supply technologies. Note that values cited by older publications are less reliable as these refer to shorter time periods. [Table 10.10]

Technology	Source	Country / region	Period	Learning rate (%)	Performance measure
Onshore wind					
	Neij, 1997	Denmark	1982-1995	4	Price of wind turbine (USD/kW)
	Mackay and Probert, 1998	USA	1981-1996	14	Price of wind turbine (USD/kW)
	Neij, 1999	Denmark	1982-1997	8	Price of wind turbine (USD/kW)
	Durstewitz, 1999	Germany	1990-1998	8	Price of wind turbine (USD/kW)
	IEA, 2000	USA	1985-1994	32	Electricity production cost (USD/kWh)
	IEA, 2000	EU	1980-1995	18	Electricity production cost (USD/kWh)
	Kouvaritakis et al., 2000	OECD	1981-1995	17	Price of wind turbine (USD/kW)
	Neij, 2003	Denmark	1982-1997	8	Price of wind turbine (USD/kW)
	Junginger et al., 2005a	Spain	1990-2001	15	Turnkey investment costs (EUR/kW)
	Junginger et al., 2005a	UK	1992-2001	19	Turnkey investment costs (EUR/kW)
	Söderholm and Sundqvist, 2007	Germany, UK, Denmark	1986-2000	5	Turnkey investment costs (EUR/kW)
	Neij, 2008	Denmark	1981-2000	17	Electricity production cost (USD/kWh)
	Kahouli-Brahmi, 2009	Global	1979-1997	17	Investment costs (USD/kW)
	Nemet, 2009	Global	1981-2004	11	Investment costs (USD/kW)
	Wiser and Bolinger, 2010	Global	1982-2009	9	Investment costs (USD/kW)
Offshore wind					
	Isles, 2006	8 EU countries	1991-2006	3	Investment cost of wind farms (USD/kW)
Photovoltaics (PV)					
	Harmon, 2000	Global	1968-1998	20	Price PV module (USD/Wpeak)
	IEA, 2000	EU	1976-1996	21	Price PV module (USD/Wpeak)
	Williams, 2002	Global	1976-2002	20	Price PV module (USD/Wpeak)
	ECN, 2004	EU	1976-2001	20-23	Price PV module (USD/Wpeak)
	ECN, 2004	Germany	1992-2001	22	Price of balance of system costs
	van Sark et al., 2007	Global	1976-2006	21	Price PV module (USD/Wpeak)
	Kruck and Eltrop, 2007	Germany	1977-2005	13	Price PV module (EUR/Wpeak)
	Kruck and Eltrop, 2007	Germany	1999-2005	26	Price of balance of system costs
	Nemet, 2009	Global	1976-2006	15-21	Price PV module (USD/Wpeak)
Concentrating Solar Power (CSP)					
	Enermodal, 1999	USA	1984-1998	8-15	Plant investment cost (USD/kW)
Biomass					
	IEA, 2000	EU	1980-1995	15	Electricity production cost (USD/kWh)
	Goldemberg et al., 2004	Brazil	1985-2002	29	Prices for ethanol fuel (USD/m^3)
	Junginger et al., 2005b	Sweden, Finland	1975-2003	15	Forest wood chip prices (EUR/GJ)
	Junginger et al., 2006	Denmark	1984-1991	15	Biogas production costs (EUR/Nm^3)
	Junginger et al., 2006	Sweden	1990-2002	8-9	Biomass CHP power (EUR/kWh)
	Junginger et al., 2006	Denmark	1984-2001	0-15	Biogas production costs (EUR/Nm^3)
	Junginger et al., 2006	Denmark	1984-1998	12	Biogas plants (€/m^3 biogas/day)
	Van den Wall Bake et al., 2009	Brazil	1975-2003	19	Ethanol from sugarcane (USD/m^3)
	Goldemberg et al., 2004	Brazil	1980-1985	7	Ethanol from sugarcane (USD/m^3)
	Goldemberg et al., 2004	Brazil	1985-2002	29	Ethanol from sugarcane (USD/m^3)
	Van den Wall Bake et al., 2009	Brazil	1975-2003	20	Ethanol from sugarcane (USD/m^3)
	Hettinga et al., 2009	USA	1983-2005	18	Ethanol from corn (USD/m^3)
	Hettinga et al., 2009	USA	1975-2005	45	Corn production costs (USD/t corn)
	Van den Wall Bake et al., 2009	Brazil	1975-2003	32	Sugarcane production costs (USD/t)

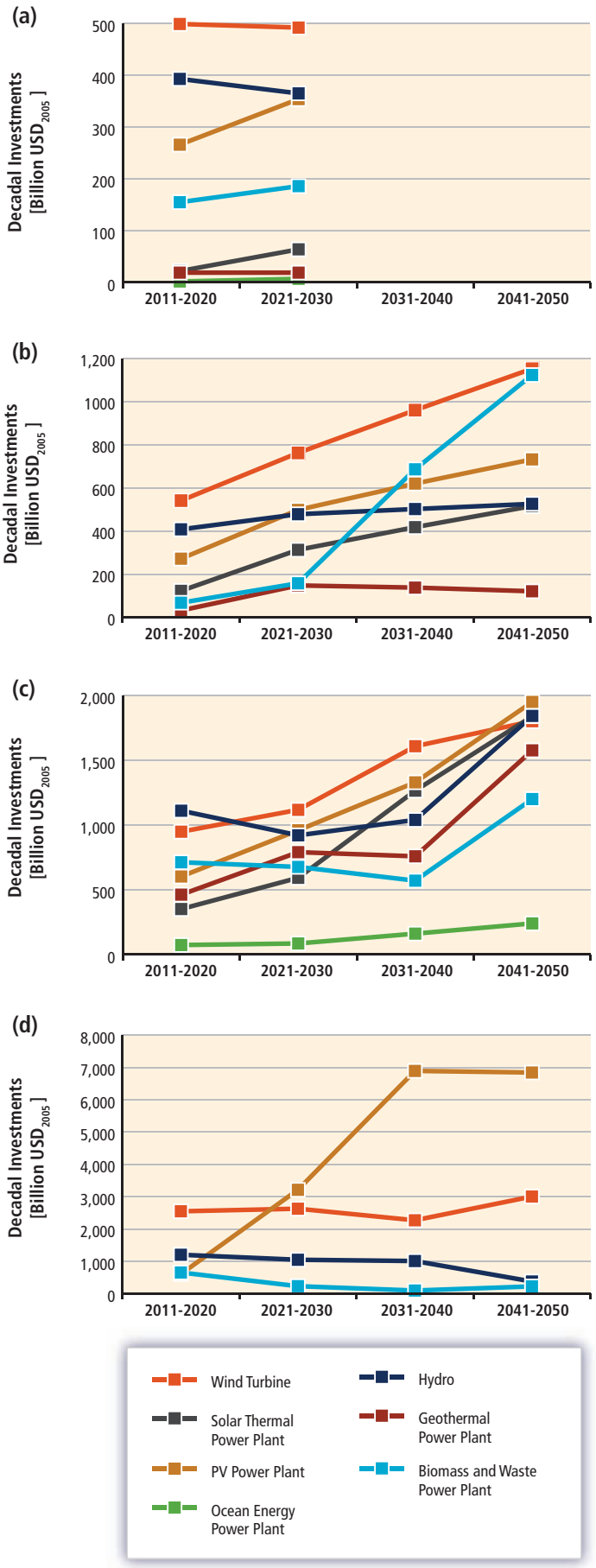


Figure TS.10.14 | Illustrative global *decadal* investments (in billion USD_{2005}) needed in order to achieve ambitious climate protection goals: (b) MiniCAM-EMF22 (first-best 2.6 W/m² overshoot scenario, nuclear and carbon capture technologies are permitted); (c) ER-2010 (450 ppm CO_2eq, nuclear and carbon capture technologies are not permitted); and (d) ReMIND-RECIPE (450 ppm CO_2, nuclear power plants and carbon capture technologies are permitted). Compared to the other scenarios, the PV share is high in (d) as concentrating solar power has not been considered. For comparison, (a) shows the IEA-WEO2009-Baseline (baseline scenario without climate protection). Sources: (a) IEA (2009); (b) Calvin et al. (2009); (c) Teske et al. (2010); and (d) Luderer et al. (2009).

considerations. These factors contribute to the uncertainty of external costs. [10.6.5]

However, the knowledge about external costs and benefits due to RE sources can provide some guidance for society to select best alternatives and to steer the energy system towards overall efficiency and high welfare gains. [10.6.5]

11. Policy, Financing and Implementation

11.1 Introduction

RE capacity is increasing rapidly around the world, but a number of barriers continue to hold back further advances. Therefore, if RE is to contribute substantially to the mitigation of climate change, and to do so quickly, various forms of economic support policies as well as policies to create an enabling environment are likely to be required. [11.1]

RE policies have promoted an increase in RE shares by helping to overcome various barriers that impede technology development and deployment of RE. RE policies might be enacted at all levels of government—from local to state/provincial to national to international—and range from basic R&D for technology development through to support for installed RE systems or the electricity, heat or fuels they produce. In some countries, regulatory agencies and public utilities may be given responsibility for, or on their own initiative, design and implement support mechanisms for RE. Nongovernmental actors, such as international agencies and development banks, also have important roles to play. [1.4, 11.1, 11.4, 11.5]

RE may be measured by additional qualifiers such as time and reliability of delivery (availability) and other metrics related to RE's integration into networks. There is also much that governments and other actors can do to create an environment conducive for RE deployment. [11.1, 11.6]

11.1.1 The rationale of renewable energy-specific policies in addition to climate change policies

Renewable energies can provide a host of benefits to society. Some RE technologies are broadly competitive with current market energy prices.

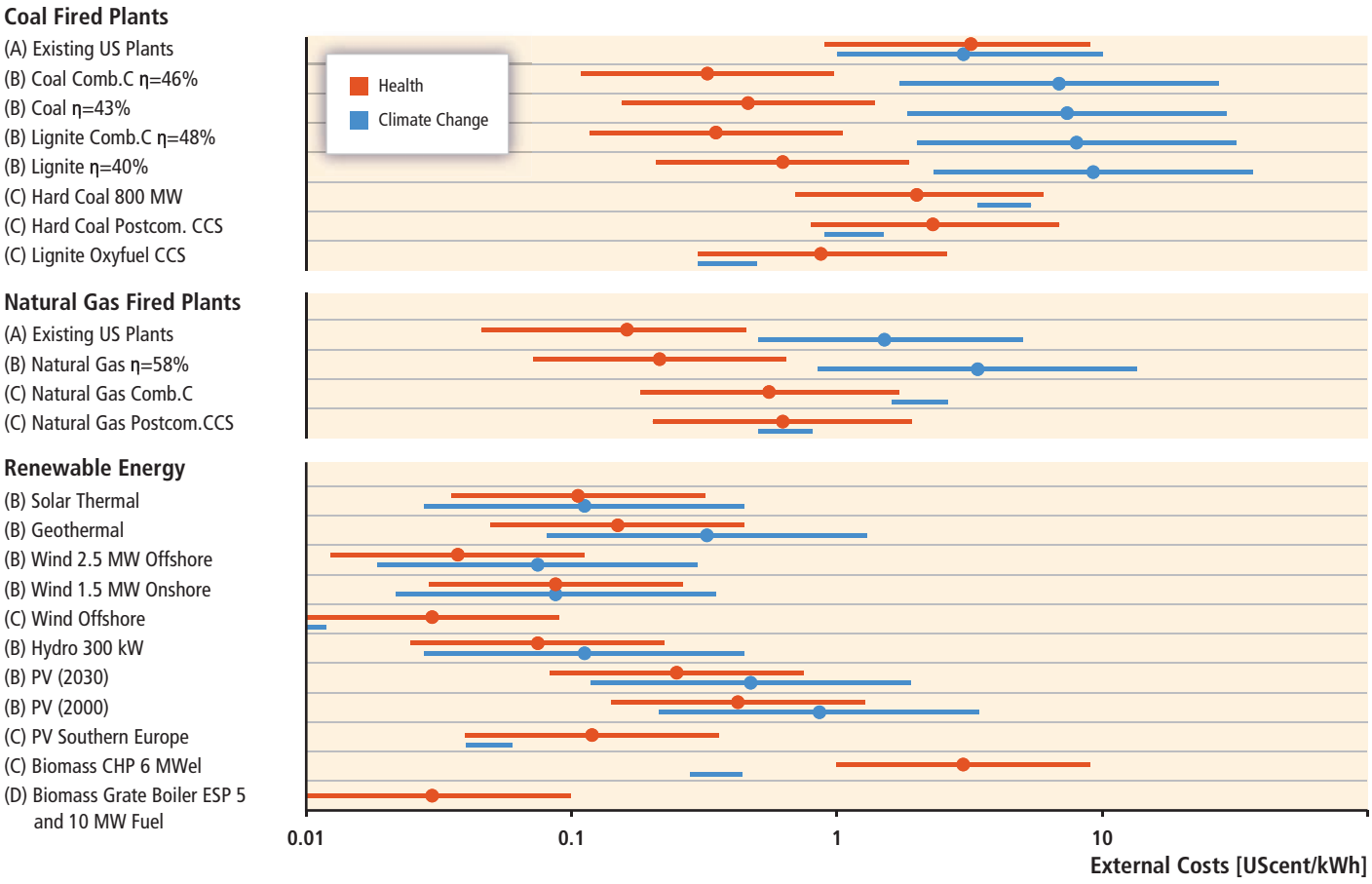


Figure TS.10.15 | Illustration of external costs due to the lifecycle of electricity production based on RE and fossil energy. Note the logarithmic scale of the figure. The black lines indicate the range of the external cost due to climate change and the red lines indicate the range of the external costs due to air pollutant health effects. External costs due to climate change mainly dominate in fossil energy if not equipped with CCS. Comb.C: Combined Cycle; Postcom: Post-Combustion; η: efficiency factor. The results are based on four studies having different assumptions (A–D). The uncertainty for the external costs of health impacts is assumed to be a factor of three. [Figure 10.36]

Of the other RE technologies that are not yet broadly competitive, many can provide competitive energy services in certain circumstances. In most regions of the world, however, policy measures are still required to facilitate an increasing deployment of RE. [11.1, 10.5]

Climate policies (carbon taxes, emissions trading or regulatory policies) decrease the relative costs of low-carbon technologies compared to carbon-intensive technologies. It is questionable, however, whether climate policies (e.g., carbon pricing) alone are capable of promoting RE at sufficient levels to meet the broader environmental, economic and social objectives related to RE. [11.1.1]

Two separate market failures create the rationale for the additional support of innovative RE technologies that have high potential for technological development, even if an emission market (or GHG pricing policy in general) exists. The first market failure refers to the external cost of GHG emissions. The second market failure is in the field of innovation: if firms underestimate the future benefits of investments into learning RE technologies or if they cannot appropriate these benefits, they will invest less than is optimal from a macroeconomic perspective. In addition to GHG pricing policies, RE-specific policies may be appropriate from an economic point of view if the related opportunities for technological development are to be addressed (or if the goals beyond climate change mitigation are pursued). Potentially adverse consequences such as lock-in, carbon leakage and rebound effects should be taken into account in the design of a portfolio of policies. [11.1.1, 11.5.7.3]

11.1.2 Policy timing and strength

The timing, strength and level of coordination of R&D versus deployment policies have implications for the efficiency and effectiveness of the policies, and for the total cost to society in three main ways: 1) whether a country promotes RE immediately or waits until costs have declined further; 2) once a country has decided to support RE, the timing, strength and coordination of when R&D policies give way to deployment policies; and 3) the cost and benefit of accelerated versus slower 'market demand' policy implementation. With regard to the first, in order to achieve full competitiveness with fossil fuel technologies, significant upfront investments in RE will be required until the break-even point is achieved. When those investments should be made depends on the goal. If the

international community aims to stabilize global temperature increases at 2°C, then investments in low-carbon technologies must start almost immediately.

11.2 Current trends: Policies, financing and investment

An increasing number and variety of RE policies have driven substantial growth in RE technologies in recent years. Until the early 1990s, few countries had enacted policies to promote RE. Since then, and particularly since the early- to mid-2000s, policies have begun to emerge in a growing number of countries at the municipal, state/provincial and national levels, as well as internationally (see Figure TS.11.1). [1.4, 11.1, 11.2.1, 11.4, 11.5]

Initially, most policies adopted were in developed countries, but an increasing number of developing countries have enacted policy frameworks at various levels of government to promote RE since the late 1990s and early 2000s. Of those countries with RE electricity policies by early 2010, approximately half were developing countries from every region of the world. [11.2.1]

Most countries with RE policies have more than one type of mechanism in place, and many existing policies and targets have been strengthened over time. Beyond national policies, the number of international policies and partnerships is increasing. Several hundred city and local governments around the world have also established goals or enacted renewable promotion policies and other mechanisms to spur local RE deployment. [11.2.1]

The focus of RE policies is shifting from a concentration almost entirely on electricity to include the heating/cooling and transportation sectors. These trends are matched by increasing success in the development of a range of RE technologies and their manufacture and implementation (see Chapters 2 through 7), as well as by a rapid increase in annual investment in RE and a diversification of financing institutions, particularly since 2004/2005. [11.2.2]

In response to the increasingly supportive policy environment, the overall RE sector globally has seen a significant rise in the level of investment since 2004-2005. Financing occurs over what is known as the 'continuum' or stages of technology development. The five segments of the continuum are: 1) R&D; 2) technology development and commercialization; 3) equipment manufacture and sales; 4) project construction; and 5) the refinancing and sale of companies, largely through mergers and acquisitions. Financing has been increasing over time in each of these stages, providing indications of the RE sector's current and expected growth, as follows: [11.2.2]

- Trends in (1) R&D funding and (2) technology investment are indicators of the long- to mid-term expectations for the sector—investments are being made that will begin to pay off in several years' time, once the technology is fully commercialized. [11.2.2.2, 11.2.2.3]
- Trends in (3) manufacturing and sales investment are an indicator of near-term expectations for the sector—essentially, that the growth in market demand will continue. [11.2.2.4]
- Trends in (4) construction investment are an indicator of current sector activity, including the extent to which internalizing costs associated with GHGs can result in new financial flows to RE projects. [11.2.2.5]
- Trends in (5) industry mergers and acquisitions can reflect the overall maturity of the sector, and increasing refinancing activity over time indicates that larger, more conventional investors are entering the sector, buying up successful early investments from first movers. [11.2.2.6]

11.3 Key drivers, opportunities and benefits

Renewable energy can provide a host of benefits to society. In addition to the reduction of CO_2 emissions, governments have enacted RE policies to meet any number of objectives, including the creation of local environmental and health benefits; facilitation of energy access, particularly for rural areas; advancement of energy security goals by diversifying the portfolio of energy technologies and resources; and improving social and economic development through potential employment opportunities and economic growth. [11.3.1–11.3.4]

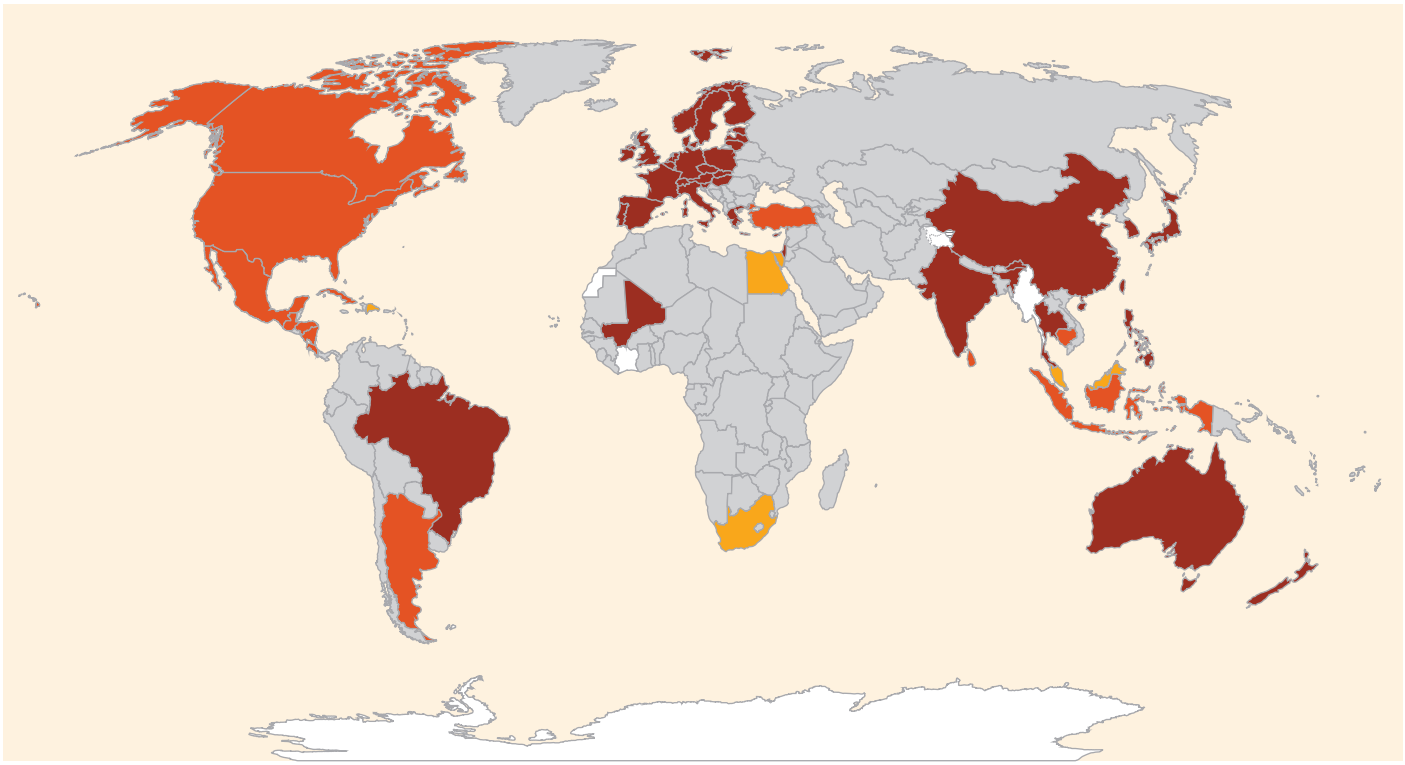
The relative importance of the drivers for RE differ from country to country, and may vary over time. Energy access has been described as the primary driver in developing countries whereas energy security and environmental concerns have been most important in developed countries. [11.3]

11.4 Barriers to renewable energy policymaking, implementation and financing

RE policies have promoted an increase in RE shares by helping to overcome various barriers that impede technology development and deployment of RE. Barriers specific to RE policymaking, to implementation and to financing (e.g., market failures) may further impede deployment of RE. [1.4, 11.4]

Barriers to making and enacting policy include a lack of information and awareness about RE resources, technologies and policy options; lack of understanding about best policy design or how to undertake energy transitions; difficulties associated with quantifying and internalizing external costs and benefits; and lock-in to existing technologies and policies. [11.4.1]

2005



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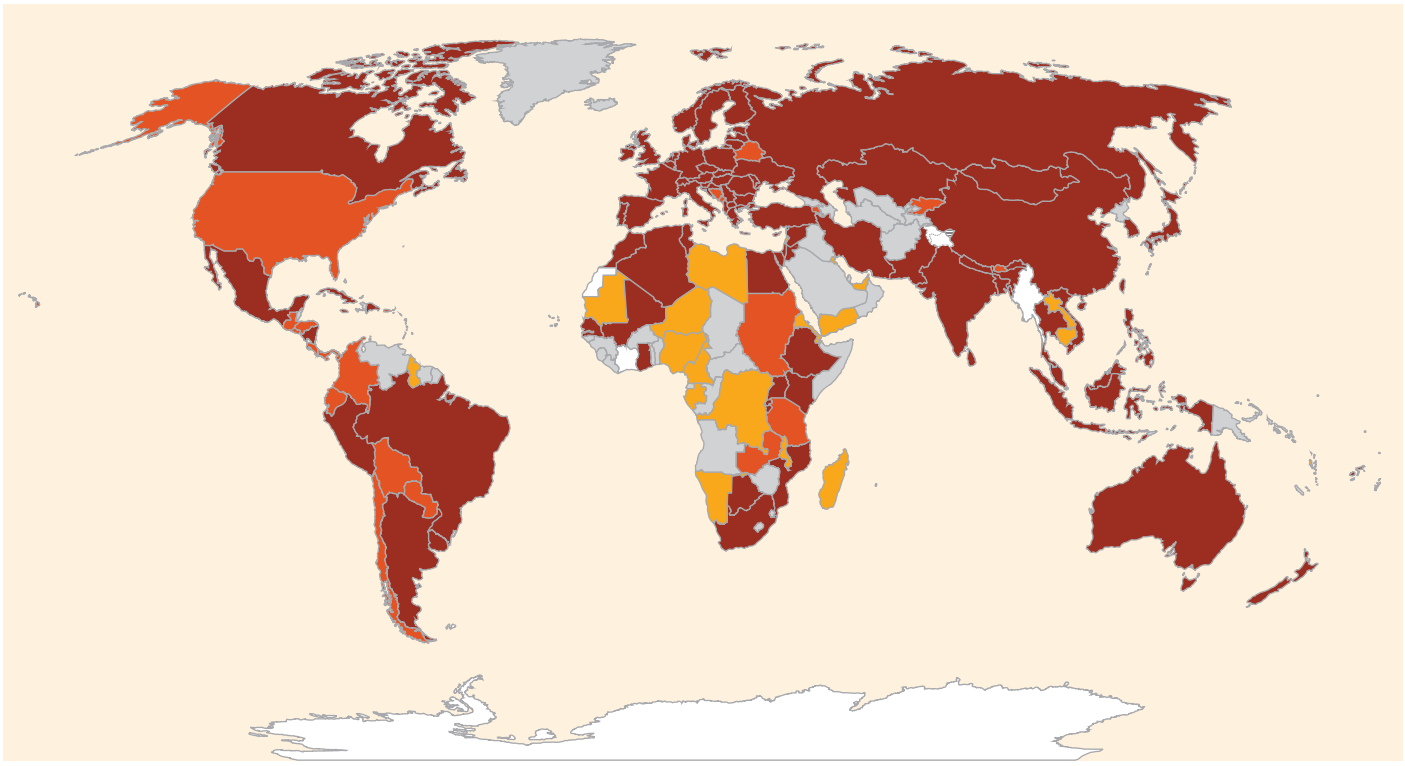

Figure TS.11.1 | Countries with at least one RE target and/or at least one RE-specific policy, in mid-2005 and in early 2011. This figure includes only national-level targets and policies (not municipal or state/provincial) and is not necessarily all-inclusive. [Figure 11.1]

Barriers related to policy implementation include conflicts with existing regulations; lack of skilled workers; and/or lack of institutional capacity to implement RE policies. [11.4.2]

Barriers to financing include a lack of awareness among financiers and lack of timely and appropriate information; issues related to financial structure and project scale; issues related to limited track records; and, in some countries, institutional weakness, including imperfect capital markets and insufficient access to affordable financing, all of which increase perceived risk and thus increase costs and/or make it more difficult to obtain RE project financing. Most importantly, many RE technologies are not economically competitive with current energy market prices, making them financially unprofitable for investors absent various forms of policy support, and thereby restricting investment capital. [11.4.3]

11.5 Experience with and assessment of policy options

Many policy options are available to support RE technologies, from their infant stages to demonstration and pre-commercialization, and through to maturity and wide-scale deployment. These include government R&D policies (supply-push) for advancing RE technologies, and deployment policies (demand-pull) that aim to create a market for RE technologies. Policies could be categorized in a variety of ways and no globally-agreed list of RE policy options or groupings exists. For the purpose of simplification, R&D and deployment policies have been organized within the following categories [11.5]:

- **Fiscal incentive:** actors (individuals, households, companies) are allowed a reduction of their contribution to the public treasury via income or other taxes or are provided payments from the public treasury in the form of rebates or grants.
- **Public finance:** public support for which a financial return is expected (loans, equity) or financial liability is incurred (guarantee); and
- **Regulation:** rule to guide or control conduct of those to whom it applies.

Although targets are a central component of policies, policies in place may not need specific targets to be successful. Further, targets without policies to deliver them are unlikely to be met. [11.5]

The success of policy instruments is determined by how well they are able to achieve various objectives or criteria, including:

- **Effectiveness:** extent to which intended objectives are met;
- **Efficiency:** ratio of outcomes to inputs, or RE targets realized for economic resources spent;
- **Equity:** the incidence and distributional consequences of a policy; and
- **Institutional feasibility:** the extent to which a policy instrument is likely to be viewed as legitimate, gain acceptance, and be adopted and implemented, including the ability to implement a policy once it has been designed and adopted. [11.5.1]

Most literature focuses on effectiveness and efficiency of policies. Elements of specific policy options make them more or less apt to achieve the various criteria, and how these policies are designed and implemented can also determine how well they meet these criteria. The selection of policies and details of their design ultimately will depend on the goals and priorities of policymakers. [11.5.1]

11.5.1 Research and development policies for renewable energy

R&D, innovation, diffusion and deployment of new low-carbon technologies create benefits to society beyond those captured by the innovator, resulting in under-investment in such efforts. Thus, government R&D can play an important role in advancing RE technologies. Not all countries can afford to support R&D with public funds, but in the majority of countries where some level of support is possible, public R&D for RE enhances the performance of nascent technologies so that they can meet the demands of initial adopters. Public R&D also improves existing technologies that already function in commercial environments. [11.5.2]

Government R&D policies include fiscal incentives, such as academic R&D funding, grants, prizes, tax credits, and use of public research centres; as well as public finance, such as soft or convertible loans, public equity stakes, and public venture capital funds. Investments falling under the rubric of R&D span a wide variety of activities along the technology development lifecycle, from RE resource mapping to improvements in commercial RE technologies. [11.5.2]

The success of R&D policies depends on a number of factors, some of which can be clearly determined, and others which are debated in the literature. Successful outcomes from R&D programmes are not solely related to the total amount of funding allocated, but are also related to the consistency of funding from year to year. On-off operations in R&D are detrimental to technical learning, and learning and cost reductions depend on continuity, commitment and organization of effort, and where and how funds are directed, as much as they rely on the scale of effort. In the literature, there is some debate as to the most successful approach to R&D policy in terms of timing: bricolage (progress via research aiming at incremental improvements) versus breakthrough (radical technological advances) with arguments favouring either option or a combination of both. Experience has shown that it is important that subsidies for R&D (and beyond) are designed to have an 'exit-strategy'

whereby the subsidies are progressively phased out as the technology commercializes, leaving a functioning and sustainable sector in place. [11.5.2.3]

One of the most robust findings, from both the theoretical literature and technology case studies, is that R&D investments are most effective when complemented by other policy instruments—particularly, but not limited to, policies that simultaneously enhance demand for new RE technologies. Relatively early deployment policies in a technology's development accelerate learning, whether learning through R&D or learning through utilization (as a result of manufacture) and cost reduction. Together, R&D and deployment policies create a positive feedback cycle, inducing private sector investment in R&D (See Figure TS.11.2). [11.5.2.4]

11.5.2 Policies for deployment

Policy mechanisms enacted specifically to promote deployment of RE are varied and can apply to all energy sectors. They include fiscal incentives (grants, energy production payments, rebates, tax credits, reductions and exemptions, variable or accelerated depreciation); public finance (equity investment, guarantees, loans, public procurement); and regulations (quotas, tendering/bidding, FITs, green labelling and green energy purchasing, net metering, priority or guaranteed access, priority dispatch). While regulations and their impacts vary quite significantly from one end-use sector to another, fiscal incentives and public finance apply generally to all sectors. [11.5.3.1]

Fiscal incentives can reduce the costs and risks of investing in RE by lowering the upfront investment costs associated with installation, reducing the cost of production, or increasing the payment received for RE generated. Fiscal incentives also compensate for the various market failures that leave RE at a competitive disadvantage compared to fossil fuels and nuclear energy, and help to reduce the financial burden of investing in RE. [11.5.3.1]

Fiscal incentives tend to be most effective when combined with other types of policies. Incentives that subsidize production are generally preferable to investment subsidies because they promote the desired outcome—energy generation. However, policies must be tailored to particular technologies and stages of maturation, and investment subsidies can be helpful when a technology is still relatively expensive or when the technology is applied at a small scale (e.g., small

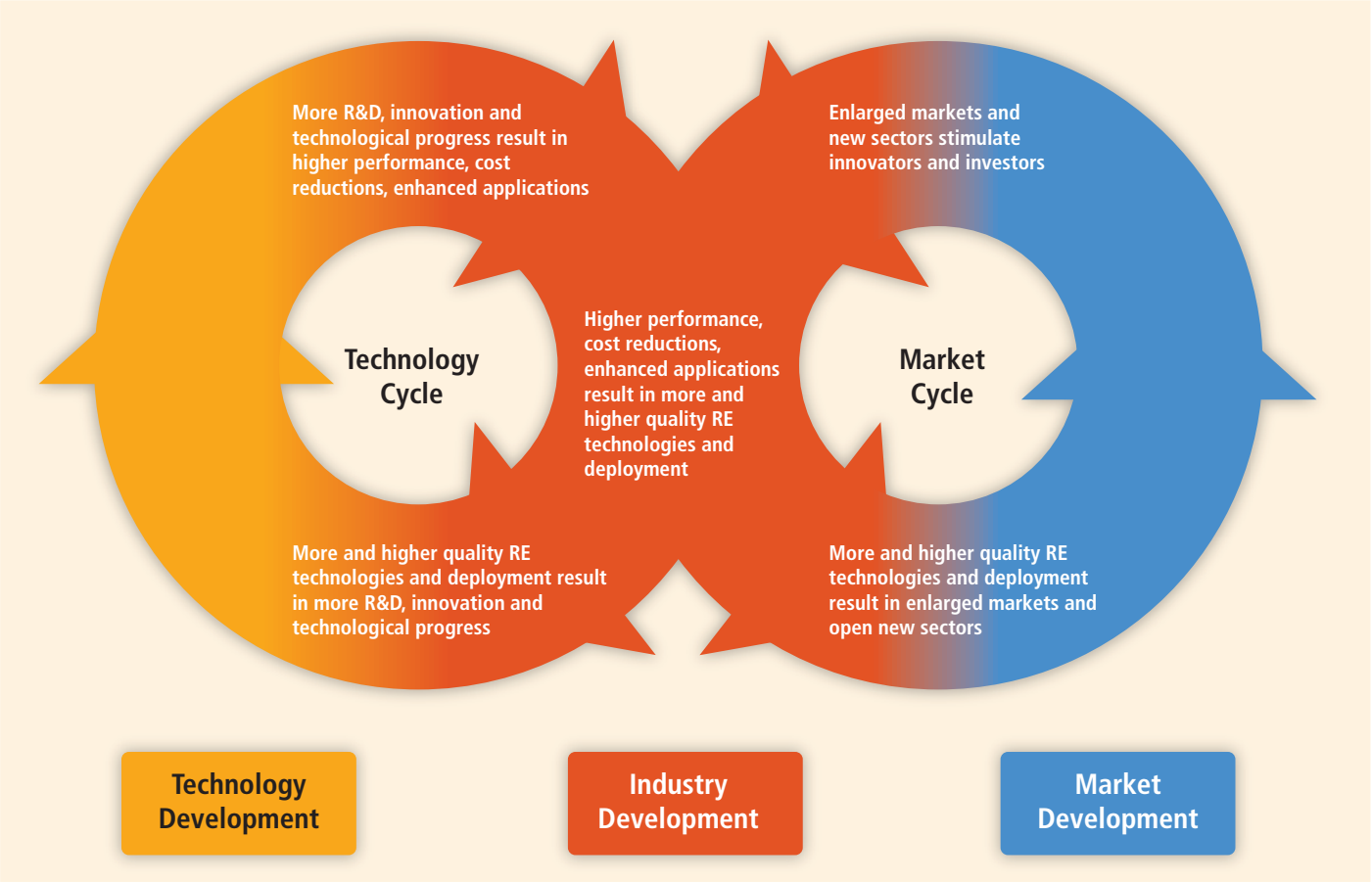

Figure TS.11.2 | The mutually-reinforcing cycles of technology development and market deployment drive down technology costs. [Figure 11.5]

rooftop solar systems), particularly if they are paired with technology standards and certification to ensure minimum quality of systems and installation. Experience with wind energy policies suggests that production payments and rebates may be preferable to tax credits because the benefits of payments and rebates are equal for people of all income levels and thus promote broader investment and use. Also, because they are generally provided at or near the time of purchase or production, they result in more even growth over time (rather than the tendency to invest in most capacity toward the end of a tax period). Tax-based incentives have historically tended to be used to promote only the most mature and cheapest available technologies. Generally, tax credits work best in countries where there are numerous profitable, tax-paying private sector firms that are in a position to take advantage of them. [11.5.3.1]

Public finance mechanisms have a twofold objective: to directly mobilize or leverage commercial investment into RE projects, and to indirectly create scaled-up and commercially sustainable markets for these technologies. In addition to the more traditional public finance policies such as soft loans and guarantees, a number of innovative mechanisms are emerging at various levels of government, including the municipal level. These include financing of RE projects through long-term loans to property owners that allow repayment to be matched with energy savings (for example, Property Assessed Clean Energy in California), and the 'recycling' of government funds for multiple purposes (e.g., using public funds saved through energy efficiency improvements for RE projects). [11.5.3.2]

Public procurement of RE technologies and energy supplies is a frequently cited but not often utilized mechanism to stimulate the market for RE. Governments can support RE development by making commitments to purchase RE for their own facilities or encouraging clean energy options for consumers. The potential of this mechanism is significant: in many nations, governments are the largest consumer of energy, and their energy purchases represent the largest components of public expenditures. [11.5.3.2]

Regulatory policies include quantity- and price-driven policies such as quotas and FITs; quality aspects and incentives; and access instruments such as net metering. Quantity-driven policies set the quantity to be achieved and allow the market to determine the price, whereas price-driven policies set the price and allow the market to determine quantity. Quantity-driven policies can be used in all three end-use sectors in the form of obligations or mandates. Quality incentives include green energy purchasing and green labelling programmes (occasionally mandated by governments, but not always), which provide information to consumers about the quality of energy products to enable consumers to make voluntary decisions and drive demand for RE. [11.5.3.3]

Policies for deployment: Electricity

To date, far more policies have been enacted to promote RE for electricity generation than for heating and cooling or transport. These include fiscal incentives and public finance to promote investment in and generation of RE electricity, as well as a variety of electricity-specific regulatory policies. Although governments use a variety of policy types to promote RE electricity, the most common policies in use are FITs and quotas or Renewable Portfolio Standards (RPS). [11.5.4]

There is a wealth of literature assessing quantity-based (quotas, RPS; and tendering/bidding policies) and price-based (fixed-price and premium-price FITs) policies, primarily quotas and FITs, and with a focus on effectiveness and efficiency criteria. A number of historical studies, including those carried out for the European Commission, have concluded that 'well-designed' and 'well–implemented' FITs have to date been the most efficient (defined as comparison of total support received and generation cost) and effective (ability to deliver an increase in the share of RE electricity consumed) support policies for promoting RE electricity. [11.5.4]

One main reason for the success of well-implemented FITs is that they usually guarantee high investment security due to the combination of long-term fixed-price payments, network connection, and guaranteed grid access for all generation. Well-designed FITs have encouraged both technological and geographic diversity, and have been found to be more suitable for promoting projects of varying sizes. The success of FIT policies depends on the details. The most effective and efficient policies have included most or all of the following elements [11.5.4.3]:

- Utility purchase obligation;
- Priority access and dispatch;
- Tariffs based on cost of generation and differentiated by technology type and project size, with carefully calculated starting values;
- Regular long-term design evaluations and short-term payment level adjustments, with incremental adjustments built into law in order to reflect changes in technologies and the marketplace, to encourage innovation and technological change, and to control costs;
- Tariffs for all potential generators, including utilities;
- Tariffs guaranteed for a long enough time period to ensure an adequate rate of return;
- Integration of costs into the rate base and shared equally across country or region;
- Clear connection standards and procedures to allocate costs for transmission and distribution;
- Streamlined administrative and application processes; and
- Attention to preferred exempted groups, for example, major users on competitiveness grounds or low-income and other vulnerable customers.

Experiences in several countries demonstrate that the effectiveness of quota schemes can be high and compliance levels achieved if RE certificates are delivered under well-designed policies with long-term contracts that mute (if not eliminate) price volatility and reduce risk. However, they have been found to benefit the most mature, least-cost technologies. This effect can be addressed in the design of the

policy if different RE options are distinguished or are paired with other incentives. The most effective and efficient quantity-based mechanisms have included most if not all of the following elements, particularly those that help to minimize risk [11.5.4.3]:

- Application to large segment of the market (quota only);
- Clearly defined eligibility rules including eligible resources and actors (applies to quotas and tendering/bidding);
- Well-balanced supply-demand conditions with a clear focus on new capacities—quotas should exceed existing supply but be achievable at reasonable cost (quota only);
- Long-term contracts/specific purchase obligations and end dates, and no time gaps between one quota and the next (quota only);
- Adequate penalties for non-compliance, and adequate enforcement (applies to quotas and tendering/bidding);
- Long-term targets, of at least 10 years (quota only);
- Technology-specific bands or carve-outs to provide differentiated support (applies to quotas and tendering/bidding); and
- Minimum payments to enable adequate return and financing (applies to quotas and tendering/bidding).

Net metering enables small producers to 'sell' into the grid, at the retail rate, any renewable electricity that they generate in excess of their total demand in real time as long as that excess generation is compensated for by excess customer load at other times during the designated netting period. It is considered a low-cost, easily administered tool for motivating customers to invest in small-scale, distributed power and to feed it into the grid, while also benefiting providers by improving load factors if RE electricity is produced during peak demand periods. On its own, however, it is generally insufficient to stimulate significant growth of less competitive technologies like PV at least where generation costs are higher than retail prices. [11.5.4]

Policies for deployment: Heating and cooling

An increasing number of governments are adopting incentives and mandates to advance RE heating and cooling (H/C) technologies. Support for RE H/C presents policymakers with a unique challenge due to the often distributed nature of heat generation. Heating and cooling services can be provided via small- to medium-scale installations that service a single dwelling, or can be used in large-scale applications to provide district heating and cooling. Policy instruments for both RE heating (RE-H) and cooling (RE-C) need to specifically address the more heterogeneous characteristics of resources, including their wide range in scale, varying ability to deliver different levels of temperature, widely distributed demand, relationship to heat load, variability of use, and the absence of a central delivery or trading mechanism. [11.5.5]

The number of policies to support RE sources of heating and cooling has increased in recent years, resulting in increasing generation of RE H/C. However, a majority of support mechanisms have been focused on RE-H. Policies in place to promote RE-H include fiscal incentives such as rebates and grants, tax reductions and tax credits; public finance policies like loans; regulations such as use obligations; and educational efforts. [11.5.5.1–11.5.5.3, 11.6]

To date, fiscal incentives have been the prevalent policy in use, with grants being the most commonly applied. Tax credits available after the installation of a RE-H system (i.e., ex-post) may be logistically advantageous over, for example, grants requiring pre-approval before installation, though there is limited experience with this option. Regulatory mechanisms like use obligations and quotas have attracted increased interest for their potential to encourage growth of RE-H independent of public budgets, though there has been little experience with these policies to date. [11.5.5]

Similar to RE electricity and RE transport, RE H/C policies will be better suited to particular circumstances/locations if, in their design, consideration is given to the state of maturity of the particular technology, of the existing markets and of the existing supply chains. Production incentives are considered be more effective for larger H/C systems, such as district heating grids, than they are for smaller, distributed onsite H/C generation installations for which there are few cost-effective metering or monitoring procedures. [11.5.5]

Though there are some examples of policies supporting RE-C technologies, in general policy aiming to drive deployment of RE-C solely is considerably less well-developed than that for RE-H. Many of the mechanisms described in the above paragraphs could also be applied to RE-C, generally with similar advantages and disadvantages. The lack of experience with deployment policies for RE-C is probably linked to the early levels of technological development of many RE-C technologies. R&D support as well as policy support to develop the early market and supply chains may be of particular importance for increasing the deployment of RE-C technologies in the near future. [11.5.5.4]

Policies for deployment: Transportation

A range of policies has been implemented to support the deployment of RE for transport, though the vast majority of these policies and related experiences have been specific to biofuels. Biofuel support policies aim to promote domestic consumption via fiscal incentives (e.g., tax exemptions for biofuel at the pump) or regulations (e.g., blending mandates), or to promote domestic production via public finance (e.g., loans) for production facilities, via feedstock support or tax incentives (e.g., excise tax exemptions). Most commonly, governments enact a combination of policies. [11.5.6]

Tax incentives are commonly used to support biofuels because they change their cost-competitiveness relative to fossil fuels. They can be installed along the whole biofuel value chain, but are most commonly provided to either biofuel producers (e.g., excise tax exemptions/credits) and/or to end consumers (e.g., tax reductions for biofuels at the pump). [11.5.6]

However, several European and other G8+5 countries have begun gradually shifting from the use of tax breaks for biofuels to blending mandates. It is difficult to assess the level of support under biofuel mandates because prices implied by these obligations are generally

not public (in contrast to the electricity sector, for example). While mandates are key drivers in the development and growth of most modern biofuels industries, they are found to be less appropriate for the promotion of specific types of biofuel because fuel suppliers tend to blend low-cost biofuels. By nature, mandates need to be carefully designed and accompanied by further requirements in order to reach a broader level of distributional equity and to minimize potential negative social and environmental impacts. Those countries with the highest share of biofuels in transport fuel consumption have had hybrid systems that combine mandates (including penalties) with fiscal incentives (tax exemptions foremost). [11.5.6]

Synthesis

Some policy elements have been shown to be more effective and efficient in rapidly increasing RE deployment and enabling governments and society to achieve specific targets. The details of policy design and implementation can be as important in determining effectiveness and efficiency as the specific policies that are used. Key policy elements include [11.5.7]:

- Adequate value derived from subsidies, FITs, etc. to cover cost such that investors are able to recover their investment at a rate of return that matches their risk.
- Guaranteed access to networks and markets or at a minimum clearly defined exceptions to that guaranteed access.
- Long-term contracts to reduce risk thereby reducing financing costs.
- Provisions that account for diversity of technologies and applications. RE technologies are at varying levels of maturity and with different characteristics, often facing very different barriers. Multiple RE sources and technologies may be needed to mitigate climate change, and some that are currently less mature and/or more costly than others could play a significant role in the future in meeting energy needs and reducing GHG emissions.
- Incentives that decline predictably over time as technologies and/or markets advance.
- Policy that is transparent and easily accessible so that actors can understand the policy and how it works, as well as what is required to enter the market and/or to be in compliance. Also includes longer-term transparency of policy goals, such as medium- and long-term policy targets.
- Inclusive, meaning that the potential for participation is as broad as possible on both the supply side (traditional producers, distributors of technologies or energy supplies, whether electricity, heat or fuel), and the demand side (businesses, households, etc.), which can 'self-generate' with distributed RE, enabling broader participation that unleashes more capital for investment, helps to build broader public support for RE, and creates greater competition.
- Attention to preferred exempted groups, for example, major users on competitiveness grounds or low-income and vulnerable customers on equity and distributional grounds.

It is also important to recognize that there is no one-size-fits-all policy, and policymakers can benefit from the ability to learn from experience and adjust programmes as necessary. Policies need to respond to local political, economic, social, ecological, cultural and financial needs and conditions, as well as factors such as the level of technological maturity, availability of affordable capital, and the local and national RE resource base. In addition, a mix of policies is generally needed to address the various barriers to RE. Policy frameworks that are transparent and sustained—from predictability of a specific policy, to pricing of carbon and other externalities, to long-term targets for RE—have been found to be crucial for reducing investment risks and facilitating deployment of RE and the evolution of low-cost applications. [11.5.7]

Macroeconomic impacts of renewable energy policies

Payment for supply-push type RE support tends to come from public budgets (multinational, national, local), whereas the cost of demand-pull mechanisms often lands on the end users. For example, if a renewable electricity policy is added to a countries' electricity sector, this additional cost is often borne by electricity consumers, although exemptions or re-allocations can reduce costs for industrial or vulnerable customers where necessary. Either way, there are costs to be paid. If the goal is to transform the energy sector over the next several decades, then it is important to minimize costs over this entire period; it is also important to include all costs and benefits to society in that calculation. [11.5.7.2]

Conducting an integrated analysis of costs and benefits of RE is extremely demanding because so many elements are involved in determining net impacts. Effects fall into three categories: direct and indirect costs of the system as well as benefits of RE expansion; distributional effects (in which economic actors or groups enjoy benefits or suffer burdens as a result of RE support); and macroeconomic aspects such as impacts on GDP or employment. For example, RE policies provide opportunities for potential economic growth and job creation, but measuring net effects is complex and uncertain because the additional costs of RE support create distributional and budget effects on the economy. Few studies have examined such impacts on national or regional economies; however, those that have been carried out have generally found net positive economic impacts. [11.3.4, 11.5.7.2]

Interactions and potential unintended consequences of renewable energy and climate policies

Due to overlapping drivers and rationales for RE deployment and overlapping jurisdictions (local, national, international) substantial interplay

may occur among policies at times with unintended consequences. Therefore, a clear understanding of the interplay among policies and the cumulative effects of multiple policies is crucial. [11.3, 11.5.7, 11.6.2]

If not applied globally and comprehensively, both carbon pricing and RE policies create risks of 'carbon leakage', where RE policies in one jurisdiction or sector reduce the demand for fossil fuel energy in that jurisdiction or sector, which *ceteris paribus* reduces fossil fuel prices globally and hence increases demand for fossil energy in other jurisdictions or sectors. Even if implemented globally, suboptimal carbon prices and RE policies could potentially lead to higher carbon emissions. For example, if fossil fuel resource owners fear more supportive RE deployment policies in the long term, they could increase resource extraction as long as RE support is moderate. Similarly, the prospect of future carbon price increases may encourage owners of oil and gas wells to extract resources more rapidly, while carbon taxes are lower, undermining policymakers' objectives for both the climate and the spread of RE technology. The conditions of such a 'green paradox' are rather specific: carbon pricing would have to begin at low levels and increase rapidly. Simultaneously, subsidized RE would have to remain more expensive than fossil fuel-based technologies. However, if carbon prices and RE subsidies begin at high levels from the beginning, such green paradoxes become unlikely. [11.5.7]

The cumulative effect of combining policies that set fixed carbon prices, like carbon taxes, with RE subsidies is largely additive: in other words, extending a carbon tax with RE subsidies decreases emissions and increases the deployment of RE. However, the effect on the energy system of combining endogenous-price policies, like emissions trading and/or RE quota obligations, is usually not as straightforward. Adding RE policies on top of an emissions trading scheme usually reduces carbon prices which, in turn, makes carbon-intensive (e.g., coal-based) technologies more attractive compared to other non-RE abatement options such as natural gas, nuclear energy and/or energy efficiency improvements. In such cases, although overall emissions remain fixed by the cap, RE policies reduce the costs of compliance and/or improve social welfare only if RE technologies experience specific externalities and market barriers to a greater extent than other energy technologies. [11.5.7]

Finally, RE policies alone (i.e., without carbon pricing) are not necessarily an efficient instrument to reduce carbon emissions because they do not provide enough incentives to use all available least-cost mitigation options, including non-RE low-carbon technologies and energy efficiency improvements. [11.5.7]

11.6 Enabling environment and regional issues

RE technologies can play a greater role in climate change mitigation if they are implemented in conjunction with broader 'enabling' policies that can facilitate change in the energy system. An 'enabling' environment encompasses different institutions, actors (e.g., the finance community, business community, civil society, government), infrastructures (e.g., networks and markets), and political outcomes (e.g., international agreements/cooperation, climate change strategies) (see Table TS.11.1). [11.6]

A favourable or 'enabling' environment for RE can be created by encouraging innovation in the energy system; addressing the possible interactions of a given policy with other RE policies as well as with other non-RE policies; easing the ability of RE developers to obtain finance and to successfully site a project; removing barriers for access to networks and markets for RE installations and output; enabling technology transfer and capacity building; and by increasing education and awareness raising at the institutional level and within communities. In turn, the existence of an 'enabling' environment can increase the efficiency and effectiveness of policies to promote RE. [11.6.1–11.6.8]

A widely accepted conclusion in innovation literature is that established socio-technical systems tend to narrow the diversity of innovations because the prevailing technologies develop a fitting institutional environment. This may give rise to strong path dependencies and exclude (or lock out) rivalling and potentially better-performing alternatives. For these reasons, socio-technical system change takes time, and it involves change that is systemic rather than linear. RE technologies are being integrated into an energy system that, in much of the world, was constructed to accommodate the existing energy supply mix. As a result, infrastructure favours the currently dominant fuels, and existing lobbies and interests all need to be taken into account. Due to the intricacies of technological change, it is important that all levels of government (from local through to international) encourage RE development through policies, and that nongovernmental actors also be involved in policy formulation and implementation. [11.6.1]

Government policies that complement each other are more likely to be successful, and the design of individual RE policies will also affect the success of their coordination with other policies. Attempting to actively promote the complementarities of policies across multiple sectors—from energy to agriculture to water policy, etc.—while also considering the independent objectives of each, is not an easy task and may create win-win and/or win-lose situations, with possible trade-offs. This implies a need for strong central coordination to eliminate contradictions and conflicts among sectoral policies and to simultaneously coordinate action at more than one level of governance. [11.6.2]

A broader enabling environment includes a financial sector that can offer access to financing on terms that reflect the specific risk/reward profile of a RE technology or project. The cost of financing and access to it depends on the broader financial market conditions prevalent at the time of investment, and on the specific risks of a project, technology, and actors involved. Beyond RE-specific policies, broader conditions can

Table TS.11.1 | Factors and participants contributing to a successful RE governance regime. [Table 11.4]

Dimensions of an Enabling Environment >> Factors and actors contributing to the success of RE policy	Section 11.6.2 Integrating Policies (national/ supranational policies)	Section 11.6.3 Reducing Financial and Investment Risk	Section 11.6.4 Planning and Permitting at the local level	Section 11.6.5 Providing infrastructures networks and markets for RE technology	Section 11.6.6 Technology Transfer and Capacity Building	Section 11.6.7 Learning from actors beyond government
Institutions	Integrating RE policies with other policies at the design level reduces potential for conflict among government policies	Development of financing institutions and agencies can aid cooperation between countries, provide soft loans or international carbon finance (CDM). Long-term commitment can reduce the perception of risk	Planning and permitting processes enable RE policy to be integrated with non-RE policies at the local level	Policymakers and regulators can enact incentives and rules for networks and markets, such as security standards and access rules	Reliability of RE technologies can be ensured through certification Institutional agreements enable technology transfer	Openness to learning from other actors can complement design of policies and enhance their effectiveness by working within existing social conditions
Civil society (individuals, households, NGOs, unions ...)	Municipalities or cities can play a decisive role in integrating state policies at the local level	Community investment can share and reduce investment risk Public-private partnerships in investment and project development can contribute to reducing risks associated with policy instruments Appropriate international institutions can enable an equitable distribution of funds	Participation of civil society in local planning and permitting processes might allow for selection of the most socially relevant RE projects	Civil society can become part of supply networks through co-production of energy and new decentralized models.	Local actors and NGOs can be involved in technology transfer through new business models bringing together multi-national companies / NGOs / Small and Medium Enterprises	Civil society participation in open policy processes can generate new knowledge and induce institutional change Municipalities or cities may develop solutions to make RE technology development possible at the local level People (individually or collectively) have a potential for advancing energy-related behaviours when policy signals and contextual constraints are coherent
Finance and business communities		Public private partnerships in investment and project development can contribute to reducing risks associated with policy instruments	RE project developers can offer know-how and professional networks in : i) aligning project development with planning and permitting requirements ; ii) adapting planning and permitting processes to local needs and conditions Businesses can be active in lobbying for coherent and integrated policies	Clarity of network and market rules improves investor confidence	Financing institutions and agencies can partner with national governments, provide soft loans or international carbon finance (CDM).	Multi-national companies can involve local NGOs or SMEs as partners in new technology development (new business models) Development of corporations and international institutions reduces risk of investment
Infrastructures	Policy integration with network and market rules can enable development of infrastructure suitable for a low-carbon economy	Clarity of network and market rules reduces risk of investment and improves investor confidence		Clear and transparent network and market rules are more likely to lead to infrastructures complementary to a low-carbon future		City and community level frameworks for the development of long-term infrastructure and networks can sustain the involvement of local actors in policy development

Continued next Page →

Dimensions of an Enabling Environment >> Factors and actors contributing to the success of RE policy	Section 11.6.2 Integrating Policies (national/ supranational policies)	Section 11.6.3 Reducing Financial and Investment Risk	Section 11.6.4 Planning and Permitting at the local level	Section 11.6.5 Providing infrastructures networks and markets for RE technology	Section 11.6.6 Technology Transfer and Capacity Building	Section 11.6.7 Learning from actors beyond government
Politics (international agreements / cooperation, climate change strategy, technology transfer...)	Supra-national guidelines (e.g., EU on "streamlining", ocean planning, impact study) may contribute to integrating RE policy with other policies	Long-term political commitment to RE policy reduces investors risk in RE projects	Supra- national guidelines may contribute to evolving planning and permitting processes	Development cooperation helps sustain infrastructure development and allows easier access to low-carbon technologies	CDMs, Intellectual property rights (IPR) and patent agreements can contribute to technology transfer	Appropriate input from non-government institutions stimulates more agreements that are socially connected UNFCCC process mechanisms such as Expert Group on Technology Transfer (EGTT), the Global Environment Facility (GEF), and the Clean Development Mechanism (CDM) and Joint Implementation (JM) may provide guidelines to facilitate the involvement of non-state actors in RE policy development

include political and currency risks, and energy-related issues such as competition for investment from other parts of the energy sector, and the state of energy sector regulations or reform. [11.6.3]

The successful deployment of RE technologies to date has depended on a combination of favourable planning procedures at both national and local levels. Universal procedural fixes, such as 'streamlining' of permitting applications, are unlikely to resolve conflicts among stakeholders at the level of project deployment because they would ignore place- and scale-specific conditions. A planning framework to facilitate the implementation of RE might include the following elements: aligning stakeholder expectations and interests; learning about the importance of context for RE deployment; adopting benefit-sharing mechanisms; building collaborative networks; and implementing mechanisms for articulating conflict for negotiation. [11.6.4]

After a RE project receives planning permission, investment to build it is only forthcoming once its economic connection to a network is agreed; when it has a contract for the 'off-take' of its production into the network; and when its sale of energy, usually via a market, is assured. The ability, ease and cost of fulfilling these requirements is central to the feasibility of a RE project. Moreover, the methods by which RE is integrated into the energy system will have an effect on the total system cost of RE integration and the cost of different scenario pathways. In order to ensure the timely expansion and reinforcement of infrastructure for and connection of RE projects, economic regulators may need to allow 'anticipatory' or 'proactive' network investment and/or allow projects to connect in advance of full infrastructure reinforcement. [11.6.5, 8.2.1.3]

For many countries, a major challenge involves gaining access to RE technologies. Most low-carbon technologies, including RE technologies, are developed and concentrated in a few countries. It has been argued that many developing nations are unlikely to 'leapfrog' pollution-intensive stages of industrial development without access to clean technologies that have been developed in more advanced economies. However, technologies such as RE technologies typically do not flow across borders unless environmental policies in the recipient country provide incentives for their adoption. Further, technology transfer should not replace but rather should complement domestic efforts at capacity building. In order to have the capacity to adapt, install, maintain, repair and improve on RE technologies in communities without ready access to RE, investment in technology transfer must be complemented by investment in community-based extension services that provide expertise, advice and training regarding installation, technology adaptation, repair and maintenance. [11.6.6]

In addition to technology transfer, institutional learning plays an important role in advancing deployment of RE. Institutional learning is conducive to institutional change, which provides space for institutions to improve the choice and design of RE policies. It also encourages a stronger institutional capacity at the deeper, often more local, level where numerous decisions are made on siting and investments in RE projects. Institutional learning can occur if policymakers can draw on nongovernmental actors, including private actors (companies, etc.) and civil society for collaborative approaches in policymaking. Information and education are often emphasized as key policy tools for influencing energy-related behaviours. However, the effectiveness of education- and information-based policies is limited by contextual factors, which cautions against an over-reliance on information- and education-based policies alone. Changes in energy-related behaviours are the outcome of a process in which personal norms or attitudes interact with prices, policy signals, and the RE technologies themselves, as well as the social context in which individuals

find themselves. These contextual factors point to the importance of collective action as a more effective, albeit more complex medium for change than individual action. This supports coordinated, systemic policies that go beyond narrow 'attitude-behaviour-change' policies if policymakers wish to involve individuals in the RE transition. [11.6.7, 11.6.8]

11.7 A structural shift

If decision makers intend to increase the share of RE and, at the same time, meet ambitious climate mitigation targets, then long-standing commitments and flexibility to learn from experience will be critical. To achieve GHG concentration stabilization levels with high shares of RE, a structural shift in today's energy systems will be required over the next few decades. Such a transition to low-carbon energy differs from previous energy transitions (e.g., from wood to coal, or coal to oil) because the available time span is restricted to a few decades, and because RE must develop and integrate into a system constructed in the context of an existing energy structure that is very different from what might be required under higher penetration RE futures. [11.7]

A structural shift towards a world energy system that is mainly based on renewable energy might begin with a prominent role for energy efficiency in combination with RE. This requires, however, a reasonable carbon pricing policy in the form of a tax or emission trading scheme that avoids carbon leakage and rebound effects. Additional policies are required that extend beyond R&D to support technology deployment; the creation of an enabling environment that includes education and awareness raising; and the systematic development of integrative policies with broader sectors, including agriculture, transportation, water management and urban planning. [11.6, 11.7] The policy frameworks that induce the most RE investment are those designed to reduce risks and enable attractive returns, and to provide stability over a time frame relevant to the investment. [11.5] The appropriate and reliable mix of instruments is even more important where energy infrastructure is not yet developed and energy demand is expected to increase significantly in the future. [11.7]

Annexes

ANNEX I

Glossary, Acronyms, Chemical Symbols and Prefixes

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Glossary, Acronyms, Chemical Symbols and Prefixes

Glossary entries (highlighted in **bold**) are by preference subjects; a main entry can contain **subentries**, in bold italic, for example, ***Final Energy*** is defined under the entry **Energy**. The Glossary is followed by a list of acronyms/abbreviations, a list of chemical names and symbols, and a list of prefixes (international standard units). Some definitions are adapted from C.J. Cleveland and C. Morris, 2006: *Dictionary of Energy*, Elsevier, Amsterdam. Definitions of regions and country groupings are given in Section A.II.6 of Annex II of this report.

Glossary

Adaptation: Initiatives and measures to reduce the vulnerability or increase the resilience of natural and human systems to actual or expected climate change impacts. Various types of adaptation exist, for example, anticipatory and reactive, private and public, and autonomous and planned. Examples are raising river or coastal dikes, retreating from coastal areas subject to flooding from sea level rise or introducing alternative temperature-appropriate or drought-adapted crops for conventional ones.

Aerosols: A collection of airborne solid or liquid particles, typically between 0.01 and 10 µm in size and residing in the atmosphere for at least several hours. Aerosols may be of natural or anthropogenic origin. See also black carbon.

Afforestation: Direct human-induced conversion of land that has not been forested historically to forested land through planting, seeding and/or the human-induced promotion of natural seed sources.[1] See also deforestation, reforestation, land use.

Annex I countries: The group of countries included in Annex I (as amended since Malta was added after that date) to the UNFCCC, including developed countries and some countries with economies in transition. Under Articles 4.2 (a) and 4.2 (b) of the Convention, Annex I countries were encouraged to return individually or jointly to their 1990 levels of greenhouse gas emissions by 2000. The group is largely similar to the Annex B countries to the Kyoto Protocol. By default, the other countries are referred to as **Non-Annex I countries**. See also UNFCCC, Kyoto Protocol.

Annex B countries: This is the subset of Annex I countries that have specified greenhouse gas reduction commitments under the Kyoto Protocol. The group is largely similar to the Annex I countries to the UNFCCC. By default, the other countries are referred to as Non-Annex I countries. See also UNFCCC, Kyoto Protocol.

Anthropogenic: Related to or resulting from the influence of human beings on nature.

> ***Anthropogenic emissions*** of greenhouse gases, greenhouse gas precursors and aerosols result from burning fossil fuels, deforestation, land use changes, livestock, fertilization, industrial, commercial and other activities that result in a net increase in emissions.

Availability (of a production plant): The percentage of time a plant is ready to produce, measured as uptime to total time (total time = uptime + downtime due to maintenance and outages).

Balancing power/reserves: Due to instantaneous and short-term fluctuations in electric loads and uncertain availability of power plants there is a constant need for spinning and quick-start generators that balance demand and supply at the imposed quality levels for frequency and voltage.

Barrier: Any obstacle to developing and deploying a renewable energy (RE) potential that can be overcome or attenuated by a policy, programme or measure. Barriers to RE deployment are unintentional or intentionally constructed impediments made by man (e.g., badly oriented buildings or power grid access criteria that discriminate against independent RE generators). Distinct from barriers are issues like intrinsically natural properties impeding the application of some RE sources at some place or time (e.g., flat land impedes hydropower and night the collection of direct solar energy).

> ***Barrier removal*** includes correcting market failures directly or reducing the transactions costs in the public and private sectors by, for example, improving institutional capacity, reducing risk and uncertainty, facilitating market transactions and enforcing regulatory policies.

Baseline: The reference scenario for measurable quantities from which an alternative outcome can be measured, for example, a non-intervention scenario is used as a reference in the analysis of intervention scenarios. A baseline may be an extrapolation of recent trends, or it may assume frozen technology or costs. See also business as usual, models, scenario.

1 For a discussion of the term *forest* and related terms such as *afforestation*, *reforestation* and *deforestation*, see IPCC 2000: *Land Use, Land-Use Change, and Forestry*, A Special Report of the IPCC [R.T. Watson, I.A. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo, D.J. Dokken (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Benchmark: A measurable variable used as a baseline or reference in evaluating the performance of a technology, a system or an organization. Benchmarks may be drawn from internal experience, from external correspondences or from legal requirements and are often used to gauge changes in performance over time.

Biodiversity: The variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, among species and of ecosystems.

Bioenergy: Energy derived from any form of biomass.

Biofuel: Any liquid, gaseous or solid fuel produced from biomass, for example, soybean oil, alcohol from fermented sugar, black liquor from the paper manufacturing process, wood as fuel, etc. Traditional biofuels include wood, dung, grass and agricultural residues.

First-generation manufactured biofuel is derived from grains, oilseeds, animal fats and waste vegetable oils with mature conversion technologies.

Second-generation biofuel uses non-traditional biochemical and thermochemical conversion processes and feedstock mostly derived from the lignocellulosic fractions of, for example, agricultural and forestry residues, municipal solid waste, etc.

Third-generation biofuel would be derived from feedstocks like algae and energy crops by advanced processes still under development. These second- and third-generation biofuels produced through new processes are also referred to as next-generation or advanced biofuels or advanced biofuel technologies.

Biomass: Material of biological origin (plants or animal matter), excluding material embedded in geological formations and transformed to fossil fuels or peat. The International Energy Agency (*World Energy Outlook 2010*) defines **traditional biomass** as biomass consumption in the residential sector in developing countries that refers to the often unsustainable use of wood, charcoal, agricultural residues and animal dung for cooking and heating. All other biomass use is defined as **modern biomass**, differentiated further by this report into two groups.

Modern bioenergy encompasses electricity generation and combined heat and power (CHP) from biomass and municipal solid waste (MSW), biogas, residential space and hot water in buildings and commercial applications from biomass, MSW, and biogas, and liquid transport fuels.

Industrial bioenergy applications include heating through steam generation and self generation of electricity and CHP in the pulp and paper industry, forest products, food and related industries.

Black carbon: Operationally defined aerosol species based on measurement of light absorption and chemical reactivity and/or thermal stability; consists of soot, charcoal and/or light-absorbing refractory organic matter.

Business as usual (BAU): The future is projected or predicted on the assumption that operating conditions and applied policies remain what they are at present. See also baseline, models, scenario.

Capacity: In general, the facility to produce, perform, deploy or contain.

Generation capacity of a renewable energy installation is the maximum power, that is, the maximum quantity of energy delivered per unit of time.

Capacity credit is the share of the capacity of a renewable energy unit counted as guaranteed available during particular time periods and accepted as a 'firm' contribution to total system generation capacity.

Capacity factor is the ratio of the actual output of a generating unit over a period of time (typically a year) to the theoretical output that would be produced if the unit were operating uninterruptedly at its **nameplate capacity** during the same period of time. Also known as rated capacity or nominal capacity, **nameplate capacity** is the facility's intended output level for a sustained period under normal circumstances.

Capacity building: In the context of climate change policies, the development of technical skills and institutional capability (the art of doing) and capacity (sufficient means) of countries to enable their participation in all aspects of adaptation to, mitigation of and research on climate change. See also mitigation capacity.

Carbon cycle: Describes the flow of carbon (in various forms, e.g., carbon dioxide, methane, etc) through the atmosphere, oceans, terrestrial biosphere and lithosphere.

Carbon dioxide (CO_2): CO_2 is a naturally occurring gas and a by-product of burning fossil fuels or biomass, of land use changes and of industrial processes. It is the principal anthropogenic greenhouse gas that affects Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore it has a global warming potential of 1.

Carbon dioxide capture and storage (CCS): CO_2 from industrial and energy-related sources is separated, compressed and transported to a storage location for long-term isolation from the atmosphere.

Cellulose: The principal chemical constituent of the cell walls of plants and the source of fibrous materials for the manufacturing of

various goods like paper, rayon, cellophane, etc. It is the main input for manufacturing second-generation biofuels.

Clean Development Mechanism (CDM): A mechanism under the Kyoto Protocol through which developed (Annex B) countries may finance greenhouse gas emission reduction or removal projects in developing (Non-Annex B) countries, and receive credits for doing so which they may apply for meeting mandatory limits on their own emissions.

Climate Change: Climate change refers to a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of these properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that Article 1 of the UNFCCC defines 'climate change' as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". The UNFCCC thus makes a distinction between 'climate change' attributable to human activities altering atmospheric composition, and 'climate variability' attributable to natural causes.

CO_2-equivalent emission (CO_2eq): The amount of CO_2 emission that would cause the same radiative forcing as an emitted amount of a greenhouse gas or of a mixture of greenhouse gases, all multiplied by their respective global warming potentials, which take into account the differing times they remain in the atmosphere. See also global warming potential.

Co-benefits: The ancillary benefits of targeted policies that accrue to non-targeted, valuable objectives, for example, a wider use of renewable energy may also reduce air pollutants while lowering CO_2 emissions. Different definitions exist in the literature with co-benefits either being addressed intentionally (character of an opportunity) or gained unintentionally (character of a windfall profit). The term co-impact is more generic in covering both benefits and costs. See also drivers and opportunities.

Cogeneration: At thermal electricity generation plants otherwise wasted heat is utilized. The heat from steam turbines or hot flue gases exhausted from gas turbines may be used for industrial purposes, heating water or buildings or for district heating. Also referred to as combined heat and power (CHP).

Combined-cycle gas turbine (CCGT): A power plant that combines two processes for generating electricity. First, gas or light fuel oil feeds a gas turbine that exhausts hot flue gases (> 600°C). Second, heat recovered from these gases, with additional firing, is the source for producing steam that drives a steam turbine. The turbines rotate separate alternators. It becomes an **integrated CCGT** when the fuel is syngas from a coal or biomass gasification reactor with exchange of energy flows between the gasification and CCGT plants.

Compliance: Compliance is whether and to what extent countries adhere to the provisions of an accord or individuals or firms adhere to regulations. Compliance depends on implementing policies ordered, and on whether measures follow up the policies.

Conversion: Energy shows itself in numerous ways, with transformations from one type to another called energy conversions. For example, kinetic energy in wind flows is captured as rotating shaft work further converted to electricity; solar light is converted into electricity by photovoltaic cells. Also, electric currents of given characteristics (e.g., direct/alternating, voltage level) are converted to currents with other characteristics. A **converter** is the equipment used to realize the conversion.

Cost: The consumption of resources such as labour time, capital, materials, fuels, etc. as the consequence of an action. In economics, all resources are valued at their **opportunity cost**, which is the value of the most valuable alternative use of the resources. Costs are defined in a variety of ways and under a variety of assumptions that affect their value. The negative of costs are benefits and often both are considered together, for example, net cost is the difference between gross costs and benefits.

Private costs are carried by individuals, companies or other entities that undertake the action.

Social costs include additionally the external costs for the environment and for society as a whole, for example, **damage costs** of impacts on ecosystems, economies and people due to climate change.

Total cost includes all costs due to a specific activity; **average (unit, specific) cost** is total costs divided by the number of units generated; **marginal or incremental cost** is the cost of the last additional unit.

Project costs of a renewable energy project include **investment cost** (costs, discounted to the starting year of the project, of making the renewable energy device ready to commence production); **operation and maintenance (O&M) costs** (which occur during operation of the renewable energy facility); and **decommissioning costs** (which occur once the device has ceased production to restore the state of the site of production).

Lifecycle costs include all of the above discounted to the starting year of a project.

Levelized cost of energy (see Annex II) is the unique cost price of the outputs (US cent/kWh or USD/GJ) of a project that makes the

present value of the revenues (benefits) equal to the present value of the costs over the lifetime of the project. See also discounting and present value.

There are many more categories of costs labelled with names that are often unclear and confusing, for example, installation costs may refer to the hardware equipment installed, or to the activities to put the equipment in place.

Cost–benefit analysis: Monetary measurement of all negative and positive impacts associated with a given action. Costs and benefits are compared in terms of their difference and/or ratio as an indicator of how a given investment or other policy effort pays off seen from the society's point of view.

Cost-effectiveness analysis: A reduction of cost–benefit analysis in which all the costs of a portfolio of projects are assessed in relation to a fixed policy goal. The policy goal in this case represents the benefits of the projects and all the other impacts are measured as costs or as negative costs (benefits). The policy goal can be, for example, realizing particular renewable energy potentials.

Deforestation: The natural or anthropogenic process that converts forest land to non-forest. See also afforestation, reforestation and land use.

Demand-side management: Policies and programmes for influencing the demand for goods and/or services. In the energy sector, demand-side management aims at reducing the demand for electricity and other forms of energy required to deliver energy services.

Density: Quantity or mass per unit volume, unit area or unit length.

Energy density is the amount of energy per unit volume or mass (for example, the heating value of a litre of oil).

Power density is typically understood as the capacity deliverable of solar, wind, biomass, hydropower or ocean power per unit area (watts/m^2). For batteries the capacity per unit weight (watts/kg) is used.

Direct solar energy - See solar energy

Discounting: A mathematical operation making monetary (or other) amounts received or expended at different points in time (years) comparable across time (see Annex II). The operator uses a fixed or possibly time-varying discount rate (>0) from year to year that makes future value worth less today. A **descriptive discounting approach** accepts the discount rates that people (savers and investors) actually apply in their day-to-day decisions (**private discount rate**). In a **prescriptive (ethical** or **normative) discounting approach**, the discount rate is fixed from a social perspective, for example, based on an ethical judgement about the interests of future generations (**social discount rate**). In this report, potentials of renewable energy supplies are assessed using discount rates of 3, 7 and 10%.

Dispatch (power dispatching / dispatchable): Electrical power systems that consist of many power supply units and grids are governed by system operators. They allow generators to supply power to the system for balancing demand and supply in a reliable and economical way. Generation units are fully dispatchable when they can be loaded from zero to their nameplate capacity without significant delay. Not fully dispatchable are variable renewable sources that depend on natural currents, but also large-scale thermal plants with shallow ramping rates in changing their output. See also balancing, capacity, grid.

District heating (DH): Hot water (steam in old systems) is distributed from central stations to buildings and industries in a densely occupied area (a district, a city or an industrialized area). The insulated two-pipe network functions like a water-based central heating system in a building. The central heat sources can be waste heat recovery from industrial processes, waste incineration plants, geothermal sources, cogeneration power plants or stand-alone boilers burning fossil fuels or biomass. More and more DH systems also provide cooling via cold water or slurries (**district heating and cooling - DHC**).

Drivers: In a policy context, drivers provide an impetus and direction for initiating and supporting policy actions. The deployment of renewable energy is, for example, driven by concerns about climate change or energy security. In a more general sense, a driver is the leverage to bring about a reaction, for example, emissions are caused by fossil fuel consumption and/or economic growth. See also opportunities.

Economies of scale (scale economies): The unit cost of an activity declines when the activity is extended, for example, more units are produced.

Ecosystem: An open system of living organisms, interacting with each other and with their abiotic environment, that is capable of self-regulation to a certain degree. Depending on the focus of interest or study the extent of an ecosystem may range from very small spatial scales to the entire planet.

Electricity: The flow of passing charge through a conductor, driven by a difference in voltage between the ends of the conductor. Electrical power is generated by work from heat in a gas or steam turbine or from wind, oceans or falling water, or produced directly from sunlight using a photovoltaic device or chemically in a fuel cell. Being a current, electricity cannot be stored and requires wires and cables for its transmission (see grid). Because electric current flows immediately, the demand for electricity must be matched by production in real time.

Emissions: **Direct emissions** are released and attributed at points in a specific renewable energy chain, whether a sector, a technology or an activity. For example, methane emissions from decomposing submerged

organic materials in hydropower reservoirs, or the release of CO_2 dissolved in hot water from geothermal plants, or CO_2 from biomass combustion. **Indirect emissions** are due to activities outside the considered renewable energy chain but which are required to realize the renewable energy deployment. For example, emissions from increased production of fertilizers used in the cultivation of biofuel crops or emissions from displaced crop production or deforestation as the result of biofuel crops. **Avoided emissions** are emission reductions arising from mitigation measures like renewable energy deployment.

Emission factor: An emission factor is the rate of emission per unit of activity, output or input.

Emissions trading: A market-based instrument to reduce greenhouse gas or other emissions. The environmental objective or sum of total allowed emissions is expressed as an emissions cap. The cap is divided in tradable emission permits that are allocated—either by auctioning or handing out for free (grandfathering)—to entities within the jurisdiction of the trading scheme. Entities need to surrender emission permits equal to the amount of their emissions (e.g., tonnes of CO_2). An entity may sell excess permits. Trading schemes may occur at the intra-company, domestic or international level and may apply to CO_2, other greenhouse gases or other substances. Emissions trading is also one of the mechanisms under the Kyoto Protocol.

Energy: The amount of work or heat delivered. Energy is classified in a variety of types and becomes available to human ends when it flows from one place to another or is converted from one type into another. Daily, the sun supplies large flows of radiation energy. Part of that energy is used directly, while part undergoes several conversions creating water evaporation, winds, etc. Some share is stored in biomass or rivers that can be harvested. Some share is directly usable such as daylight, ventilation or ambient heat.

Primary energy (also referred to as energy sources) is the energy embodied in natural resources (e.g., coal, crude oil, natural gas, uranium, and renewable sources). It is defined in several alternative ways. The International Energy Agency utilizes the physical energy content method, which defines primary energy as energy that has not undergone any anthropogenic conversion. The method used in this report is the direct equivalent method (see Annex II), which counts one unit of secondary energy provided from non-combustible sources as one unit of primary energy, but treats combustion energy as the energy potential contained in fuels prior to treatment or combustion. Primary energy is transformed into **secondary energy** by cleaning (natural gas), refining (crude oil to oil products) or by conversion into electricity or heat. When the secondary energy is delivered at the end-use facilities it is called **final energy** (e.g., electricity at the wall outlet), where it becomes **usable energy** in supplying services (e.g., light).

Embodied energy is the energy used to produce a material substance (such as processed metals or building materials), taking into account energy used at the manufacturing facility (zero order), energy used in producing the materials that are used in the manufacturing facility (first order), and so on.

Renewable energy (RE) is any form of energy from solar, geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use. Renewable energy is obtained from the continuing or repetitive flows of energy occurring in the natural environment and includes low-carbon technologies such as solar energy, hydropower, wind, tide and waves and ocean thermal energy, as well as renewable fuels such as biomass. For a more detailed description see specific renewable energy types in this glossary, for example, biomass, solar, hydropower, ocean, geothermal and wind.

Energy access: People are provided the ability to benefit from affordable, clean and reliable energy services for basic human needs (cooking and heating, lighting, communication, mobility) and productive uses.

Energy carrier: A substance for delivering mechanical work or transfer of heat. Examples of energy carriers include: solid, liquid or gaseous fuels (e.g., biomass, coal, oil, natural gas, hydrogen); pressurized/heated/cooled fluids (air, water, steam); and electric current.

Energy efficiency: The ratio of useful energy or other useful physical outputs obtained from a system, conversion process, transmission or storage activity to the input of energy (measured as kWh/kWh, tonnes/kWh or any other physical measure of useful output like tonne-km transported, etc.). Energy efficiency is a component of energy intensity.

Energy intensity: The ratio of energy inputs (in Joules) to the economic output (in dollars) that absorbed the energy input. Energy intensity is the reciprocal of energy productivity. At the national level, energy intensity is the ratio of total domestic primary (or final) energy use to gross domestic product (GDP). The energy intensity of an economy is the weighted sum of the energy intensities of particular activities with the activities' shares in GDP as weights. Energy intensities are obtained from available statistics (International Energy Agency, International Monetary Fund) and published annually for most countries in the world. Energy intensity is also used as a name for the ratio of energy inputs to output or performance in physical terms (e.g., tonnes of steel output, tonne-km transported, etc.) and in such cases, is the reciprocal of energy efficiency.

Energy productivity: The reciprocal of energy intensity.

Energy savings: Decreasing energy intensity by changing the activities that demand energy inputs. Energy savings can be realized by techni-

cal, organizational, institutional and structural actions and by changed behaviour.

Energy security: The goal of a given country, or the global community as a whole, to maintain an adequate energy supply. Measures encompass safeguarding access to energy resources; enabling development and deployment of technologies; building sufficient infrastructure to generate, store and transmit energy supplies; ensuring enforceable contracts of delivery; and access to energy at affordable prices for a specific society or groups in society.

Energy services: Energy services are the tasks to be performed using energy. A specific energy service such as lighting may be supplied by a number of different means from daylighting to oil lamps to incandescent, fluorescent or light-emitting diode devices. The amount of energy used to provide a service may vary over a factor of 10 or more, and the corresponding greenhouse gas emissions may vary from zero to a very high value depending on the source of energy and the type of end-use device.

Energy transfer: Energy is transferred as work, light or heat. **Heat transfer** spontaneously occurs from objects at higher temperature to objects at lower temperature and is classified as conduction (when the objects have contact), convection (when a fluid like air or water takes the heat from the warmer object and is moved to the colder object to deliver the heat) and radiation (when heat travels through space in the form of electromagnetic waves).

Externality / external cost / external benefit: Externalities arise from a human activity, when agents responsible for the activity do not take full account of the activity's impact on others' production and consumption possibilities, and no compensation exists for such impacts. When the impact is negative, they are external costs. When positive they are referred to as external benefits.

Feed-in tariff: The price per unit of electricity that a utility or power supplier has to pay for distributed or renewable electricity fed into the grid by non-utility generators. A public authority regulates the tariff. There may also be a tariff for supporting renewable heat supplies.

Financing: Raising or providing money or capital by individuals, businesses, banks, venture funds, public instances, etc. for realizing a project or continuing an activity. Depending on the financier the money is raised and is provided differently. For example, businesses may raise money from internal company profits, debt or equity (shares).

> ***Project financing*** of renewable energy may be provided by financiers to distinct, single-purpose companies, whose renewable energy sales are usually guaranteed by power purchase agreements.
>
> ***Non-recourse financing*** is known as off-balance sheet since the financiers rely on the certainty of project cash flows to pay back the loan, not on the creditworthiness of the project developer.
>
> ***Public equity financing*** is capital provided for publicly listed companies.
>
> ***Private equity financing*** is capital provided directly to private companies.
>
> ***Corporate financing*** by banks via debt obligations uses 'on-balance sheet' assets as collateral and is therefore limited by the debt ratio of companies that must rationalize each additional loan with other capital needs.

Fiscal incentive: Actors (individuals, households, companies) are granted a reduction of their contribution to the public treasury via income or other taxes.

Fuel cell: A fuel cell generates electricity in a direct and continuous way from the controlled electrochemical reaction of hydrogen or another fuel and oxygen. With hydrogen as fuel it emits only water and heat (no CO_2) and the heat can be utilized (see cogeneration).

General equilibrium models: General equilibrium models consider simultaneously all the markets and feedback effects among them in an economy leading to market clearance.

Generation control: Generation of electricity at a renewable energy plant may be subject to various controls.

> ***Active control*** is a deliberate intervention in the functioning of a system (for example, wind turbine **pitch control**: changing the orientation of the blades for varying a wind turbine's output).
>
> ***Passive control*** is when natural forces adjust the functioning of a system (for example, wind turbine **stall control**: the design of the blade shape such that at a desired speed the blade spills the wind in order to automatically control the wind turbine's output).

Geothermal energy: Accessible thermal energy stored in the Earth's interior, in both rock and trapped steam or liquid water (hydrothermal resources), which may be used to generate electric energy in a thermal power plant, or to supply heat to any process requiring it. The main sources of geothermal energy are the residual energy available from planet formation and the energy continuously generated from radionuclide decay.

Geothermal gradient: Rate at which the Earth's temperature increases with depth, indicating heat flowing from the Earth's warm interior to its colder parts.

Global warming potential (GWP): GWP is an index, based upon radiative properties of well-mixed greenhouse gases, measuring the radiative forcing of a unit mass of a given well-mixed greenhouse gas in today's atmosphere integrated over a chosen time horizon, relative

to that of CO_2. The GWP represents the combined effect of the differing lengths of time that these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. The Kyoto Protocol ranks greenhouse gases on the basis of GWPs from single pulse emissions over subsequent 100-year time frames. See also climate change and CO_2-equivalent emission.

Governance: Governance is a comprehensive and inclusive concept of the full range of means for deciding, managing and implementing policies and measures. Whereas govern*ment* is defined strictly in terms of the nation-state, the more inclusive concept of gover*nance*, recognizes the contributions of various levels of government (global, international, regional, local) and the contributing roles of the private sector, of nongovernmental actors and of civil society to addressing the many types of issues facing the global community.

Greenhouse gases (GHGs): Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere and clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Besides CO_2, N_2O and CH_4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

Grid (electric grid, electricity grid, power grid): A network consisting of wires, switches and transformers to transmit electricity from power sources to power users. A large network is layered from low-voltage (110-240 V) distribution, over intermediate voltage (1-50 kV) to high-voltage (above 50 kV to MV) transport subsystems. Interconnected grids cover large areas up to continents. The grid is a power exchange platform enhancing supply reliability and economies of scale.

Grid connection for a power producer is mostly crucial for economical operation.

Grid codes are technical conditions for equipment and operation that a power producer must obey for getting supply access to the grid; also consumer connections must respect technical rules.

Grid access refers to the acceptance of power producers to deliver to the grid.

Grid integration accommodates power production from a portfolio of diverse and some variable generation sources in a balanced power system. See also transmission and distribution.

Gross Domestic Product (GDP): The sum of gross value added, at purchasers' prices, by all resident and non-resident producers in the economy, plus any taxes and minus any subsidies not included in the value of the products in a country or a geographic region for a given period, normally one year. It is calculated without deducting for depreciation of fabricated assets or depletion and degradation of natural resources.

Heat exchanger: Devices for efficient **heat transfer** from one medium to another without mixing the hot and cold flows, for example, radiators, boilers, steam generators, condensers.

Heat pump: Installation that transfers heat from a colder to a hotter place, opposite to the natural direction of heat flows (see energy transfer). Technically similar to a refrigerator, heat pumps are used to extract heat from ambient environments like the ground (geothermal or ground source), water or air. Heat pumps can be inverted to provide cooling in summer.

Human Development Index (HDI): The HDI allows the assessment of countries' progress regarding social and economic development as a composite index of three indicators: 1) health measured by life expectancy at birth; 2) knowledge as measured by a combination of the adult literacy rate and the combined primary, secondary and tertiary school enrolment ratio; and 3) standard of living as gross domestic product per capita (in purchasing power parity). The HDI only acts as a broad proxy for some of the key issues of human development; for instance, it does not reflect issues such as political participation or gender inequalities.

Hybrid vehicle: Any vehicle that employs two sources of propulsion, most commonly a vehicle that combines an internal combustion engine with an electric motor and storage batteries.

Hydropower: The energy of water moving from higher to lower elevations that is converted into mechanical energy through a turbine or other device that is either used directly for mechanical work or more commonly to operate a generator that produces electricity. The term is also used to describe the kinetic energy of stream flow that may also be converted into mechanical energy of a generator through an in-stream turbine to produce electricity.

Informal sector/economy: The informal sector/economy is broadly characterized as comprising production units that operate at a small scale and at a low level of organization, with little or no division between labour and capital as factors of production, and with the primary objective of generating income and employment for the persons concerned. The economic activity of the informal sector is not accounted for in determining sectoral or national economic activity.

Institution: A structure, a mechanism of social order or cooperation, which governs the behaviour of a group of individuals within a human

community. Institutions are intended to be functionally relevant for an extended period, able to help transcend individual interests and help govern cooperative human behaviour. The term can be extended to also cover regulations, technology standards, certification and the like.

Integrated assessment: A method of analysis that combines results and models from the physical, biological, economic and social sciences, and the interactions between these components in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it. See also models.

Kyoto Protocol: The Kyoto Protocol to the UNFCCC was adopted at the Third Session of the Conference of the Parties in 1997 in Kyoto. It contains legally binding commitments, in addition to those included in the UNFCCC. Annex B countries agreed to reduce their anthropogenic greenhouse gas emissions (CO_2, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride) by at least 5% below 1990 levels in the commitment period 2008 to 2012. The Kyoto Protocol came into force on 16 February 2005. See also UNFCCC.

Land use (change; direct and indirect): The total of arrangements, activities and inputs undertaken in a certain land cover type. The social and economic purposes for which land is managed (e.g., grazing, timber extraction and conservation).

> ***Land use change*** occurs whenever land is transformed from one use to another, for example, from forest to agricultural land or to urban areas. Since different land types have different carbon storage potential (e.g., higher for forests than for agricultural or urban areas), land use changes may lead to net emissions or to carbon uptake.
>
> ***Indirect land use change*** refers to market-mediated or policy-driven shifts in land use that cannot be directly attributed to land use management decisions of individuals or groups. For example, if agricultural land is diverted to fuel production, forest clearance may occur elsewhere to replace the former agricultural production. See also afforestation, deforestation and reforestation.

Landfill: A solid waste disposal site where waste is deposited below, at or above ground level. Limited to engineered sites with cover materials, controlled placement of waste and management of liquids and gases. It excludes uncontrolled waste disposal. Landfills often release methane, CO_2 and other gases as organic materials decay.

Leapfrogging: The ability of developing countries to bypass intermediate technologies and jump straight to advanced clean technologies. Leapfrogging can enable developing countries to move to a low-emissions development trajectory.

Learning curve / rate: Decreasing cost-prices of renewable energy supplies shown as a function of increasing (total or yearly) supplies. Learning improves technologies and processes over time due to experience, as production increases and/or with increasing research and development. The **learning rate** is the percent decrease of the cost-price for every doubling of the cumulative supplies (also called **progress ratio**).

Levelized cost of energy – See Cost.

Lifecycle analysis (LCA): LCA aims to compare the full range of environmental damages of any given product, technology, or service (see Annex II). LCA usually includes raw material input, energy requirements, and waste and emissions production. This includes operation of the technology/facility/product as well as all upstream processes (i.e., those occurring prior to when the technology/facility/product commences operation) and downstream processes (i.e., those occurring after the useful lifetime of the technology/facility/product), as in the 'cradle to grave' approach.

Load (electrical): The demand for electricity by (thousands to millions) power users at the same moment aggregated and raised by the losses in transport and delivery, and to be supplied by the integrated power supply system.

> ***Load levelling*** reduces the amplitude of the load fluctuations over time.
>
> ***Load shedding*** occurs when available generation or transmission capacity is insufficient to meet the aggregated loads.
>
> ***Peak load*** is the maximum load observed over a given period of time (day, week, year) and of short duration.
>
> ***Base load*** is power continuously demanded over the period.

Loans: Loans are money that public or private lenders provide to borrowers mandated to pay back the nominal sum increased with interest payments.

> ***Soft loans*** (also called soft financing or concessional funding) offer flexible or lenient terms for repayment, usually at lower than market interest rates or no interest. Soft loans are provided customarily by government agencies and not by financial institutions.
>
> ***Convertible loans*** entitle the lender to convert the loan to common or preferred stock (ordinary or preference shares) at a specified conversion rate and within a specified time frame.

Lock-in: Technologies that cover large market shares continue to be used due to factors such as sunk investment costs, related infrastructure development, use of complementary technologies and associated social and institutional habits and structures.

> ***Carbon lock-in*** means that the established technologies and practices are carbon intensive.

Low-carbon technology: A technology that over its lifecycle causes very low to zero CO_2eq emissions. See emissions.

Market failure: When private decisions are based on market prices that do not reflect the real scarcity of goods and services, they do not generate an efficient allocation of resources but cause welfare losses. Factors causing market prices to deviate from real economic scarcity are environmental externalities, public goods and monopoly power.

Measures: In climate policy, measures are technologies, processes or practices that reduce greenhouse gas emissions or impacts below anticipated future levels, for example renewable energy technologies, waste minimization processes, public transport commuting practices, etc. See also policies.

Merit order (of power plants): Ranking of all available power generating units in an integrated power system, being the sequence of their short-run marginal cost per kWh starting with the cheapest for delivering electricity to the grid.

Millennium Development Goals (MDG): A set of eight time-bound and measurable goals for combating poverty, hunger, disease, illiteracy, discrimination against women and environmental degradation. These were agreed to at the UN Millennium Summit in 2000 together with an action plan to reach these goals.

Mitigation: Technological change and changes in activities that reduce resource inputs and emissions per unit of output. Although several social, economic and technological policies would produce an emission reduction, with respect to climate change, mitigation means implementing policies to reduce greenhouse gas emissions and enhance sinks. Renewable energy deployment is a mitigation option when avoided greenhouse gas emissions exceed the sum of direct and indirect emissions (see emissions).

> ***Mitigation capacity*** is a country's ability to reduce anthropogenic greenhouse gas emissions or to enhance natural sinks, where ability refers to skills, competencies, fitness and proficiencies that a country has attained and depends on technology, institutions, wealth, equity, infrastructure and information. Mitigation capacity is rooted in a country's sustainable development path.

Models: Models are structured imitations of a system's attributes and mechanisms to mimic appearance or functioning of systems, for example, the climate, the economy of a country, or a crop. Mathematical models assemble (many) variables and relations (often in a computer code) to simulate system functioning and performance for variations in parameters and inputs.

> ***Bottom-up models*** aggregate technological, engineering and cost details of specific activities and processes.

> ***Top-down models*** apply macroeconomic theory, econometric and optimization techniques to aggregate economic variables, like total consumption, prices, incomes and factor costs.

> ***Hybrid models*** integrate bottom-up and top-down models to some degree.

Non-Annex I countries – See Annex I countries.

Non-Annex B countries – See Annex B countries.

Ocean energy: Energy obtained from the ocean via waves, tidal ranges, tidal and ocean currents, and thermal and saline gradients (note: submarine geothermal energy is covered under geothermal energy and marine biomass is covered under biomass energy).

Offset (in climate policy): A unit of CO_2-equivalent (CO_2eq) that is reduced, avoided or sequestered to compensate for emissions occurring elsewhere.

Opportunities: In general: conditions that allow for advancement, progress or profit. In the policy context, circumstances for action with the attribute of a chance character. For example, the anticipation of additional benefits that may go along with the deployment of renewable energy (enhanced energy access and energy security, reduced local air pollution) but are not intentionally targeted. See also co-benefits and drivers.

Path dependence: Outcomes of a process are conditioned by previous decisions, events and outcomes, rather than only by current actions. Choices based on transitory conditions can exert a persistent impact long after those conditions have changed.

Payback: Mostly used in investment appraisal as **financial payback**, which is the time needed to repay the initial investment by the returns of a project. A **payback gap** exists when, for example, private investors and micro-financing schemes require higher profitability rates from renewable energy projects than from fossil-fired ones. Imposing an x-times higher financial return on renewable energy investments is equivalent to imposing an x-times higher technical performance hurdle on delivery by novel renewable solutions compared to incumbent energy expansion. **Energy payback** is the time an energy project needs to deliver as much energy as had been used for setting the project online. **Carbon payback** is the time a renewable energy project needs to deliver as much net greenhouse gas savings (with respect to the fossil reference energy system) as its realization has caused greenhouse gas emissions from a perspective of lifecycle analysis (including land use changes and loss of terrestrial carbon stocks).

Photosynthesis: The production of carbohydrates in plants, algae and some bacteria using the energy of light. CO_2 is used as the carbon source.

Photovoltaics (PV): The technology of converting light energy directly into electricity by mobilizing electrons in solid state devices. The specially prepared thin sheet semiconductors are called PV cells. See solar energy.

Policies: Policies are taken and/or mandated by a government—often in conjunction with business and industry within a single country, or collectively with other countries—to accelerate mitigation and adaptation measures. Examples of policies are support mechanisms for renewable energy supplies, carbon or energy taxes, fuel efficiency standards for automobiles, etc.

Common and co-ordinated or ***harmonized policies*** refer to those adopted jointly by parties. See also measures.

Policy criteria: General: a standard on which a judgment or decision may be based. In the context of policies and policy instruments to support renewable energy, four inclusive criteria are common:

Effectiveness (efficacy) is the extent to which intended objectives are met, for instance the actual increase in the output of renewable electricity generated or shares of renewable energy in total energy supplies within a specified time period. Beyond *quantitative* targets, this may include factors such as achieved degrees of *technological diversity* (promotion of different renewable energy technologies) or of *spatial diversity* (geographical distribution of renewable energy supplies).

Efficiency is the ratio of outcomes to inputs, for example, renewable energy targets realized for economic resources spent, mostly measured at one point of time (*static efficiency*), also called cost-effectiveness. *Dynamic efficiency* adds a future time dimension by including how much innovation is triggered to improve the ratio of outcomes to inputs.

Equity covers the incidence and distributional consequences of a policy, including fairness, justice and respect for the rights of indigenous peoples. The equity criterion looks at the *distribution* of costs and benefits of a policy and at the *inclusion* and *participation* of wide ranges of different stakeholders (e.g., local populations, independent power producers).

Institutional feasibility is the extent to which a policy or policy instrument is seen as legitimate, able to gain acceptance, and able to be adopted and implemented. It covers **administrative feasibility** when compatible with the available information base and administrative capacity, legal structure and economic realities. **Political feasibility** needs acceptance and support by stakeholders, organizations and constituencies, and compatibility with prevailing cultures and traditions.

Polluter pays principle: In 1972 the OECD agreed that polluters should pay the costs of abating the own environmental pollution, for example by installation of filters, sanitation plants and other add-on techniques. This is the narrow definition. The extended definition is when polluters would additionally pay for the damage caused by their residual pollution (eventually also historical pollution). Another extension is the precautionary polluter pays principle where potential polluters are mandated to take insurance or preventive measures for pollution that may occur in the future. The acronym PPP has also other meanings, such as Preventing Pollution Pays-off, Public Private Partnership, or Purchasing Power Parity.

Portfolio analysis: Examination of a collection of assets or policies that are characterized by different risks and payoffs. The objective function is built up around the variability of returns and their risks, leading up to the decision rule to choose the portfolio with highest expected return.

Potential: Several levels of renewable energy supply potentials can be identified, although every level may span a broad range. In this report, **resource potential** encompasses all levels for a specific renewable energy resource.

Market potential is the amount of renewable energy output expected to occur under forecast market conditions, shaped by private economic agents and regulated by public authorities. Private economic agents realize private objectives within given, perceived and expected conditions. Market potentials are based on expected private revenues and expenditures, calculated at private prices (incorporating subsidies, levies and rents) and with private discount rates. The private context is partly shaped by public authority policies.

Economic potential is the amount of renewable energy output projected when all social costs and benefits related to that output are included, there is full transparency of information, and assuming exchanges in the economy install a general equilibrium characterized by spatial and temporal efficiency. Negative externalities and co-benefits of all energy uses and of other economic activities are priced. Social discount rates balance the interests of consecutive human generations.

Sustainable development potential is the amount of renewable energy output that would be obtained in an *ideal setting* of perfect economic markets, optimal social (institutional and governance) systems and achievement of the sustainable flow of environmental goods and services. This is distinct from economic potential because it explicitly addresses inter- and intra-generational equity (distribution) and governance issues.

Technical potential is the amount of renewable energy output obtainable by full implementation of demonstrated technologies or practices. No explicit reference to costs, barriers or policies is made.

Technical potentials reported in the literature being assessed in this report, however, may have taken into account practical constraints and when explicitly stated there, they are generally indicated in the underlying report.

Theoretical potential is derived from natural and climatic (physical) parameters (e.g., total solar irradiation on a continent's surface). The theoretical potential can be quantified with reasonable accuracy, but the information is of limited practical relevance. It represents the upper limit of what can be produced from an energy resource based on physical principles and current scientific knowledge. It does not take into account energy losses during the conversion process necessary to make use of the resource, nor any kind of barriers.

Power: Power is the rate in which energy is transferred or converted per unit of time or the rate at which work is done. It is expressed in watts (joules/second).

Present value: The value of a money amount differs when the amount is available at different moments in time (years). To make amounts at differing times comparable and additive, a date is fixed as the 'present.' Amounts available at different dates in the future are discounted back to a present value, and summed to get the present value of a series of future cash flows. **Net present value** is the difference between the present value of the revenues (benefits) and the present value of the costs. See also discounting.

Project cost – see Cost.

Progress ratio – see Learning curve / rate.

Public finance: Public support for which a financial return is expected (loans, equity) or financial liability is incurred (guarantee).

Public good: Public goods are simultaneously used by several parties (opposite to private goods). Some public goods are fully free from rivalry in use; for others the use by some subtract from the availability for others, creating congestion. Access to public goods may be restricted dependent on whether public goods are commons, state-owned or res nullius (no one's case). The atmosphere and climate are the ultimate public goods of mankind. Many renewable energy sources are also public goods.

Public-private partnerships: Arrangements typified by joint working between the public and private sector. In the broadest sense, they cover all types of collaboration across the interface between the public and private sectors to deliver services or infrastructure.

Quota (on renewable electricity/energy): Established quotas obligate designated parties (generators or suppliers) to meet minimum (often gradually increasing) renewable energy targets, generally expressed as percentages of total supplies or as an amount of renewable energy capacity, with costs borne by consumers. Various countries use different names for quotas, for example, Renewable Portfolio Standards, Renewable Obligations. See also tradable certificates

Reactive power: The part of instantaneous power that does no real work. Its function is to establish and sustain the electric and magnetic fields required to let active power perform useful work.

Rebound effect: After implementation of efficient technologies and practices, part of the expected energy savings is not realized because the accompanying savings in energy bills may be used to acquire more energy services. For example, improvements in car engine efficiency lower the cost per kilometre driven, encouraging consumers to drive more often or longer distances, or to spend the saved money on other energy-consuming activities. Successful energy efficiency policies may lead to lower economy-wide energy demand and if so to lower energy prices with the possibility of the financial savings stimulating rebound effects. The rebound effect is the ratio of non-realized energy and resource savings compared to the potential savings in case consumption would have remained constant as before the efficiency measures were implemented. For climate change, the main concern about rebound effects is their impact on CO_2 emissions (carbon rebound).

Reforestation: Direct human-induced conversion of non-forested land to forested land through planting, seeding and/or the human-induced promotion of natural seed sources, on land that was previously forested but converted to non-forested land. See also afforestation, deforestation and land use.

Regulation: A rule or order issued by governmental executive authorities or regulatory agencies and having the force of law. Regulations implement policies and are mostly specific for particular groups of people, legal entities or targeted activities. Regulation is also the act of designing and imposing rules or orders. Informational, transactional, administrative and political constraints in practice limit the regulator's capability for implementing preferred policies.

Reliability: In general: reliability is the degree of performance according to imposed standards or expectations.

Electrical reliability is the absence of unplanned interruptions of the current by, for example, shortage of supply capacity or by failures in parts of the grid. Reliability differs from security and from fluctuations in power quality due to impulses or harmonics.

Renewable energy – see Energy

Scenario: A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key relationships and driving forces (e.g., rate of technological change, prices) on social and economic development, energy use, etc. Note that scenarios are neither predictions nor forecasts, but are useful to provide a view of the implications of alternative developments and actions. See also baseline, business as usual, models.

Seismicity: The distribution and frequency of earthquakes in time, magnitude and space, for example, the yearly number of earthquakes of magnitude between 5 and 6 per 100 km^2 or in some region.

Sink: Any process, activity or mechanism that removes a greenhouse gas or aerosol, or a precursor of a greenhouse gas or aerosol, from the atmosphere.

Solar collector: A device for converting solar energy to thermal energy (heat) of a flowing fluid.

Solar energy: Energy from the Sun that is captured either as heat, as light that is converted into chemical energy by natural or artificial photosynthesis, or by photovoltaic panels and converted directly into electricity.

Concentrating solar power (CSP) systems use either lenses or mirrors to capture large amounts of solar energy and focus it down to a smaller region of space. The higher temperatures produced can operate a thermal steam turbine or be used in high-temperature industrial processes.

Direct solar energy refers to the use of solar energy as it arrives at the Earth's surface before it is stored in water or soils.

Solar thermal is the use of direct solar energy for heat end-uses, excluding CSP.

Active solar needs equipment like panels, pumps and fans to collect and distribute the energy.

Passive solar is based on structural design and construction techniques that enable buildings to utilize solar energy for heating, cooling and lighting by non-mechanical means.

Solar irradiance: The rate of solar power incidence on a surface (W/m^2). Irradiance depends on the orientation of the surface, with as special orientations: (a) surfaces perpendicular to the beam solar radiation; (b) surfaces horizontal with or on the ground. **Full sun** is solar irradiance that is approximately 1,000 W/m^2.

Solar radiation: The sun radiates light and heat energy in wavelengths from ultraviolet to infrared. Radiation arriving at surfaces may be absorbed, reflected or transmitted.

Global solar radiation consists of **beam** (arriving on Earth in a straight line) and **diffuse radiation** (arriving on Earth after being scattered by the atmosphere and by clouds).

Standards: Set of rules or codes mandating or defining product performance (e.g., grades, dimensions, characteristics, test methods and rules for use).

Product, ***technology*** or ***performance standards*** establish minimum requirements for affected products or technologies.

Subsidy: Direct payment from the government or a tax reduction to a private party for implementing a practice the government wishes to encourage. The reduction of greenhouse gas emissions is stimulated by lowering existing subsidies that have the effect of raising emissions (such as subsidies for fossil fuel use) or by providing subsidies for practices that reduce emissions or enhance sinks (e.g., renewable energy projects, insulation of buildings or planting trees).

Sustainable development (SD): The concept of sustainable development was introduced in the World Conservation Strategy of the International Union for Conservation of Nature in 1980 and had its roots in the concept of a sustainable society and in the management of renewable resources. Adopted by the World Council for Environment and Development in 1987 and by the Rio Conference in 1992 as a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations. SD integrates the political, social, economic and environmental dimensions, and respects resource and sink constraints.

Tax: A **carbon tax** is a levy on the carbon content of fossil fuels. Because virtually all of the carbon in fossil fuels is ultimately emitted as CO_2, a carbon tax is equivalent to an **emission tax** on CO_2 emissions. An **energy tax**—a levy on the energy content of fuels—reduces demand for energy and so reduces CO_2 emissions from fossil fuel use. An **eco-tax** is a carbon, emissions or energy tax designed to influence human behaviour (specifically economic behaviour) to follow an ecologically benign path. A **tax credit** is a reduction of tax in order to stimulate purchasing of or investment in a certain product, like greenhouse gas emission-reducing technologies. A **levy** or **charge** is used as synonymous for tax.

Technological change: Mostly considered as technological *improvement*, that is, more or better goods and services can be provided from a given amount of resources (production factors). Economic models distinguish autonomous (exogenous), endogenous and induced technological change.

Autonomous (exogenous) technological change is imposed from outside the model (i.e., as a parameter), usually in the form of a time trend affecting factor or/and energy productivity and therefore energy demand or output growth.

Endogenous technological change is the outcome of economic activity *within* the model (i.e., as a variable) so that factor productivity or the choice of technologies is included within the model and affects energy demand and/or economic growth.

Induced technological change implies endogenous technological change but adds further changes *induced* by policies and measures, such as carbon taxes triggering research and development efforts.

Technology: The practical application of knowledge to achieve particular tasks that employs both technical artefacts (hardware, equipment) and (social) information ('software', know-how for production and use of artefacts).

Supply push aims at developing specific technologies through support for research, development and demonstration.

Demand pull is the practice of creating market and other incentives to induce the introduction of particular sets of technologies (e.g., low-carbon technologies through carbon pricing) or single technologies (e.g., through technology-specific feed-in tariffs).

Technology transfer: The exchange of knowledge, hardware and associated software, money and goods among stakeholders, which leads to the spread of technology for adaptation or mitigation. The term encompasses both diffusion of technologies and technological cooperation across and within countries.

Tradable certificates (tradable green certificates): Parties subject to a renewable energy quota meet the annual obligation by delivering the appropriate amount of tradable certificates to a regulatory office. The certificates are created by the office and assigned to the renewable energy producers to sell or for their own use in fulfilling their quota. See quota.

Transmission and distribution (electricity): The network that transmits electricity through wires from where it is generated to where it is used. The distribution system refers to the lower-voltage system that actually delivers the electricity to the end user. See also grid.

Turbine: Equipment that converts the kinetic energy of a flow of air, water, hot gas or steam into rotary mechanical power, used for direct drive or electricity generation (see wind, hydro, gas or steam turbines). **Condensing steam turbines** exhaust depleted steam in a heat exchanger (called condenser) using ambient cooling from water (river, lake, sea) or air sources (cooling towers). A **backpressure steam turbine** has no condenser at ambient temperature conditions, but exhausts all steam at higher temperatures for use in particular heat end-uses.

United Nations Framework Convention on Climate Change (UNFCCC): The Convention was adopted on 9 May 1992 in New York and signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Economic Community. Its ultimate objective is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". It contains commitments for all parties. Under the Convention, parties included in Annex I aimed to return greenhouse gas emissions not controlled by the Montreal Protocol to 1990 levels by the year 2000. The convention came into force in March 1994. In 1997, the UNFCCC adopted the Kyoto Protocol. See also Annex I countries, Annex B countries and Kyoto Protocol.

Valley of death: Expression for a phase in the development of some technology when it is generating a large and negative cash flow because development costs increase but the risks associated with the technology are not reduced enough to entice private investors to take on the financing burden.

Value added: The net output of a sector or activity after adding up all outputs and subtracting intermediate inputs.

Values: Worth, desirability or utility based on individual preferences. Most social science disciplines use several definitions of value. Related to nature and environment, there is a distinction between intrinsic and instrumental values, the latter assigned by humans. Within instrumental values, there is an unsettled catalogue of different values, such as (direct and indirect) use, option, conservation, serendipity, bequest, existence, etc.

Mainstream economics define the total value of any resource as the sum of the values of the different individuals involved in the use of the resource. The economic values, which are the foundation of the estimation of costs, are measured in terms of the willingness to pay by individuals to receive the resource or by the willingness of individuals to accept payment to part with the resource.

Vent (geothermal/hydrothermal/submarine): An opening at the surface of the Earth (terrestrial or submarine) through which materials and energy flow.

Venture capital: A type of private equity capital typically provided for early-stage, high-potential technology companies in the interest of generating a return on investment through a trade sale of the company or an eventual listing on a public stock exchange.

Well-to-tank (WTT): WTT includes activities from resource extraction through fuel production to delivery of the fuel to vehicle. Compared to WTW, WTT does not take into consideration fuel use in vehicle operations.

Well-to-wheel (WTW): WTW analysis refers to specific lifecycle analysis applied to transportation fuels and their use in vehicles. The WTW stage includes resource extraction, fuel production, delivery of the fuel

to vehicle, and end use of fuel in vehicle operations. Although feedstocks for alternative fuels do not necessarily come from a well, the WTW terminology is adopted for transportation fuel analysis.

Wind energy: Kinetic energy from air currents arising from uneven heating of the Earth's surface. A **wind turbine** is a rotating machine including its support structure for converting the kinetic energy to mechanical shaft energy to generate electricity. A **windmill** has oblique vanes or sails and the mechanical power obtained is mostly used directly, for example, for water pumping. A **wind farm**, **wind project** or **wind power plant** is a group of wind turbines interconnected to a common utility system through a system of transformers, distribution lines, and (usually) one substation.

Acronyms

AA-CAES	Advanced adiabatic compressed air energy storage
AC	Alternating current
AEM	Anion exchange membrane
AEPC	Alternative Energy Promotion Centre
AFEX	Ammonia fibre expansion
APU	Auxiliary power unit
AR4	4th assessment report (of the IPCC)
AR5	5th assessment report (of the IPCC)
BC	Black carbon
BCCS	Biological carbon sequestration
Bio-CCS	Biomass with carbon capture and storage
BIPV	Building-integrated photovoltaic
BMU	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety)
BNEF	Bloomberg New Energy Finance
BOS	Balance of systems
BSI	Better Sugarcane Initiative
CAES	Compressed air energy storage
CBP	Consolidated bioprocessing
CC	Combined cycle
CCIY	China Coal Industry Yearbook
CCS	Carbon dioxide capture and storage
CDM	Clean Development Mechanism
CEM	Cation exchange membrane
CER	Certified Emissions Reduction
CF	Capacity factor
CFB	Circulating fluid bed
CFD	Computational fluid dynamics
CFL	Compact fluorescent lightbulb
CHP	Combined heat and power
CIGSS	Copper indium/gallium disulfide/(di)selenide
CIS	Commonwealth of Independent States
CMA	China's Meteorological Administration
CNG	Compressed natural gas
CoC	Chain of custody
COP	Coefficient of performance
CPP	Captive power plant
CPV	Concentrating photovoltaics
CREZ	Competitive renewable energy zone
CRF	Capital recovery factor
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSP	Concentrating solar power
CPV	Concentrating photovoltaics
CSTD	Commission on Science and Technology (UN)
DALY	Disability-adjusted life year
dBA	A-weighted decibels
DC	Direct current or district cooling
DDG	Distillers dried grains
DDGS	Distillers dried grains plus solubles
DH	District heating
DHC	District heating or cooling
DHW	Domestic hot water
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre)
DLUC	Direct land use change
DME	Dimethyl ether
DNI	Direct-normal irradiance
DPH	Domestic pellet heating
DSSC	Dye-sensitized solar cell
EGS	Enhanced geothermal systems
EGTT	Expert Group on Technology Transfer
EIA	Energy Information Administration (USA)
EIT	Economy In Transition
EMEC	European Marine Energy Centre
EMF	Energy Modelling Form
EMI	Electromagnetic interference
ENSAD	Energy-Related Severe Accident Database
EPRI	Electric Power Research Institute (USA)
EPT	Energy payback time
E[R]	Energy [R]evolution
ER	Energy ratio
ERCOT	Electric Reliability Council of Texas
EREC	European Renewable Energy Council
EROEI	Energy return on energy investment
ESMAP	Energy Sector Management Program (World Bank)
ETBE	Ethyl tert-butyl ether
ETP	Energy Technology Perspectives
EU	European Union
EV	Electric vehicle
FACTS	Flexible AC transmission system
FASOM	Forest and Agricultural Sector Optimization Model
FAO	Food and Agriculture Organization (of the UN)
FFV	Flexible fuel vehicle
FQD	Fuel quality directive
FIT	Feed-in tariff
FOGIME	Crediting System in Favour of Energy Management
FRT	Fault ride through
FSU	Former Soviet Union
FTD	Fischer-Tropsch diesel
GBD	Global burden of disease
GBEP	Global Bioenergy Partnership
GCAM	Global Change Assessment Model
GCM	Global climate model; General circulation model
GDP	Gross domestic product
GEF	Global Environment Facility
GHG	Greenhouse gas
GHP	Geothermal heat pump

GIS	Geographic information system
GM	Genetically modified
GMO	Genetically modified organism
GO	Guarantee of origin
GPI	Genuine progress indicator
GPS	Global positioning system
GSHP	Ground source heat pump
HANPP	Human appropriation of terrestrial NPP
HCE	Heat collection element
HDI	Human Development Index
HDR	Hot dry rock
HDV	Heavy duty vehicle
HFCV	Hydrogen fuel cell electric vehicle
HFR	Hot fractured rock
HHV	Higher heating value
HPP	Hydropower plant
HRV	Heat recovery ventilator
HEV	Hybrid electric vehicle
HVAC	Heating, ventilation and air-conditioning
HVDC	High voltage direct current
HWR	Hot wet rock
IA	Impact assessment
IAP	Indoor air pollution
IBC	interdigitated back-contact
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
ICLEI	Local Governments for Sustainability
ICOLD	International Commission on Large Dams
ICS	Improved cookstove or Integral collector storage (Ch 3)
ICTSD	International Centre for Trade and Sustainable Development
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IHA	International Hydropower Association
ILUC	Indirect land use change
IGCC	Integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
IPR	Intellectual property rights
IQR	Inter-quartile range
IREDA	Indian Renewable Energy Development Agency
IRENA	International Renewable Energy Agency
IRM	Inorganic mineral raw materials
ISCC	Integrated solar combined-cycle
ISES	International Solar Energy Society
ISEW	Index of sustainable economic welfare
ISO	International Organization for Standardization
J	Joule
JI	Joint implementation
LCA	Lifecycle assessment
LCOE	Levelized cost of energy (or of electricity)
LCOF	Levelized cost of fuel
LCOH	Levelized cost of heat
LDV	Light duty vehicle
LED	Light-emitting diode
LHV	Lower heating value
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LR	Learning rate
LUC	Land use change
M&A	Mergers and acquisitions
MDG	Millennium Development Goals
MEH	Multiple-effect humidification
MHS	Micro-hydropower systems
MITI	Ministry of International Trade and Industry (Japan)
MSW	Municipal solid waste
NASA	National Aeronautics and Space Administration (USA)
NDRC	National Development and Reform Commission (China)
NFFO	Non Fossil Fuel Obligation
NG	Natural gas
NGO	Nongovernmental organization
Nm^3	Normal cubic metre (of gas) at standard temperature and pressure
NMVOC	Non-methane volatile organic compounds
NPP	Net primary production
NPV	Net present value
NRC	National Research Council (USA)
NREL	National Renewable Energy Laboratory (USA)
NSDS	National Sustainable Development Strategies
O&M	Operation and maintenance
OB	Oscillating-body
OC	Organic carbon
OECD	Organisation for Economic Co-operation and Development
OM	Organic matter
OPV	Organic photovoltaic
ORC	Organic Rankine Cycle
OTEC	Ocean thermal energy conversion
OWC	Oscillating water column
PACE	Property Assessed Clean Energy
PBR	Photobioreactor
PCM	Phase-change material
PDI	Power density index
PEC	Photoelectrochemical
PHEV	Plug-in hybrid electric vehicle
PM	Particulate matter
POME	Palm oil mill effluent
PPA	Purchase power agreement
PRO	Pressure-retarded osmosis
PROALCOOL	Brazilian Alcohol Program
PSA	Probabilistic safety assessment
PSI	Paul Scherrer Institute
PSP	Pumped storage plants
PTC	Production tax credit
PV	Photovoltaic

PV/T	Photovoltaic/thermal
PWR	Pressurized water reactor
R&D	Research and development
RBMK	Reaktor bolshoy moshchnosty kanalny
RCM	Regional climate model
RD&D	Research, development and demonstration
R/P	Reserves to current production (ratio)
RD	Renewable diesel
RE	Renewable energy
RE-C	Renewable energy cooling
RE-H	Renewable energy heating
RE-H/C	Renewable energy heating/cooling
REC	Renewable energy certificate
RED	Reversed electro dialysis
REN21	Renewable Energy Policy Network for the 21st Century
RES	Renewable electricity standard
RM&U	Renovation, modernization and upgrading
RMS	Root mean square
RNA	Rotor nacelle assembly
RO	Renewables obligation
RoR	Run of river
RPS	Renewable portfolio standard
RSB	Roundtable for Sustainable Biofuels
SCADA	Supervisory control and data acquisition
SCC	Stress corrosion cracking
SD	Sustainable development
SEGS	Solar Electric Generating Station (California)
SHC	Solar heating and cooling
SHP	Small-scale hydropower plant
SI	Suitability index
SME	Small and medium sized enterprises
SNG	Synthesis gas
SNV	Netherlands Development Organization
SPF	Seasonal performance factor
SPM	Summary for Policymakers
SPP	Small power producer
SPS	Sanitary and phytosanitary
SR	Short rotation
SRES	Special Report on Emission Scenarios (of the IPCC)
SRREN	Special Report on Renewable Energy Sources and Climate Change Mitigation (of the IPCC)
SSCF	Simultaneous saccharification and co-fermentation
SSF	Simultaneous saccharification and fermentation
SSP	Space-based solar power
STP	Standard temperature and pressure
SWH	Solar water heating
TBM	Tunnel-boring machines
TERM	Tonga Energy Roadmap
TGC	Tradable green certificate
TPA	Third-party access
TPES	Total primary energy supply
TPWind	European Wind Energy Technology Platform
TS	Technical Summary or thermosyphon
US	United States of America (adjective)
USA	United States of America (noun)
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNCTAD	United Nations Conference on Trade and Development
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USD	US dollar
USDOE	US Department of Energy
V	Volt
VKT	Vehicle kilometres travelled
VRB	Vanadium redox battery
W	Watt
W_e	Watt of electricity
W_p	Watt peak of PV installation
WBG	World Bank Group
WCD	World Commission on Dams
WCED	World Commission on Environment and Development
WEA	World Energy Assessment
WEO	World Energy Outlook
WindPACT	Wind Partnership for Advanced Component Technologies
WTO	World Trade Organization
WTW	Well to wheel

Chemical Symbols

a-Si	Amorphous silicon
C	Carbon
CdS	Cadmium sulphide
CdTe	Cadmium telluride
CH_4	Methane
CH_3CH_2OH	Ethanol
CH_3OCH_3	Dimethyl ether (DME)
CH_3OH	Methanol
CIGS(S)	Copper indium gallium diselenide (disulfide)
Cl	Chlorine
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
c-Si	Crystalline silicon
Cu	Copper
$CuInSe_2$	Copper indium diselenide
DME	Dimethyl ether
Fe	Iron
GaAs	Gallium arsenide
H_2	Hydrogen gas
H_2O	Water
H_2S	Hydrogen sulphide
HFC	Hydrofluorocarbons
K	Potassium
Mg	Magnesium
N	Nitrogen
N_2	Nitrogen gas
N_2O	Nitrous oxide
Na	Sodium
NaS	Sodium-sulfur
NH_3	Ammonia
Ni	Nickel
NiCd	Nickel-cadmium
NO_x	Nitrous oxides
O_3	Ozone
P	Phosphorus
PFC	Perfluorocarbon
SF_6	Sulfur hexafluoride
Si	Silicon
SiC	Silicon carbide
SO_2	Sulfur dioxide
ZnO	Zinc oxide

Prefixes (International Standard Units)

Symbol	Multiplier	Prefix
Z	10^{21}	zetta
E	10^{18}	exa
P	10^{15}	peta
T	10^{12}	tera
G	10^{9}	giga
M	10^{6}	mega
k	10^{3}	kilo
h	10^{2}	hecto
da	10	deca

Symbol	Multiplier	Prefix
d	10^{-1}	deci
c	10^{-2}	centi
m	10^{-3}	milli
µ	10^{-6}	micro
n	10^{-9}	nano
p	10^{-12}	pico
f	10^{-15}	femto
a	10^{-18}	atto

ANNEX II

Methodology

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A.II.1 Introduction

Parties need to agree upon common data, standards, supporting theories and methodologies. This annex summarizes a set of agreed upon conventions and methodologies. These include the establishment of metrics, determination of a base year, definitions of methodologies and consistency of protocols that permit a legitimate comparison between alternative types of energy in the context of climate change phenomena. This section defines or describes these fundamental definitions and concepts as used throughout this report, recognizing that the literature often uses inconsistent definitions and assumptions.

This report communicates uncertainty where relevant, for example, by showing the results of sensitivity analyses and by quantitatively presenting ranges in cost numbers as well as ranges in the scenario results. This report does not apply formal IPCC uncertainty terminology because at the time of approval of this report, IPCC uncertainty guidance was in the process of being revised.

A.II.2 Metrics for analysis in this report

A number of metrics can simply be stated or are relatively easy to define. Annex II provides the set of agreed upon metrics. Those which require further description are found below. The units used and basic parameters pertinent to the analysis of each RE type in this report include:

- International System of Units (SI) for standards and units
- Metric tonnes (t) CO_2, CO_2eq
- Primary energy values in exajoules (EJ)
- IEA energy conversion factors between physical and energy units
- Capacity: GW thermal (GW_t), GW electricity (GW_e)
- Capacity factor
- Technical and economic lifetime
- Transparent energy accounting (e.g., transformations of nuclear or hydro energy to electricity)
- Investment cost in USD/kW (peak capacity)
- Energy cost in USD_{2005}/kWh or USD_{2005}/EJ
- Currency values in USD_{2005} (at market exchange rate where applicable, no purchasing power parity is used)
- Discount rates applied = 3, 7 and 10%
- World Energy Outlook (WEO) 2008 fossil fuel price assumptions
- Baseline year = 2005 for all components (population, capacity, production, costs). Note that more recent data may also be included (e.g., 2009 energy consumption)
- Target years: 2020, 2030 and 2050.

A.II.3 Financial assessment of technologies over project lifetime

The metrics defined here provides the basis from which one renewable resource type (or project) can be compared to another. To make projects or resources comparable, at least in terms of costs, costs that may occur at various moments in time (e.g., in various years) are represented as a single number anchored at one particular year, the reference year (2005). Textbooks on investment appraisal provide background on the concepts of constant values, discounting, net present value calculations, and levelized costs, for example (Jelen and Black, 1983).

A.II.3.1 Constant (real) values

The analyses of costs are in constant or real[1] dollars (i.e., excluding the impacts of inflation) based in a particular year, the base year 2005, in USD. Specific studies on which the report depends may use market exchange rates as a default option or use purchasing power parities, but where these are part of the analysis, they will be stated clearly and, where possible, converted to USD_{2005}.

When the monetary series in the analyses are in real dollars, consistency requires that the discount rate should also be real (free of inflationary components). This consistency is often not obeyed; studies refer to 'observed market interest rates' or 'observed discount rates', which include inflation or expectations about inflation. 'Real/constant' interest rates are never directly observed, but derived from the ex-post identity:

$$(1+m) = (1+i) \times (1+f) \qquad (1)$$

where

m = nominal rate (%)
i = real or constant rate (%)
f = inflation rate (%)

The reference year for discounting and the base year for anchoring constant prices may differ in studies used in the various chapters; where possible, an attempt was made to harmonize the data to reflect discount rates applied here.

A.II.3.2 Discounting and net present value

Private agents assign less value to things further in the future than to things in the present because of a 'time preference for consumption' or to reflect a 'return on investment'. Discounting reduces future cash flows by a value less than 1. Applying this rule on a series of net cash flows in real USD, the net present value (NPV) of the project can be ascertained and, thus, compared to other projects using:

$$NPV = \sum_{j=0}^{n} \frac{Net\ cash\ flows\ (j)}{(1+i)^j} \qquad (2)$$

where

n = lifetime of the project
i = discount rate

1 The economists' term 'real' may be confusing because what they call real does not correspond to observed financial flows ('nominal', includes inflation); 'real' reflects the actual purchasing power of the flows in constant dollars.

This report's analysts have used three values of discount rates (i = 3, 7 and 10%) for the cost evaluations. The discount rates may reflect typical rates used, with the higher ones including a risk premium. The discount rate is open to much discussion and no clear parameter or guideline can be suggested as an appropriate risk premium. This discussion is not addressed here; the goal is to provide an appropriate means of comparison between projects, renewable energy types and new versus current components of the energy system.

A.II.3.3 Levelized cost

Levelized costs are used in the appraisal of power generation investments, where the outputs are quantifiable (MWh generated during the lifetime of the investment). The levelized cost is the unique break-even cost price where discounted revenues (price x quantities)[2] are equal to the discounted net expenses:

$$C_{Lev} = \frac{\sum_{j=0}^{n} \frac{Expenses_j}{(1+i)^j}}{\sum_{j=0}^{n} \frac{Quantities_j}{(1+i)^j}} \qquad (3)$$

where

C_{Lev} = levelized cost
n = lifetime of the project
i = discount rate

A.II.3.4 Annuity factor or capital cost recovery factor

A very common practice is the conversion of a given sum of money at moment 0 into a number n of constant annual amounts over the coming n future years:

Let A = annual constant amount in payments over n years
Let B = cash amount to pay for the project in year 0

A is obtained from B using a slightly modified equation 2: the lender wants to receive B back at the discount rate i. The NPV of the n times A receipts in the future therefore must exactly equal B:

$$\sum_{j=1}^{n} \frac{A}{(1+i)^j} = B, \text{or}: A\sum_{j=1}^{n} \frac{1}{(1+i)^j} = B \qquad (4)$$

We can bring A before the summation because it is a constant (not dependent on j).

The sum of the discount factors (a finite geometrical series) is deductible as a particular number. When this number is calculated, A is found by dividing B by this number. This is known as the *Capital Recovery Factor* (*CRF*) but may be known as the *Annuity Factor 'δ'*. Like NPV, the annuity factor δ depends on the two parameters i and n:

$$\delta = \frac{i \times (1+i)^n}{(1+i)^n - 1}$$

The CRF (or δ) can be used to quickly calculate levelized costs for very simple projects where investment costs during one given year are the only expenditures and where production remains constant over the lifetime (n):

$$C_{Lev} \times Q = B \times \delta, \text{ or}: C_{Lev} = (B \times \delta)/Q \qquad (5)$$

or where one can assume that operation and maintenance (O&M) costs do not change from year to year:

$$C_{Lev} = \frac{B \times \delta + O\&M}{Q} \qquad (6)$$

where

C_{Lev} = levelized cost
B = investment cost
Q = production
$O\&M$ = annual operating and maintenance costs
n = life time of the project
i = discount rate

A.II.4 Primary energy accounting

This section introduces the primary energy accounting method used throughout this report. Different energy analyses use different accounting methods that lead to different quantitative outcomes for reporting both current primary energy use and energy use in scenarios that explore future energy transitions. Multiple definitions, methodologies and metrics are applied. Energy accounting systems are utilized in the literature often without a clear statement as to which system is being used as noted by Lightfoot, 2007 and Martinot et al., 2007. An overview of differences in primary energy accounting from different statistics has been described (Macknick, 2009) and the implications of applying different accounting systems in long-term scenario analysis were illustrated by Nakicenovic et al., (1998).

Three alternative methods are predominantly used to report primary energy. While the accounting of combustible sources, including all fossil energy forms and biomass, is unambiguous and identical across the different methods, they feature different conventions on how to calculate primary energy supplied by non-combustible energy sources, i.e., nuclear energy and all renewable energy sources except biomass.

These methods are:

- *The physical energy content method* adopted, for example, by the Organisation for Economic Cooperation and Development (OECD), the International Energy Agency (IEA) and Eurostat (IEA/OECD/Eurostat, 2005),

2 This is also referred to as Levelized Price. Note that, in this case, MWh would be discounted.

- *The substitution method*, which is used in slightly different variants by BP (2009) and the US Energy Information Administration (EIA online glossary), each of which publish international energy statistics, and

- *The direct equivalent method* that is used by UN Statistics (2010) and in multiple IPCC reports that deal with long-term energy and emission scenarios (Nakicenovic and Swart, 2000; Morita et al., 2001; Fisher et al., 2007).

For non-combustible energy sources, the *physical energy content method* adopts the principle that the primary energy form should be the first energy form used downstream in the production process for which multiple energy uses are practical (IEA/OECD/Eurostat, 2005). This leads to the choice of the following *primary* energy forms:

- Heat for nuclear, geothermal and solar thermal energy; and
- Electricity for hydro, wind, tide/wave/ocean and solar photovoltaic (PV) energy.

Using this method, the primary energy equivalent of hydropower and solar PV, for example, assumes a 100% conversion efficiency to 'primary electricity', so that the gross energy input for the source is 3.6 MJ of primary energy = 1 kWh electricity. Nuclear energy is calculated from the gross generation by assuming a 33% thermal conversion efficiency,[3] that is, 1 kWh = (3.6 ÷ 0.33) = 10.9 MJ. For geothermal energy, if no country-specific information is available, the primary energy equivalent is calculated using 10% conversion efficiency for geothermal electricity (so 1 kWh = (3.6 ÷ 0.1) = 36 MJ), and 50% for geothermal heat.

The *substitution method* reports primary energy from non-combustible sources as if they had been substituted for combustible energy. Note, however, that different variants of the substitution method use somewhat different conversion factors. For example, BP applies a 38% conversion efficiency to electricity generated from nuclear and hydropower, whereas the World Energy Council used 38.6% for nuclear and non-combustible renewable sources (WEC, 1993) and the EIA uses still different values. Macknick (2009) provides a more complete overview. For useful heat generated from non-combustible energy sources, other conversion efficiencies are used.

The *direct equivalent method* counts one unit of secondary energy provided from non-combustible sources as one unit of primary energy, that is, 1 kWh of electricity or heat is accounted for as 1 kWh = 3.6 MJ of primary energy. This method is mostly used in the long-term scenarios literature, including multiple IPCC reports (IPCC, 1995; Nakicenovic and Swart, 2000; Morita et al., 2001; Fisher et al., 2007), because it deals with fundamental transitions of energy systems that rely to a large extent on low-carbon, non-combustible energy sources.

3 As the amount of heat produced in nuclear reactors is not always known, the IEA estimates the primary energy equivalent from the electricity generation by assuming an efficiency of 33%, which is the average for nuclear power plants in Europe (IEA, 2010b).

In this report, IEA data are utilized, but energy supply is reported using the *direct equivalent method*. The major difference between this and the *physical energy content method* will appear in the amount of primary energy reported for electricity production by geothermal heat, concentrating solar thermal, ocean temperature gradients or nuclear energy. Table A.II.1 compares the amounts of global primary energy by source and percentages using the *physical energy content*, the *direct equivalent* and a variant of the *substitution method* for the year 2008 based on IEA data (IEA, 2010a). In current statistical energy data, the main differences in absolute terms appear when comparing nuclear and hydropower. Since they both produced a comparable amount of electricity globally in 2008, under both *direct equivalent* and *substitution methods*, their share of meeting total final consumption is similar, whereas under the *physical energy content method*, nuclear is reported at about three times the primary energy of hydropower.

The alternative methods outlined above emphasize different aspects of primary energy supply. Therefore, depending on the application, one method may be more appropriate than another. However, none of them is superior to the others in all facets. In addition, it is important to realize that total primary energy supply does not fully describe an energy system, but is merely one indicator amongst many. Energy balances as published by the IEA (2010a) offer a much wider set of indicators, which allows tracing the flow of energy from the resource to final energy use. For instance, complementing total primary energy consumption with other indicators, such as total final energy consumption and secondary energy production (e.g., electricity, heat), using different sources helps link the conversion processes with the final use of energy. See Figure 1.16 and the associated discussion for a summary of this approach.

For the purpose of this report, the *direct equivalent method* is chosen for the following reasons.

- It emphasizes the secondary energy perspective for non-combustible sources, which is the main focus of the analyses in the technology chapters (Chapters 2 through 7).

- All non-combustible sources are treated in an identical way by using the amount of secondary energy they provide. This allows the comparison of all non-CO_2-emitting renewable and nuclear energy sources on a common basis. Primary energy of fossil fuels and biomass combines both the secondary energy and the thermal energy losses from the conversion process. When fossil fuels or biofuels are replaced by nuclear systems or other renewable technologies than biomass, the total of reported primary energy decreases substantially (Jacobson, 2009).

- Energy and CO_2 emissions scenario literature that deals with fundamental transitions of the energy system to avoid dangerous anthropogenic interference with the climate system over the long term (50 to 100 years) has used the direct equivalent method most frequently (Nakicenovic and Swart, 2000; Fisher et al., 2007).

Table A.II.1 | Comparison of global total primary energy supply in 2008 using different primary energy accounting methods (data from IEA, 2010a).

	Physical content method		Direct equivalent method		Substitution method[1]	
	EJ	%	EJ	%	EJ	%
Fossil fuels	418.15	81.41	418.15	85.06	418.15	79.14
Nuclear	29.82	5.81	9.85	2.00	25.90	4.90
Renewable:	65.61	12.78	63.58	12.93	84.27	15.95
Bioenergy[2]	*50.33*	*9.80*	*50.33*	*10.24*	*50.33*	*9.53*
Solar	*0.51*	*0.10*	*0.50*	*0.10*	*0.66*	*0.12*
Geothermal	*2.44*	*0.48*	*0.41*	*0.08*	*0.82*	*0.16*
Hydro	*11.55*	*2.25*	*11.55*	*2.35*	*30.40*	*5.75*
Ocean	*0.00*	*0.00*	*0.00*	*0.00*	*0.01*	*0.00*
Wind	*0.79*	*0.15*	*0.79*	*0.16*	*2.07*	*0.39*
Other	0.03	0.01	0.03	0.01	0.03	0.01
Total	**513.61**	**100.00**	**491.61**	**100.00**	**528.35**	**100.00**

Notes:

1 For the substitution method, conversion efficiencies of 38% for electricity and 85% for heat from non-combustible sources were used. BP uses the conversion value of 38% for electricity generated from hydro and nuclear sources. BP does not report solar, wind and geothermal in its statistics; here, 38% for electricity and 85% for heat is used.

2 Note that IEA reports first-generation biofuels in secondary energy terms (the primary biomass used to produce the biofuel would be higher due to conversion losses, see Sections 2.3 and 2.4).

Table A.II.2 shows the differences in the primary energy accounting for the three methods for a scenario that would produce a 550 ppm CO_2eq stabilization by 2100.

While the differences between applying the three accounting methods to current energy consumption are modest, differences grow significantly when generating long-term lower CO_2 emissions energy scenarios where non-combustion technologies take on a larger relative role (Table A.II.2). The accounting gap between the different methods becomes bigger over time (Figure A.II.1). There are significant differences in individual non-combustible sources in 2050 and even the share of total renewable primary energy supply varies between 24 and 37% across the three methods (Table A.II.2). The biggest absolute gap (and relative difference) for a single source is for geothermal energy, with about 200 EJ difference between the direct equivalent and the physical energy content method, and the gap between hydro and nuclear primary energy remains considerable. The scenario presented here is fairly representative and by no means extreme. The chosen 550 ppm stabilization target is not particularly stringent nor is the share of non-combustible energy very high.

A.II.5 Lifecycle assessment and risk analysis

This section describes methods and underlying literature and assumptions of analyses of energy payback times and energy ratios (A.II.5.1),

Table A.II.2 | Comparison of global total primary energy supply in 2050 using different primary energy accounting methods based on a 550 ppm CO_2eq stabilization scenario (Loulou et al., 2009).

	Physical content method		Direct equivalent method		Substitution method	
	EJ	%	EJ	%	EJ	%
Fossil fuels	581.6	55.2	581.56	72.47	581.6	61.7
Nuclear	81.1	7.7	26.76	3.34	70.4	7.8
Renewable:	390.1	37.1	194.15	24.19	290.4	30.8
Bioenergy	*120.0*	*11.4*	*120.0*	*15.0*	*120.0*	*12.7*
Solar	*23.5*	*2.2*	*22.0*	*2.8*	*35.3*	*3.8*
Geothermal	*217.3*	*20.6*	*22.9*	*2.9*	*58.1*	*6.2*
Hydro	*23.8*	*2.3*	*23.8*	*3.0*	*62.6*	*6.6*
Ocean	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Wind	*5.5*	*0.5*	*5.5*	*0.7*	*14.3*	*1.5*
Total	**1,052.8**	**100**	**802.5**	**100**	**942.4**	**100**

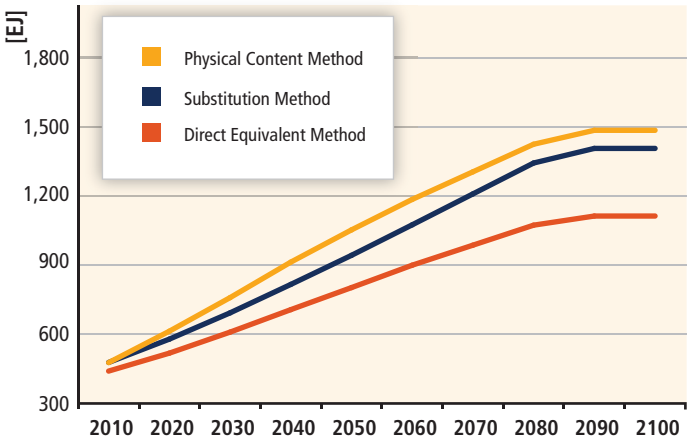

Figure A.II.1 | Comparison of global total primary energy supply between 2010 and 2100 using different primary energy accounting methods based on a 550 ppm CO_2eq stabilization scenario (Loulou et al., 2009).

lifecycle GHG emissions (A.II.5.2), operational water use (A.II.5.3) and hazards and risks (A.II.5.4) of energy technologies as presented in Chapter 9. Results of the analysis carried out for lifecycle GHG emissions are also included in Sections 2.5, 3.6, 4.5, 5.6, 6.5 and 7.6. Please note that the literature bases for the reviews in A.II.5.2 and A.II.5.3 are included as lists within the respective sections.

A.II.5.1 Energy payback time and energy ratio

The Energy Ratio, *ER* (also referred to as the energy payback ratio, or the Energy Return on Energy Investment, *EROEI*; see Gagnon, 2008), of an energy supply system of power rating P and load factor λ, is defined as the ratio

$$ER = \frac{E_{life}}{E} = \frac{P \times 8760\,hy^{-1} \times \lambda \times T}{E}$$

of the lifetime electricity output E_{life} of the plant over its lifetime T, and the total (gross) energy requirement E for construction, operation and decommissioning (Gagnon, 2008). In calculating E, it is a convention to a) exclude the energy from human labour, energy in the ground (fossil and minerals), energy in the sun, and hydrostatic potential, and b) not to discount future against present energy requirements (Perry et al., 1977; Herendeen, 1988). Further, in computing the total energy requirement E, all its constituents must be of the same energy quality (for example only electricity, or only thermal energy, see the 'valuation problem' discussed in Leach (1975), Huettner (1976), Herendeen (1988), and especially Rotty et al. (1975, pp. 5-9 for the case of nuclear energy)). Whilst E may include derived and primary energy forms (for example electricity and thermal energy), it is usually expressed in terms of primary energy, with the electricity component converted to primary energy equivalents using the thermal efficiency $R_{conv} \approx 0.3$ of a typical subcritical black-coal-fired power station as the conversion factor. This report follows these conventions. E is sometimes reported in units of kWh_e/MJ_{prim}, and sometimes in units of kWh_e/kWh_{prim}. Whilst the first option chooses the most common units for either energy form, the second option allows the reader to readily understand the percentage or multiple connecting embodied energy and energy output. Moreover, it has been argued (see Voorspools et al., (2000, p. 326)) that in the absence of alternative technologies, electricity would have to be generated by conventional means. We therefore use kWh_e/kWh_{prim} in this report.

Applying the lifecycle energy metric to an energy supply system allows defining an *energy payback time*. This is the time t_{PB} that it takes the system to supply an amount of energy that is equal to its own energy requirement E. Once again, this energy is best measured in terms of the primary energy equivalent $\frac{E_{PB}}{R_{conv}}$ of the system's electricity output E_{PB} over the payback time. Voorspools et al. (2000, p. 326) note that were the system to pay back its embodied primary energy in equal amounts of electricity, energy payback times would be more than three times as long.

Mathematically, the above condition reads

$$E = \frac{E_{PB}}{R_{conv}} = \frac{P \times 8760\,hy^{-1} \times \lambda \times t_{PB}}{R_{conv}}$$, and leads to

$$t_{PB} = \frac{E}{\frac{P \times 8760\,hy^{-1} \times \lambda}{R_{conv}}} = \frac{E}{\frac{E_{out\,annual}}{R_{conv}}}$$

(which, for example, coincides with the standard German VDI 4600 definition). Here, $\frac{E_{out\,annual}}{R_{conv}}$ is the system's annual net energy output expressed in primary energy equivalents. It can be shown that the Energy Ratio *ER* (or *EROEI*) and the energy payback time t_{PB} can be converted into each other according to

$$t_{PB} = \frac{E\,T}{\frac{E_{out\,annual}\,T}{R_{conv}}} = \frac{E\,T}{\frac{E_{life}}{R_{conv}}} = \frac{R_{conv}}{ER}\,T \quad .$$

Note that the energy payback time is not dependent on the lifetime T, because

$$t_{PB} = \frac{E\,R_{conv}}{P \times 8760\,hy^{-1} \times \lambda} \quad .$$

Energy payback times have been partly converted from energy ratios found in the literature (Lenzen, 1999, 2008; Lenzen and Munksgaard, 2002; Lenzen et al., 2006; Gagnon, 2008; Kubiszewski et al., 2010) based on the assumed average lifetimes given in Table 9.8 (Chapter 9). Note that energy payback as defined in the glossary (Annex I) and used in some technology chapters refers to what is defined here as energy payback time.

A.II.5.2 Review of lifecycle assessments of electricity generation technologies

The National Renewable Energy Laboratory (NREL) carried out a comprehensive review of published lifecycle assessments (LCAs) of

electricity generation technologies. Of 2,165 references collected, 296 passed screens, described below, for quality and relevance and were entered into a database. This database forms the basis for the assessment of lifecycle greenhouse gas (GHG) emissions from electricity generation technologies in this report. Based on estimates compiled in the database, plots of published estimates of lifecycle GHG emissions appear in each technology chapter of this report (Chapters 2 through 7) and in Chapters 1 and 9, where lifecycle GHG emissions from RE technologies are compared to those from fossil and nuclear electricity generation technologies. The following subchapters describe the methods applied in this review (A.II.5.2.1), and list all references that are shown in the final results, sorted by technology (A.II.5.2.2).

A.II.5.2.1 Review methodology

Broadly, the review followed guidelines for *systematic reviews* as commonly performed, for instance, in the medical sciences (Neely et al., 2010). The methods of reviews in the medical sciences differ somewhat from those in the physical sciences, in that there is an emphasis on multiple, independent reviews of each candidate reference using predefined screening criteria; the formation of a review team composed of, in this case, LCA experts, technology experts and literature search experts that meets regularly to ensure consistent application of the screening criteria; and an exhaustive search of published literature to ensure no bias by, for instance, publication type (journal, report, etc.).

It is critical to note at the outset that this review did not alter (except for unit conversion) or audit for accuracy the estimates of lifecycle GHG emissions published in studies that pass the screening criteria. Additionally, no attempt was made to identify or screen for outliers, or pass judgment on the validity of input parameter assumptions. Because estimates are plotted as published, considerable methodological inconsistency is inherent, which limits comparability of the estimates both within particular power generation technology categories and across the technology categories. This limitation is partially counteracted by the comprehensiveness of the literature search and the breadth and depth of literature revealed. Few attempts have been made to broadly review the LCA literature on electricity generation technologies. Those that do exist tend to focus on individual technologies and are more limited in comprehensiveness compared to the present review (e.g., Lenzen and Munksgaard, 2002; Fthenakis and Kim, 2007; Lenzen, 2008; Sovacool, 2008b; Beerten et al., 2009; Kubiszewski et al., 2010).

The review procedure included the following steps: literature collection, screening and analysis.

Literature collection

Starting in May of 2009, potentially relevant literature was identified through multiple mechanisms, including searches in major bibliographic databases (e.g., Web of Science, WorldCat) using a variety of search algorithms and combinations of key words, review of reference lists of relevant literature, and specialized searches on websites of known studies series (e.g., European Union's ExternE and its descendants) and known LCA literature databases (e.g., the library contained within the SimaPro LCA software package). All collected literature was first categorized by content (with key information from every collected reference recorded in a database) and added to a bibliographic database.

The literature collection methods described here apply to all classes of electricity generation technologies reviewed in this report except for oil and hydropower. LCA data for hydropower and oil were added at a later stage to the NREL database and have therefore undergone a less comprehensive literature collection process.

Literature screening

Collected references were independently subjected to three rounds of screening by multiple experts to select references that met criteria for quality and relevance. References often reported multiple GHG emission estimates based on alternative scenarios. Where relevant, the screening criteria were applied at the level of the scenario estimate, occasionally resulting in only a subset of scenarios analyzed in a given reference passing the screens.

References having passed the first quality screen included peer-reviewed journal articles, scientifically detailed conference proceedings, PhD theses, and reports (authored by government agencies, academic institutions, non-governmental organizations, international institutions, or corporations) published after 1980 and in English. Attempts were made to obtain English versions of non-English publications and a few exceptions were translated. The first screen also ensured that the accepted references were LCAs, defined as analyzing two or more lifecycle phases (with exceptions for PV and wind energy given that the literature demonstrates that the vast majority of lifecycle GHG emissions occur in the manufacturing phase (Frankl et al., 2005; Jungbluth et al., 2005)).

All references passing the first screen were then directly judged based on more stringent quality and relevance criteria:

- Employed a currently accepted attributional LCA and GHG accounting method (consequential LCAs were not included because their results are fundamentally not comparable to results based on attributional LCA methods; see Section 9.3.4 for further description of attributional and consequential LCAs);
- Reported inputs, scenario/technology characteristics, important assumptions and results in enough detail to trace and trust the results; and
- Evaluated a technology of modern or future relevance.

For the published results to be analyzed, estimates had to pass a final set of criteria:

- To ensure accuracy in transcription, only GHG emission estimates that were reported numerically (i.e., not only graphically) were included.

- Estimates duplicating prior published work were not included.
- Results had to have been easily convertible to the functional unit chosen for this study: grams of CO_2eq per kWh generated.

Table A.II.3 reports the counts of references at each stage in the screening process for the broad classes of electricity generation technologies considered in this report.

Analysis of estimates

Estimates of lifecycle GHG emissions from studies passing both screens were then analyzed and plotted. First, estimates were categorized by technology within the broad classes considered in this report, listed in Table A.II.3. Second, estimates were converted to the common functional unit of g CO_2eq per kWh generated. This conversion was performed using no exogenous assumptions; if any were required, that estimate was not included. Third, estimates of total lifecycle GHG emissions that included contributions from either land use change (LUC) or heat production (in cases of cogeneration) were removed. This step required that studies that considered LUC- or heat-related GHG emissions had to report those contributions separately such that estimates included here pertain to the generation of electricity alone. Finally, distributional information required for display in box and whisker plots were calculated: minimum, 25th percentile value, 50th percentile value, 75th percentile value and maximum. Technologies with data sets composed of less than five estimates (e.g., geothermal) have been plotted as discrete points rather than superimposing synthetic distributional information.

The resulting values underlying Figure 9.8 are shown in Table A.II.4. Figures displayed in technology chapters are based on the same data set, yet displayed with a higher level of resolution regarding technology subcategories (e.g., on- and offshore wind energy).

A.II.5.2.2 List of references

Below, all references for the review of lifecycle assessments of greenhouse gas emissions from electricity generation that are shown in the final results in this report are listed, sorted by technology and in alphabetical order.

Biomass-based power generation (52)

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Table A.II.3 | Counts of LCAs of electricity generation technologies ('references') at each stage in the literature collection and screening process and numbers of scenarios ('estimates') of lifecycle GHG emissions evaluated herein.

Technology category	References reviewed	References passing the first screen	References passing the second screen	References providing lifecycle GHG emissions estimates	Estimates of lifecycle GHG emissions passing screens
Biopower	369	162	84	52	226
Coal	273	192	110	52	181
Concentrating solar power	125	45	19	13	42
Geothermal Energy	46	24	9	6	8
Hydropower	89	45	11	11	28
Natural gas	251	157	77	40	90
Nuclear Energy	249	196	64	32	125
Ocean energy	64	30	6	5	10
Oil	68	45	19	10	24
Photovoltaics	400	239	75	26	124
Wind Energy	231	174	72	49	126
TOTALS	**2165**	**1309**	**546**	**296**	**984**
% of total reviewed		60%	25%	14%	
% of those passing first screen			42%	23%	
% of those passing second screen				54%	

Note: Some double counting is inherent in the totals given that some references investigated more than one technology.

Table A.II.4 | Aggregated results of literature review of LCAs of GHG emissions from electricity generation technologies as displayed in Figure 9.8 (g CO_2eq/kWh).

Values	Bio-power	Solar		Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Nuclear Energy	Natural Gas	Oil	Coal
		PV	CSP								
Minimum	-633	5	7	6	0	2	2	1	290	510	675
25th percentile	360	29	14	20	3	6	8	8	422	722	877
50th percentile	18	46	22	45	4	8	12	16	469	840	1001
75th percentile	37	80	32	57	7	9	20	45	548	907	1130
Maximum	75	217	89	79	43	23	81	220	930	1170	1689
CCS min	-1368								65		98
CCS max	-594								245		396

Note: CCS = Carbon capture and storage, PV = Photovoltaic, CSP = Concentrating solar power.

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A.II.5.3 Review of operational water use of electricity generation technologies

This overview describes the methods of a comprehensive review of published estimates of operational water withdrawal and consumption intensity of electricity generation technologies. Results are discussed in Section 9.3.4.4 and shown in Figure 9.14.

A.II.5.3.1 Review methodology

Lifecycle water consumption and withdrawal literature for electricity generating technologies was reviewed, but due to lack of quality and breadth of data, the review focused exclusively on operational water use. Lifecycle literature considered here are studies that passed the screening process used in this report's review of lifecycle GHG emissions from electricity generation technologies (see A II.5.2). Upstream water use for biofuel energy crops is not subject of this section.

This review did not alter (except for unit conversion) or audit for accuracy the estimates of water use published in studies that passed the screening criteria. Also, because estimates are used as published, considerable methodological inconsistency is inherent, which limits comparability. A few attempts have been made to review the operational water use literature for electricity generation technologies, though all of these were limited in their comprehensiveness of either technologies or of primary literature considered (Gleick, 1993; Inhaber, 2004; NETL, 2007a,b; WRA, 2008; Fthenakis

and Kim, 2010). The present review therefore informs the discourse of this report in a unique way.

Literature collection

The identification of relevant literature started with a core library of references held previously by the researchers, followed by searching in major bibliographic databases using a variety of search algorithms and combinations of key words, and then reviewing reference lists of every collected reference. All collected literature was added to a bibliographic database. The literature collection methods described here apply to all classes of electricity generation technologies reviewed in this report.

Literature screening

Collected references were independently subjected to screening to select references that met criteria for quality and relevance. Operational water use studies must have been written in English, addressed operational water use for facilities located in North America, provided sufficient information to calculate a water use intensity factor (in cubic metres per megawatt-hour generated), made estimates of water consumption that did not duplicate others previously published, and have been in one of the following formats: journal article, conference proceedings, or report (authored by government agencies, nongovernmental organizations, international institutions, or corporations). Estimates of national average water use intensity for particular technologies, estimates of existing plant operational water use, and estimates derived from laboratory experiments were considered equally. Given the paucity of available estimates of water consumption for electricity generation technologies and that the estimates that have been published are being used in the policy context already, no additional screens based on quality or completeness of reporting were applied.

Analysis of estimates

Estimates were categorized by fuel technology and cooling systems. Certain aggregations of fuel technology types and cooling system types were made to facilitate analysis. Concentrating solar power includes both parabolic trough and power tower systems. Nuclear includes pressurized water reactors and boiling water reactors. Coal includes subcritical and supercritical technologies. For recirculating cooling technologies, no distinction is made between natural draft and mechanical draft cooling tower systems. Similarly, all pond-cooled systems are treated identically. Estimates were converted to the common functional unit of cubic meters per MWh generated. This conversion was performed using no exogenous assumptions; if any were required, that estimate was not analyzed.

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A.II.5.4 Risk analysis

This section introduces the methods applied for the assessment of hazards and risks of energy technologies presented in Section 9.3.4.7, and provides references and central assumptions (Table A.II.5).

A large variety of definitions of the term risk exists, depending on the field of application and the object under study (Haimes, 2009). In engineering and natural sciences, risk is frequently defined in a quantitative way: risk (R) = probability (p) × consequence (C). This definition does not include subjective factors of risk perception and aversion, which can also influence the decision-making process, that is, stakeholders may make trade-offs between quantitative and qualitative risk factors (Gregory and Lichtenstein, 1994; Stirling, 1999). Risk assessment and evaluation is further complicated when certain risks significantly transcend everyday levels; their handling posing a challenge for society (WBGU, 2000). For example, Renn et al. (2001) assigned risks into three categories or areas, namely (1) the normal area manageable by routine operations and existing laws and regulations, (2) the intermediate area, and (3) the intolerable area (area of permission). Kristensen et al. (2006) proposed a modified classification scheme to further improve the characterization of risk. Recently, additional aspects such as critical infrastructure protection, complex interrelated systems and 'unknown unknowns' have become a major focus (Samson et al., 2009; Aven and Zio, 2011; Elahi, 2011).

The evaluation of the 'hazards and risks' of various energy technologies as presented in Section 9.3.4.7 builds upon the approach of comparative risk assessment as it has been established at the Paul Scherrer Institut (PSI) since the 1990s;[4] at the core of which is the Energy-Related Severe Accident Database (ENSAD) (Hirschberg et al., 1998, 2003a; Burgherr et al., 2004, 2008; Burgherr and Hirschberg, 2005). The consideration of full energy chains is essential because an accident can happen in any chain stage from exploration, extraction, processing and storage, long distance transport, regional and local distribution, power and/or heat generation, waste treatment, and disposal. However, not all these stages are applicable to every energy chain. For fossil energy chains (coal, oil, natural gas) and hydropower, extensive historical experience is contained in ENSAD for the period 1970 to 2008. In the case of nuclear power, Probabilistic Safety Assessment (PSA) is employed to address hypothetical accidents (Hirschberg et al., 2004a). In contrast, consideration of renewable energy technologies other than hydropower is based on available accident statistics, literature review and expert judgment because of limited or lacking historical experience. It should be noted that available analyses have limited scope and do not include proba-

4 In a recent study, Felder (2009) compared the ENSAD database with another energy accident compilation (Sovacool, 2008a). Despite numerous and partially substantial differences between the two data sets, several interesting findings with regard to methodological and policy aspects were addressed. However, the study was based on the first official release of ENSAD (Hirschberg et al., 1998), and thus disregarded all subsequent updates and extensions. Another study by Colli et al. (2009) took a slightly different approach using a rather broad set of so-called Risk Characterization Indicators, however the actual testing with illustrative examples was based on ENSAD data.

bilistic modelling of hypothetical accidents. This may have bearing particularly on results for solar PV.

No consensus definition of the term 'severe accident' exists in the literature. Within the framework of PSI's database ENSAD, an accident is considered to be severe if it is characterized by one or several of the following consequences:

- At least 5 fatalities or
- At least 10 injured or
- At least 200 evacuees or
- An extensive ban on consumption of food or
- Releases of hydrocarbons exceeding 10,000 metric tons or
- Enforced clean-up of land and water over an area of at least 25 km^2 or
- Economic loss of at least 5 million USD_{2000}

For large centralized energy technologies, results are given for three major country aggregates, namely for OECD and non-OECD countries as well as EU 27. Such a distinction is meaningful because of the substantial differences in management, regulatory frameworks and general safety culture between highly developed countries (i.e., OECD and EU 27) and the mostly less-developed non-OECD countries (Burgherr and Hirschberg, 2008). In the case of China, coal chain data were only analyzed for the years 1994 to 1999 when data on individual accidents from the China Coal Industry Yearbook (CCIY) were available, indicating that previous years were subject to substantial underreporting (Hirschberg et al., 2003a,b). For the period 2000 to 2009, only annual totals of coal chain fatalities from CCIY were available, which is why they were not combined with the data from the previous period. For renewable energy technologies except hydropower, estimates can be considered representative for developed countries (e.g., OECD and EU 27).

Comparisons of the various energy chains were based on data normalized to the unit of electricity production. For fossil energy chains the thermal energy was converted to an equivalent electrical output using a generic efficiency factor of 0.35. For nuclear, hydropower and new renewable technologies the normalization is straightforward since the generated product is electrical energy. The Gigawatt-electric-year (GW_e yr) was chosen because large individual plants have capacities in the neighbourhood of 1 GW of electrical output (GW_e). This makes the GW_e yr a natural unit to use when presenting normalized indicators generated within technology assessments.

A.II.6 Regional definitions and country groupings

The IPCC SRREN uses the following regional definitions and country groupings, largely based on the definitions of the *World Energy Outlook 2009* (IEA, 2009). Grouping names and definitions vary in the published literature, and in the SRREN in some instances there may be slight deviations from the standard below. Alternative grouping names that are used in the SRREN are given in parenthesis.

Africa

Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Democratic Republic of Congo, Côte d'Ivoire, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, United Republic of Tanzania, Togo, Tunisia, Uganda, Zambia and Zimbabwe.

Annex I Parties to the United Nations Framework Convention on Climate Change

Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Liechtenstein, Lithuania, Luxembourg, Monaco, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom and United States.

Eastern Europe/Eurasia (also sometimes referred to as 'Transition Economies')

Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, the former Yugoslav Republic of Macedonia, the Republic of Moldova, Romania, Russian Federation, Serbia, Slovenia, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan. For statistical reasons, this region also includes Cyprus, Gibraltar and Malta.

European Union

Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden and United Kingdom.

G8

Canada, France, Germany, Italy, Japan, Russian Federation, United Kingdom and United States.

Latin America

Antigua and Barbuda, Aruba, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, the British Virgin Islands, the Cayman Islands,

Table A.II.5 | Overview of data sources and assumptions for the calculation of fatality rates and maximum consequences.

Coal
• ENSAD database at PSI; severe (≥5 fatalities) accidents.[1] • OECD: 1970-2008; 86 accidents; 2,239 fatalities. EU 27: 1970-2008; 45 accidents; 989 fatalities. Non-OECD without China: 1970-2008; 163 accidents; 5.808 fatalities (Burgherr et al., 2011). Previous studies: Hirschberg et al. (1998); Burgherr et al. (2004, 2008). • China (1994-1999): 818 accidents; 11,302 fatalities (Hirschberg et al., 2003a; Burgherr and Hirschberg, 2007). • China (2000-2009): for comparison, the fatality rate in the period 2000 to 2009 was calculated based on data reported by the State Administration of Work Safety (SATW) of China.2 Annual values given by SATW correspond to total fatalities (i.e., severe and minor accidents). Thus for the fatality rate calculation it was assumed that fatalities from severe accidents comprise 30% of total fatalities, as has been found in the China Energy Technology Program (Hirschberg et al., 2003a; Burgherr and Hirschberg, 2007). Chinese fatality rate (2000-2009) = 3.14 fatalities/GW_eyr.
Oil
• ENSAD database at PSI; severe (≥5 fatalities) accidents.[1] • OECD: 1970-2008; 179 accidents; 3,383 fatalities. EU 27: 1970-2008; 64 accidents; 1,236 fatalities. Non-OECD: 1970-2008; 351 accidents; 19,376 fatalities (Burgherr et al., 2011). Previous studies: Hirschberg et al. (1998); Burgherr et al. (2004, 2008).
Natural Gas
• ENSAD database at PSI; severe (≥5 fatalities) accidents.[1] • OECD: 1970-2008; 109 accidents; 1,257 fatalities. EU 27: 1970-2008; 37 accidents; 366 fatalities. Non-OECD: 1970-2008; 77 accidents; 1,549 fatalities (Burgherr et al., 2011). Previous studies: Hirschberg et al. (1998); Burgherr et al. (2004, 2008); Burgherr and Hirschberg (2005).
Nuclear
• Generation II (Gen. II) - Pressurized Water Reactor, Switzerland; simplified Probabilistic Safety Assessment (PSA) (Roth et al., 2009). • Generation III (Gen. III) - European Pressurized Reactor (EPR) 2030, Switzerland; simplified PSA (Roth et al., 2009). Available results for the above described EPR point towards significantly lower fatality rates (early fatalities (EF): 3.83E-07 fatalities/GW_eyr; latent fatalities (LF): 1.03E-05 fatalities/GW_eyr; total fatalities (TF): 1.07E-05 fatalities/GW_eyr) due to a range of advanced features, especially with respect to Severe Accident Management (SAM) active and passive systems. However, maximum consequences of hypothetical accidents may increase (ca. 48,800 fatalities) due to the larger plant size (1,600 MW) and the larger associated radioactive inventory. • In the case of a severe accident in the nuclear chain, immediate or early (acute) fatalities are of minor importance and denote those fatalities that occur in a short time period after exposure, whereas latent (chronic) fatalities due to cancer dominate total fatalities (Hirschberg et al., 1998). Therefore, the above estimates for Gen. II and III include immediate and latent fatalities. • Three Mile Island 2, TMI-2: The TMI-2 accident occurred as a result of equipment failures combined with human errors. Due to the small amount of radioactivity released, the estimated collective effective dose to the public was about 40 person-sievert (Sv). The individual doses to members of the public were extremely low: <1 mSv in the worst case. On the basis of the collective dose one extra cancer fatality was estimated. However, 144,000 people were evacuated from the area around the plant. For more information, see Hirschberg et al. (1998). • Chernobyl: 31 immediate fatalities; PSA-based estimate of 9,000 to 33,000 latent fatalities (Hirschberg et al., 1998). • PSI's Chernobyl estimates for latent fatalities range from about 9,000 for Ukraine, Russia and Belarus to about 33,000 for the entire northern hemisphere in the next 70 years (Hirschberg et al., 1998). According to a recent study by numerous United Nations organizations, up to 4,000 persons could die due to radiation exposure in the most contaminated areas (Chernobyl Forum, 2005). This estimate is substantially lower than the upper limit of the PSI interval, which, however, was not restricted to the most contaminated areas.
Hydro
• ENSAD Database at PSI; severe (≥5 fatalities) accidents.[1] • OECD: 1970-2008; 1 accident; 14 fatalities (Teton dam failure, USA, 1976). EU 27: 1970-2008; 1 accident; 116 fatalities (Belci dam failure, Romania, 1991) (Burgherr et al., 2011). • Based on a theoretical model, maximum consequences for the total failure of a large Swiss dam range between 7,125 and 11,050 fatalities without pre-warning, but can be reduced to 2 to 27 fatalities with 2 hours pre-warning time (Burgherr and Hirschberg, 2005, and references therein). • Non-OECD: 1970-2008; 12 accidents; 30,007 fatalities. Non-OECD without Banqiao/Shimantan 1970-2008; 11 accidents; 4,007 fatalities; largest accident in China (Banqiao/Shimantan dam failure, China, 1975) excluded (Burgherr et al., 2011). • Previous studies: Hirschberg et al. (1998); Burgherr et al. (2004, 2008).
Photovoltaic (PV)
• Current estimates include only silicon (Si) technologies, weighted by their 2008 market shares, i.e., 86% for c-Si and 5.1% for a-Si/u-Si. • The analysis covers risks of selected hazardous substances (chlorine, hydrochloric acid, silane and trichlorosilane) relevant in the Si PV life cycle. • Accident data were collected for the USA (for which a good coverage exists), and for the years 2000 to 2008 to ensure that estimates are representative of currently operating technologies. • Database sources: Emergency Response Notification System, Risk Management Plan, Major Hazard Incident Data Service, Major Accidents Reporting System, Analysis Research and Information on Accidents, Occupational Safety and Health Update. • Since collected accidents were not only from the PV sector, the actual PV fatality share was estimated, based on the above substance amounts in the PV sector as a share of the total USA production, as well as data from the ecoinvent database. • Cumulated fatalities for the four above substances were then normalized to the unit of energy production using a generic load factor of 10% (Burgherr et al., 2008). • Assumption that 1 out of 100 accidents is severe.[3] • Current estimate for fatality rate: Burgherr et al. (2011). • Maximum consequences represent an expert judgment due to limited historical experience (Burgherr et al., 2008). • Previous studies: Hirschberg et al. (2004b); Burgherr et al. (2008); Roth et al. (2009). • Other studies: Ungers et al. (1982); Fthenakis et al. (2006); Fthenakis and Kim (2010).

Continued next Page →

Wind Onshore

- Data sources: Windpower Death Database (Gipe, 2010) and Wind Turbine Accident Compilation (Caithness Windfarm Information Forum, 2010).
- Fatal accidents in Germany in the period 1975-2010; 10 accidents; 10 fatalities. 3 car accidents, where driver distraction from wind farm is given as reason, were excluded from the analysis.
- Assumption that 1 out of 100 accidents is severe.[3]
- Current estimate for fatality rate: Burgherr et al. (2011).
- Maximum consequences represent an expert judgment due to limited historical experience (Roth et al., 2009).
- Previous study: Hirschberg et al. (2004b).

Wind Offshore

- Data sources: see onshore above.
- Up to now there were 2 fatal accidents during construction in the UK (2009 and 2010) with 2 fatalities, and 2 fatal accidents during research activities in the USA (2008) with 2 fatalities.
- For the current estimate, only UK accidents were used, assuming a generic load factor of 0.43 (Roth et al., 2009) for the currently installed capacity of 1,340 MW (Renewable UK, 2010).
- Assumption that 1 out of 100 accidents is severe.[3]
- Current estimate for fatality rate: Burgherr et al. (2011).
- Maximum consequences: see onshore above.

Biomass: Combined Heat and Power (CHP) Biogas

- ENSAD Database at PSI; severe (≥5 fatalities) accidents.[1] Due to limited historical experience, the CHP Biogas fatality rate was approximated using natural gas accident data from the local distribution chain stage.
- OECD: 1970-2008; 24 accidents; 260 fatalities (Burgherr et al., 2011).
- Maximum consequences represent an expert judgment due to limited historical experience (Burgherr et al., 2011).
- Previous studies: Roth et al. (2009).

Enhanced Geothermal System (EGS)

- For the fatality rate calculations, only well drilling accidents were considered. Due to limited historical experience, exploration accidents in the oil chain were used as a rough approximation because of similar drilling equipment.
- ENSAD Database at PSI; severe (≥5 fatalities) accidents.[1]
- OECD: 1970-2008; oil exploration, 7 accidents; 63 fatalities (Burgherr, et al. 2011).
- For maximum consequences an induced seismic event was considered to be potentially most severe. Due to limited historical experience, the upper fatality boundary from the seismic risk assessment of the EGS project in Basel (Switzerland) was taken as an approximation (Dannwolf and Ulmer, 2009).
- Previous studies: Roth et al. (2009).

Notes: 1. Fatality rates are normalized to the unit of energy production in the corresponding country aggregate. Maximum consequences correspond to the most deadly accident that occurred in the observation period. 2. Data from SATW for the years 2000 to 2005 were reported in the China Labour News Flash No. 60 (2006-01-06) available at www.china-labour.org.hk/en/node/19312 (accessed December 2010). SATW data for the years 2006 to 2009 were published by Reuters, available at www.reuters.com/article/idUSPEK206148 (2006), uk.reuters.com/article/idUKPEK32921920080112 (2007), uk.reuters.com/article/idUKTOE61D00V20100214 (2008 and 2009), (all accessed December 2010). 3. For example, the rate for natural gas in Germany is about 1 out of 10 (Burgherr and Hirschberg, 2005), and for coal in China about 1 out of 3 (Hirschberg et al., 2003b).

Chile, Colombia, Costa Rica, Cuba, Dominica, the Dominican Republic, Ecuador, El Salvador, the Falkland Islands, French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, St. Kitts and Nevis, Saint Lucia, Saint Pierre et Miquelon, St. Vincent and the Grenadines, Suriname, Trinidad and Tobago, the Turks and Caicos Islands, Uruguay and Venezuela.

Middle East

Bahrain, the Islamic Republic of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, the United Arab Emirates and Yemen. It includes the neutral zone between Saudi Arabia and Iraq.

Non-OECD Asia (also sometimes referred to as 'developing Asia')

Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China, Chinese Taipei, the Cook Islands, East Timor, Fiji, French Polynesia, India, Indonesia, Kiribati, the Democratic People's Republic of Korea, Laos, Macau, Malaysia, Maldives, Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Papua New Guinea, the Philippines, Samoa, Singapore, Solomon Islands, Sri Lanka, Thailand, Tonga, Vietnam and Vanuatu.

North Africa

Algeria, Egypt, Libyan Arab Jamahiriya, Morocco and Tunisia.

OECD – Organisation for Economic Cooperation and Development

OECD Europe, OECD North America and OECD Pacific as listed below. Countries that joined the OECD in 2010 (Chile, Estonia, Israel and Slovenia) are not yet included in the statistics used in this report.

OECD Europe

Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

OECD North America

Canada, Mexico and the United States.

OECD Pacific

Australia, Japan, Korea and New Zealand.

OPEC (Organization of Petroleum Exporting Countries)

Algeria, Angola, Ecuador, Islamic Republic of Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, United Arab Emirates and Venezuela.

Sub-Saharan Africa

Africa regional grouping excluding the North African regional grouping and South Africa.

A.II.7 General conversion factors for energy

Table A.II.6 provides conversion factors for a variety of energy-related units.

Table A.II.6 | Conversion factors for energy units (IEA, 2010b).

To:	TJ	Gcal	Mtoe	MBtu	GWh
From:	**multiply by:**				
TJ	1	238.8	2.388×10^{-5}	947.8	0.2778
Gcal	4.1868×10^{-3}	1	10^{-7}	3.968	1.163×10^{-3}
Mtoe	4.1868×10^{4}	10^{7}	1	3.968×10^{7}	11,630
MBtu	1.0551×10^{-3}	0.252	2.52×10^{-8}	1	2.931×10^{-4}
GWh	3.6	860	8.6×10^{-5}	3,412	1

Notes: MBtu: million British thermal unit; GWh: gigawatt hour; Gcal: gigacalorie; TJ: terajoule; Mtoe: megatonne of oil equivalent.

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ANNEX III

Recent Renewable Energy Cost and Performance Parameters

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Annex III Recent Renewable Energy Cost and Performance Parameters

Annex III is intended to become a 'living document', which will be updated in the light of new information in order to serve as an input to the IPCC Fifth Assessment Report (AR5). Scientists that are interested in supporting this process are invited to contact the IPCC WG III Technical Support Unit (TSU) (using srren_cost@ipcc-wg3.de) in order to get further information concerning the submission process.[1] Comments and new data input will be considered for inclusion in Volume 3 of the IPCC AR5 according to the procedures of the IPCC review system.

This Annex contains recent cost and performance parameter information for currently commercially available renewable power generation technologies (Table A.III.1), heating technologies (Table A.III.2) and biofuel production processes (Table A.III.3). It summarizes information that determines the levelized cost of energy or energy carriers supplied by the respective technologies.

The input ranges are based on assessments of various studies by authors of the respective technology chapters (Chapters 2 through 7). If not stated otherwise, the data ranges provided here are worldwide aggregates. Data are generally for 2008, but can be as recent as 2009. They represent roughly the mid-80% of values found in the literature, hence, excluding outliers. The availability and quality of different sources of data varies significantly across individual technologies for a variety of reasons.[2] Some expert judgment is therefore required to determine data ranges that are representative of particular classes of technologies and specific periods of time and valid globally.

The references to specific information are quoted in the footnotes. If the full dataset is based on one particular reference, it is included in the reference column of the green part of the table. Further information on the data reported in the table is provided in the footnotes and in Chapters 2 through 7 (see in particular Sections 2.7, 3.8, 4.7, 5.8, 6.7 and 7.8).

The levelized cost of electricity (LCOE), heat (LCOH) and transport fuels (LCOF)[3] are calculated based on the data compiled here and the methodology described in Annex II, using three different real discount rates (3, 7 and 10%). They represent the full range of possible levelized cost values resulting from the lower and upper bounds of input data in this table. More precisely, the lower bound of the levelized cost ranges is based on the low ends of the ranges of investment, operation and maintenance (O&M) and (if applicable) feedstock cost and the high ends of the ranges of capacity factors and lifetimes as well as (if applicable) the high ends of the ranges of conversion efficiencies and by-product revenue stated in this table. The higher bound of the levelized cost ranges is accordingly based on the high end of the ranges of investment, O&M and (if applicable) feedstock costs and the low end of the ranges of capacity factors and lifetimes as well as (if applicable) the low ends of the ranges of conversion efficiencies and by-product revenue.[4]

These levelized cost figures (violet parts of the tables) are discussed in Sections 1.3.2 and 10.5.1 of the main report. Most technology chapters (Chapters 2 through 7) provide more detail on the sensitivity of the levelized costs to particular input parameters beyond discount rates (see in particular Sections 2.7, 3.8, 4.7, 5.8, 6.7 and 7.8). These sensitivity analyses provide additional insights into the relative weight of the large number of parameters that determine the levelized costs under more specific conditions.

In addition to the technology-specific sensitivity analysis in the respective chapters (Chapters 2 through 7) and the discussions in Sections 1.3.2 and 10.5.1, Figures A.III.2 through A.III.4 (a, b) show the sensitivity of the levelized cost in a complementary way using so-called tornado graphs (Figures A.III.2 through A.III.4 a) as well as their 'negatives' (Figures A.III.2 through A.III.4 b).

Figures A.III.1a and A.III.1b show schematic versions of the tornado graphs and their 'negatives', respectively, explaining how to read them correctly.

1 No individual responses can be guaranteed, but all emails as well as relevant material attached to those emails will be archived and made available in appropriate form to the authors involved in the AR5 process.

2 No standardized uncertainty language has been used in this report. Nonetheless, the authors of this Annex have carefully assessed available data and highlighted data limitations and uncertainties in the footnotes. A fair impression of the breadth of the reference base can be deduced from the list of references in this Annex.

3 The levelized cost represents the cost of an energy generating system over its lifetime. It is calculated as the per unit price at which energy must be generated from a specific source over its lifetime to break even. The levelized costs usually include all private costs that accrue upstream in the value chain, but they do not include the downstream cost of delivery to the final customer, the cost of integration, or external environmental or other costs. Subsidies for RE generation and tax credits are not included. However, indirect taxes and subsidies on inputs or commodities affecting the prices of inputs and, hence, private cost, cannot be fully excluded.

4 This approach assumes that input parameters to the LCOE/LCOH/LCOF calculation are independent from each other. This is a simplifying assumption that implies that the lower ranges of LCOE/LCOH/LCOF (as a combination of best-case input values) may in some cases be lower than is most often the case, while the upper range of LCOE/LCOH/LCOFs (as a combination of worst-case input values) may in some cases be higher than what is generally considered economically attractive from a private investors' perspective. The extent to which this approach introduces a structural bias in the LCOE/LCOH/LCOF ranges, however, is reduced by taking a rather conservative approach to the range of input values (partly involving expert judgement), that is, by restricting input values roughly to the medium 80% range where possible.

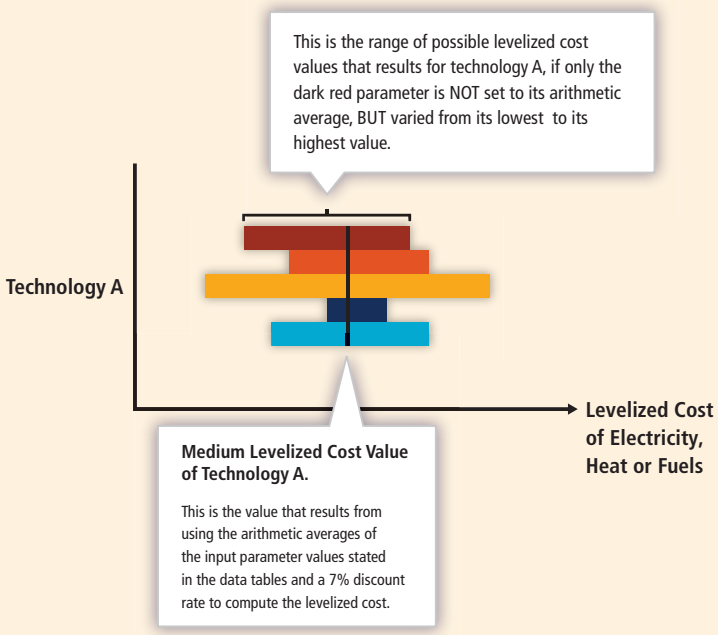

Figure A.III.1a | Tornado graph. Starting from the medium levelized cost value at a 7% interest rate, a broader range of levelized cost values becomes possible if individual parameters are varied over the full of range of values that these parameters may take on under different conditions. If the LCOE/LCOH/LCOF of a technology is very sensitive to variation of a particular parameter, then the corresponding bar will be broad. This means that a variation of that particular parameter may lead to LCOE/LCOH/LCOF values that can deviate strongly from the medium LCOE/LCOH/LCOF value. If the LCOE/LCOH/LCOF of a technology is robust for variations of the respective parameter, the bars will be narrow and only slight deviations from the medium LCOE/LCOH/LCOF value may result from variation of that parameter. Note, however, that no or narrow bars may also be the result of no or limited variation of the input parameters.

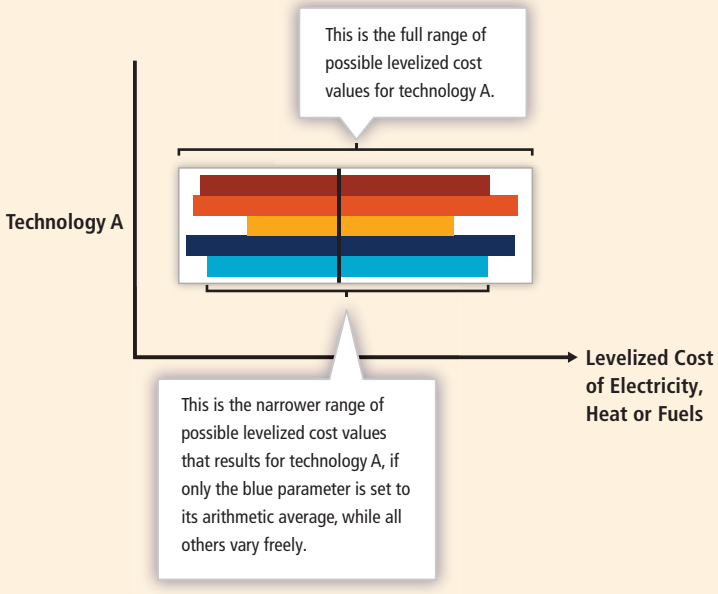

Figure A.III.1b | 'Negative' of tornado graph. Starting from the low and high bounds of the full range of levelized cost values at a 3% and 10% interest rate, respectively, a narrower range of levelized cost values remains possible if individual parameters are fixed at their respective medium values. If the LCOE/LCOH/LCOF of a technology is very sensitive to variations of a particular parameter, then the corresponding bar that remains will be narrowed to a large degree. Such parameters are of particular importance in determining the LCOE/LCOH/LCOF under more specific conditions. If the LCOE/LCOH/LCOF of a technology is robust for variations of the respective parameter, the remaining range will remain close to the full range of possible LCOE/LCOH/LCOF values. Such parameters are of less importance in determining the LCOE/LCOH/LCOF more precisely. Note, however, that no or small deviations from the full range may also be the result of no or limited variation of the input parameters.

Table A.III.1 | Cost-performance parameters for RE power generation technologies.[i]

		Input data									Output data		
Resource	Technology	Typical size of the device (MW)[ii]	Investment cost (USD/kW)	O&M cost, fixed annual (USD/kW) and/or (non-feed) variable (US¢/kWh)	By-product revenue (US¢/kWh)[iii]	Feedstock cost ($USD/GJ_{feed,\ HHV}$[iv])	Feedstock conversion efficiency$_{el}$ (%)	Capacity factor (%)	Economic design lifetime (years)	References	LCOE[v] (US¢/kWh) Discount rate 3%	7%	10%
Bioenergy	Dedicated Biopower CFB[vi]	25–100	2,700–4,100[vii]	87 USD/kW and 0.40 US¢/kWh	N/A[viii]	1.25–5.0[ix]	28	70–80	20	McGowin (2008)	6.1–13	6.9–15	7.9–16
	Dedicated Biopower Stoker[x]	See above	2,600–4,000[vii]	84 USD/kW and 0.34 US¢/kWh	N/A[viii]	See above	27	See above	See above		5.6–13	6.7–15	7.7–16
	Dedicated Biopower (Stoker CHP[xi])	See above	2,800–4,200[vii]	86 USD/kW and 0.35 US¢/kWh	1.0[xii]	See above	24	See above	See above		5.1–13	6.3–15	7.3–17
	Co-firing: Co-feed	20–100	430–500[xiii]	12 USD/kW and 0.18 US¢/kWh	N/A[viii]	See above	36	See above	See above	McGowin (2008)	2.0–5.9	2.2–6.2	2.3–6.4
	Co-firing: Separate Feed	See above	760–900[xiii]	18 USD/kW	N/A[viii]	See above	36	See above	See above	Bain (2011)	2.3–6.3	2.6–6.7	2.9–7.1
	CHP (ORC[xiv])	0.65–1.6	6,500–9,800	59–80 USD/kW and 4.3–5.1 US¢/kWh	7.7[xv, xvi]	See above	14	55–68	See above	Obernberger et al. (2008)	8.6–26	12–32	15–37
	CHP (Steam Turbine)	2.5–10	4,100–6,200[xvii]	54 USD/kW and 3.5 US¢/kWh	5.4[xv, xviii]	See above	18	See above	See above		6.2–18	8.3–22	10–26
	CHP (Gasification ICE)[xix]	2.2–13	1,800–2,100	65–71 USD/kW and 1.1-1.9 US¢/kWh	1.0–4.5[xv, xx]	See above	28–30	See above	See above		2.1–11	3.0–13	3.8–14
Direct Solar Energy	PV (Residential Rooftop)	0.004–0.01	3,700–6,800[xxi]	19–110 USD/kW[xxii]	N/A[viii]	N/A[viii]	N/A[viii]	12–20[xxiii]	20–30	see Section 3.8 and footnotes	12–53	18–71	23–86
	PV (Commercial Rooftop)	0.02–0.5	3,500–6,600[xxi]	18–100 USD/kW[xxii]	N/A[viii]	N/A[viii]	N/A[viii]	See above	See above		11–52	17–69	22–83
	PV (Utility Scale, Fixed Tilt)	0.5–100[xxiv]	2,700–5,200[xxi]	14–69 USD/kW[xxii]	N/A[viii]	N/A[viii]	N/A[viii]	15–21[xxiii]	See above		8.4–33	13–43	16–52
	PV (Utility Scale, One-Axis)	0.5–100[xxiv]	3,100–6,200[xxi]	16–75 USD/kW[xxii]	N/A[viii]	N/A[viii]	N/A[viii]	15–27[xxiii]	See above		7.4–39	11–52	15–62
	CSP	50–250[xxv]	6,000–7,300[xxvi]	60–82 USD/kW[xxvii]	N/A[viii]	N/A[viii]	N/A[viii]	35–42[xxviii]	See above		11–19	16–25	20–31
Geothermal Energy	Geothermal Energy (Condensing-Flash Plants)	10–100	1,800–3,600[xxix]	150–190 USD/kW[xxx]	N/A[viii]	N/A[viii]	N/A[viii]	60–90[xxxi]	25–30[xxxii]	see Section 4.7 and footnotes	3.1–8.4	3.8–11	4.5–13
	Geothermal Energy (Binary-Cycle Plants)	2–20	2,100–5,200[xxix]	See above	N/A[viii]	N/A[viii]	N/A[viii]	See above	See above		3.3–11	4.1–14	4.9–17
Hydropower	All	<0.1 – >20,000[xxxiii]	1,000–3,000[xxxiv]	25–75 USD/kW[xxxv]	N/A[viii]	N/A[viii]	N/A[viii]	30–60[xxxvi]	40–80[xxxvii]	see Chapter 5 and footnotes	1.1–7.8	1.8–11	2.4–15
Ocean Energy	Tidal Range[xxxviii]	<1 – >250[xxxix]	4,500–5,000[xxx-viii]	100 USD/kW[xxxviii]	N/A[viii]	N/A[viii]	N/A[viii]	22.5–28.5[xl]	40[xli, xxxviii]	see Section 6.7 and footnotes	12–16	18–24	23–32

Continued next page →

		Input data									Output data		
Resource	Technology	Typical size of the device (MW)[ii]	Investment cost (USD/kW)	O&M cost, fixed annual (USD/kW) and/or (non-feed) variable (US¢/kWh)	By-product revenue (US¢/kWh)[iii]	Feedstock cost (USD/$GJ_{feed, HHV}$[iv])	Feedstock conversion efficiency$_{el}$ (%)	Capacity factor (%)	Economic design lifetime (years)	References	LCOE[v] (US¢/kWh)		
											Discount rate		
											3%	7%	10%
Wind Energy	Wind Energy (Onshore,Large Turbines)	5–300[xii]	1,200–2,100[xiii]	1.2–2.3 US¢/kWh	N/A[viii]	N/A[viii]	N/A[viii]	20–40[xiv]	20[xv]	see Chapter 7	3.5–10	4.4–14	5.2–17
	Wind Energy (Off-Shore, Large Turbines)	20–120[xii]	3,200–5,000[xvi]	2.0–4.0 US¢/kWh	N/A[viii]	N/A[viii]	N/A[viii]	35–45[xii]	See above		7.5–15	9.7–19	12–23

General remarks/notes:

i All data are rounded to 2 significant digits. Most technology chapters (Chapters 2 through 7) provide additional and/or more detailed cost and performance information in the respective chapters' sections on cost trends. Direct comparison between levelized cost estimates taken directly from the literature should take the underlying assumptions into due consideration.

ii Device sizes are intended to be representative of current/recent sizes. If future sizes are expected to differ from these values, this is included in the footnotes to the relevant technologies.

iii For combined heat and power (CHP) plants, heat production is considered as a by-product in the calculation of the levelized cost of electricity providing full capital cost information as a stand-alone plant.

iv HHV: Higher heating value. LHV: Lower heating value.

v LCOE: Levelized cost of electricity. The levelized cost usually includes all private costs that accrue upstream in the value chain of electricity production, but they do not include the cost of transmission and distribution to the final customer. Output subsidies for RE generation and tax credits are not included. However, indirect taxes and subsidies on inputs or commodities affecting the prices of inputs and, hence, private cost, cannot be fully excluded. Depending on the context of discussion, LCOE may also stand for levelized cost of energy.

Bioenergy:

vi A circulating fluid bed (CFB) is a turbulent (high gas flow) fluid bed where solid particles are captured and returned to the bed. A fluid bed itself is a collection of small solid particles suspended and kept in motion by an upward flow of fluid, typically a gas.

vii The reference data are for a 50 MW plant. Investment costs for larger and smaller plants have been rescaled according to the power law: Specific investment $cost_{size\ 2}$ = Investment $cost_{size\ 1}$ x (Size 2/Size 1)$^{n-1}$, where the scaling factor n = 0.7. Capital cost estimates include facilities for fuel handling and preparation, boiler and air quality control, steam turbine and auxiliaries, balance of plant, general facilities and engineering fee, project and process contingency, allowance for funds used during construction, owner costs, and taxes and fees.

viii The abbreviation 'N/A' means here 'not applicable'.

ix Feedstock is wood with HHV = 20.0 GJ/t, LHV = 18.6 GJ/t.

x A mechanical stoker is a machine or device that feeds fuel to a boiler.

xi CHP: Combined heat and power.

xii The calculation of the by-product revenue for the large-scale CHP plant assumes: heat output used for industrial applications is 5.38 GJ of heat per MWh electricity; steam is valued at USD_{2005} 4.85/GJ (75% of US pulp and paper purchased steam price) (EIA, 2009, Table 7.2); and 75% of heat output is sold.

xiii The reference data are for a 50 MW plant. Investment costs for larger and smaller plants have been rescaled according to the power law: Specific investment $cost_{size\ 2}$ = Investment $cost_{size\ 1}$ x (Size 2/Size 1)$^{n-1}$, where the scaling factor n = 0.9 (Peters et al., 2003). The cofiring investment costs estimates were developed for retrofits of existing coal-fired power plants in the USA and include facilities for fuel handling and preparation, additional expenditures for boiler modifications, balance of plant, general facilities and engineering, project and process contingency, allowance for funds used during construction, owner costs, and taxes and fees. Cofiring cost estimate protocols in the USA do not include prorated boiler costs.

xiv ORC: Organic Rankine Cycle.

xv For the calculation of the by-product revenue for small-scale CHP plants, hot water is valued at USD_{2005} 12.51/GJ (average of Rauch (2010) and Skjoldborg (2010)), 33% of gross value is taken into account, because the operator can only recover a portion of the value and because use of hot water is seasonal.

xvi Heat output used for hot water is 18.51 GJ of heat per MWh electricity.

xvii The reference data are for a 5 MW CHP plant. Investment costs for larger and smaller plants have been rescaled according to the power law: Specific investment $cost_{size\ 2}$ = Investment $cost_{size\ 1}$ x (Size 2/Size 1)$^{n-1}$, where the scaling factor n =0.7 (Peters et al., 2003).

Continued next page →

xviii Heat output used for hot water is 12.95 GJ of heat per MWh electricity.

xix ICE: Internal combustion engine.

xx Heat output used for hot water is in the range of 2.373 to 10.86 GJ/MWh.

Direct solar energy – photovoltaic (PV) systems:

xxi In 2009, wholesale factory PV module prices decreased by more than 50%. As a result, the market prices for installed PV systems in Germany, the most competitive market, decreased by over 30% in 2009 compared to about 10% in 2008 (see Section 3.8.3). 2009 market price data from Germany is used as the lower bound for investment costs of residential rooftop systems (Bundesverband Solarwirtschaft e.V., 2010) and for utility-scale fixed tilt systems (Bloomberg, 2010). Based on US market data for 2008 and 2009, larger, commercial rooftop systems are assumed to have a 5% lower investment cost than the smaller, residential rooftop systems (NREL, 2011b; see also section 3.8.3). Tracking systems are assumed to have a 15-20% higher investment cost than the one-axis, non-tracking systems considered here (NREL, 2011a; see also Section 3.8.3). Capacity-weighted averages of investment costs in the USA in 2009 (NREL, 2011b) are used as upper bound to capture the investment cost ranges typical of roughly 80% of global installations in 2009 (see Section 3.4.1 and Section 3.8.3).

xxii O&M costs of PV systems are low and are given in a range between 0.5 and 1.5% annually of the initial investment costs (Breyer et al., 2009; IEA, 2010c).

xxiii The main parameter that influences the capacity factor of a PV system is the actual annual solar irradiation in kWh/m²/yr at a given location and the type of system. Capacity factors of some recently installed systems are provided in Sharma (2011).

xxiv The upper limit of utility-scale PV systems represents current status. Much larger systems (up to 1 GW) are in the proposal and development phase and might be realized within the next decade.

Direct solar energy – concentrating solar power (CSP):

xxv Project sizes of CSP plants can minimally match the size of a single power generating system (e.g., a 25 kW dish/engine system). However, the range provided is typical for projects being built or proposed today. 'Power Parks' consisting of multiple CSP plants in a single location are also being proposed at sizes of up to or exceeding 1 GW (4 x 250 MW).

xxvi Cost ranges are for parabolic trough plants with six hours of thermal energy storage in 2009. Investment cost includes direct plus indirect costs where indirect costs include engineering, procurement and construction mark-up, owner costs, land, and taxes. Investment costs are lower for plants without storage and higher for plants with larger storage capacity. The IEA (2010a) estimates investment costs as low as USD_{2005} 3,800/kW for plants without storage and as high as USD_{2005} 7,600/kW for plants with large storage (assumed currency base year: 2009). Capacity factors vary as well, if thermal storage is installed (see note xxviii).

xxvii The IEA (2010a) states O&M costs relative to energy output as US¢ 1.2 to 2.7/kWh (assumed currency base year: 2009). Depending on actual energy output this may result in lower or higher annual O&M cost compared to the range stated here.

xxviii Capacity factor for a parabolic trough plant with six hours of thermal energy storage for solar resource classes typical of the southwest USA. Depending on the size of the thermal storage capacity, capacity factors as well as investment costs vary substantially. Apart from the Solar Electric Generating Station plants in California, new CSP plants only became operational from 2007 onwards, thus few actual performance data are available and most of the literature just gives estimated or predicted capacity factors. Sharma (2011) reports multi-year (1998-2002) average capacity factors of 12.4 to 27.7% for plants without thermal storage, but with natural gas backup. The IEA (2010a) states that plants in Spain with 15 hours of storage may produce up to 6,600 hours per year. This is equivalent to a 75% capacity factor, if production occurs at full capacity during the 6,600 hours. Larger storage also increases investment costs (see note xxvi).

Geothermal energy:

xxix Investment cost includes: exploration and resource confirmation; drilling of production and injection wells; surface facilities and infrastructure; and the power plant. For expansion projects (i.e., new plants in the same geothermal field) investment costs can be 10 to 15% lower (see Section 4.7.1). Investment cost ranges are based on Bromley et al. (2010) (see also Figure 4.7).

xxx O&M costs are based on Hance (2005). In New Zealand, O&M costs range from US¢ 1 to 1.4/kWh for 20 to 50 MW_e plant capacity (Barnett and Quinlivan, 2009), which are equivalent to USD 83 to 117/kW/yr, i.e. considerably lower than those given by Hance (2005). For further information see Section 4.7.2.

xxxi The current (data for 2008-2009) worldwide capacity factor (CF) for condensing (flash) and binary-cycle plants in operation is 74.5%. Excluding some outliers, the lower and upper bounds can be estimated as 60 and 90%. Typical CFs for new geothermal power plants are over 90% (Hance, 2005; DiPippo, 2008; Bertani, 2010). The worldwide average CF for 2020 is projected to be 80%, and could be 85% in 2030 and as high as 90% in 2050 (see Sections 4.7.3 and 4.7.5).

xxxii 25 to 30 years is the common lifetime of geothermal power plants worldwide. This payback period allows for refurbishment or replacement of the aging surface plant at the end of its lifetime, but is not equivalent to the economic resource lifetime of the geothermal reservoir, which is typically much longer (e.g., Larderello, Wairakei, The Geysers: Section 4.7.3). In some reservoirs, however, the possibility of resource degradation over time is one of several factors that affect the economics of continuing plant operation.

Hydropower:

xxxiii The mid-80% of project sizes is not well documented for hydropower. The range stated here is indicative of the full range of project sizes. Hydropower projects are always site-specific as they are designed to use the flow and head at each site. Therefore, projects can be very small, down to a few kW in a small stream, and up to several thousand MW, for example 18,000 MW for the Three Gorges project in China (which will be 22,400 MW when completed) (see Section 5.1.2). 90% of the installed hydropower capacity and 94% of hydropower energy production today is in hydropower plants >10 MW in size (IJHD, 2010).

xxxiv The investment cost for hydropower projects can be as low as USD 400 to 500/kW but most realistic projects today lie in the range of USD 1,000 to 3,000/kW (Section 5.8.1).

xxxv O&M costs are usually given as a percentage of investment cost for hydropower projects. Typical values range from 1 to 4%, while the table relies on an average value of 2.5% applied to the range of investment costs. This will usually be sufficient to cover refurbishment of mechanical and electrical equipment like turbine overhaul, generator rewinding and reinvestments in communication and control systems (Section 5.8.1).

Continued next page →

xxxvi Capacity factors (CF) will be determined by hydrological conditions, installed capacity and plant design, and the way the plant is operated (i.e., the degree of plant output regulation). For power plant designs intended for maximum energy production (base-load) and with some regulation, CFs will often be from 30 to 60%. Figure 5.20 shows average CFs for different world regions. For peaking-type power plants the CF will be much lower, down to 20%, as these stations are designed with much higher capacity in order to meet peaking needs. CFs for run-of-river systems vary across a wide range (20 to 95%) depending on the geographical and climatological conditions, technology and operational characteristics (see Section 5.8.3).

xxxvii Hydropower plants in general have very long physical lifetimes. There are many examples of hydropower plants that have been in operation for more than 100 years, with regular upgrading of electrical and mechanical systems but no major upgrades of the most expensive civil structures (dams, tunnels, etc.). The IEA (2010d) reports that many plants built 50 to 100 years ago are still operating today. For large hydropower plants, the lifetime can, hence, safely be set to at least 40 years, and an 80-year lifetime is used as upper bound. For small-scale hydropower plants the typical lifetime can be set to 40 years, in some cases even less. The economic design lifetime may differ from actual physical plant lifetimes, and will depend strongly on how hydropower plants are owned and financed (see Section 5.8.1).

Ocean Energy:

xxxviii The data supplied for tidal range power plants are based on a very small number of installations (see subsequent footnotes). Therefore, all data should be considered with appropriate caution.

xxxix The only utility-scale tidal power station in the world is the 240 MW La Rance power station, which has been in successful operation since 1966. Other smaller projects have been commissioned since then in China, Canada and Russia with 3.9 MW, 20 MW and 0.4 MW, respectively. The 254 MW Sihwa barrage is expected to be commissioned in 2011 and will then become the largest tidal power station in the world. Numerous projects have been identified, some of them with very large capacities, including in the UK (Severn Estuary, 9.3 GW), India (1.8 GW), Korea (740 MW) and Russia (the White Sea and Sea of Okhotsk, 28 GW). None have been considered to be economic yet and many of them face environmental objections (Kerr, 2007). The projects at the Severn Estuary have been evaluated by the UK government and recently been deferred.

xl An earlier assessment suggests capacity factors in the range of 25 to 35% (Charlier, 2003).

xli Tidal barrages resemble hydropower plants, which in general have very long design lives. Many hydropower plants have been in operation for more than 100 years, with regular upgrading of electro-mechanical systems but no major upgrades of the most expensive civil structures (dams, tunnels etc). Tidal barrages are therefore assumed to have a similar economic design lifetime as large hydropower plants, which can safely be set to at least 40 years (see Chapter 5).

Wind energy:

xlii Typical size of the device is taken as the power plant (not turbine) size. For onshore wind energy, 5 to 300 MW plants were common from 2007 to 2009, though both smaller and larger plants are prevalent. For offshore wind energy, 20 to 120 MW plants were common from 2007 to 2009, though much larger plant sizes are expected in the future. As a modular technology, a wide range of plant sizes is common, driven by market and geographic conditions.

xliii The lowest cost onshore wind power plants have been installed in China, with higher costs experienced in the USA and Europe. The range reflects the majority of onshore wind power plants installed worldwide in 2009 (the most recent year for which solid data exist as of writing), but plants installed in China have average costs that can be even below this range (USD 1,000 to 1,350/kW is common in China). In most cases, the investment cost includes the cost of the turbines (turbines, transportation to site, and installation), grid connection (cables, sub-station, interconnection, but not more general transmission expansion costs), civil works (foundations, roads, buildings), and other costs (engineering, licensing, permitting, environmental assessments, and monitoring equipment).

xliv Capacity factors depend in part on the strength of the underlying wind resource, which varies by region and site, as well as by turbine design.

xlv Modern wind turbines that meet International Electrotechnical Commission standards are designed for a 20-year life, and turbine lifetimes may even exceed 20 years if O&M costs remain at an acceptable level. Wind power plants are typically financed over a 20-year time period.

xlvi For offshore wind power plants, the range in investment costs includes the majority of offshore wind power plants installed in the most recent years (through 2009) as well as those plants planned for completion in the early 2010s. Because costs have risen in recent years, using the cost of recent and planned projects reasonably reflects the 'current' cost of offshore wind power plants. In most cases, the investment cost includes the cost of the turbines (turbines, transportation to site, and installation), grid connection (cables, sub-station, interconnection, but not more general transmission expansion costs), civil works (foundations, roads, buildings), and other costs (engineering, licensing, permitting, environmental assessments, and monitoring equipment).

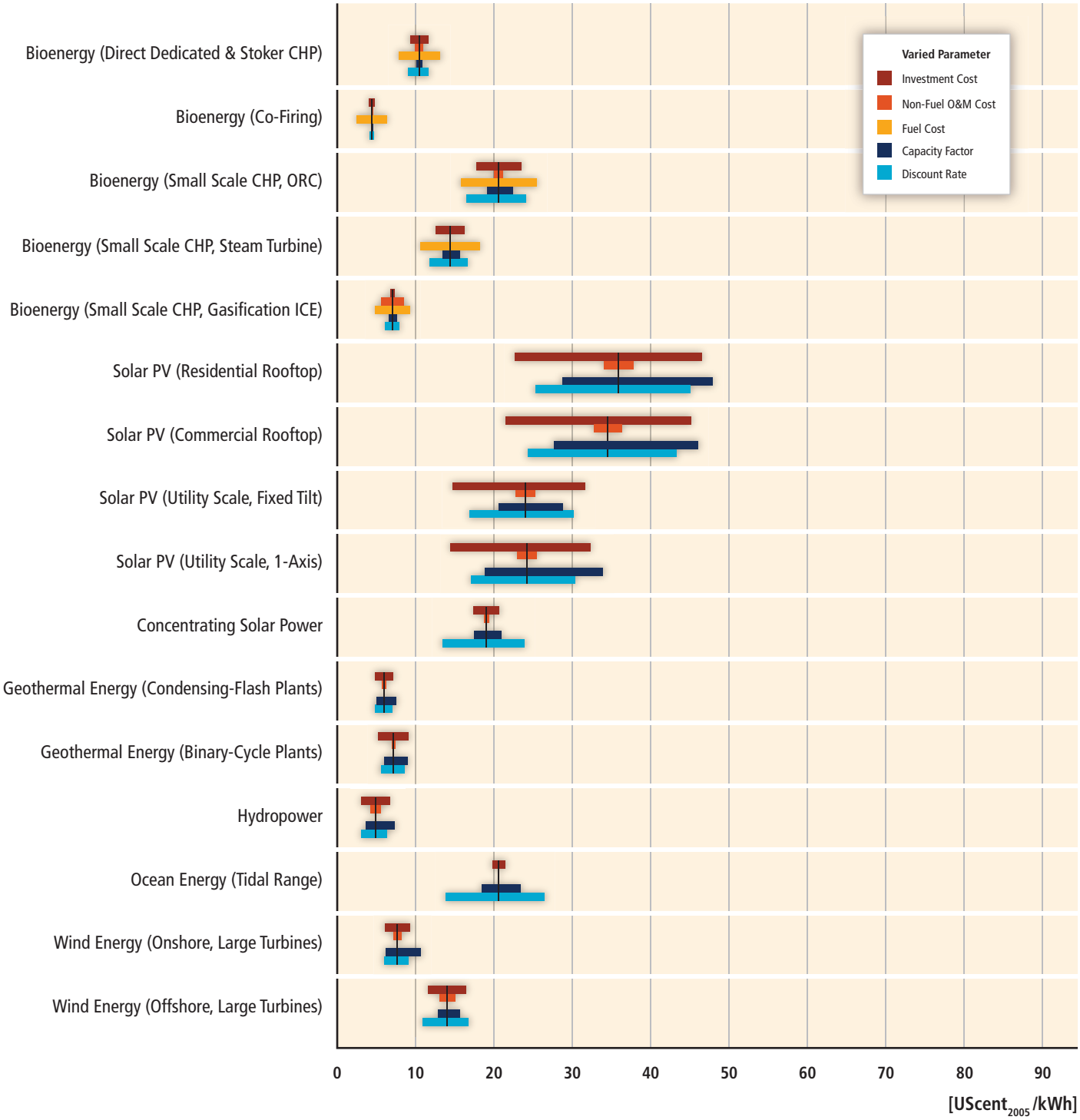

Figure A.III.2a | Tornado graph for renewable power technologies. For further explanation see Figure A.III.1a.

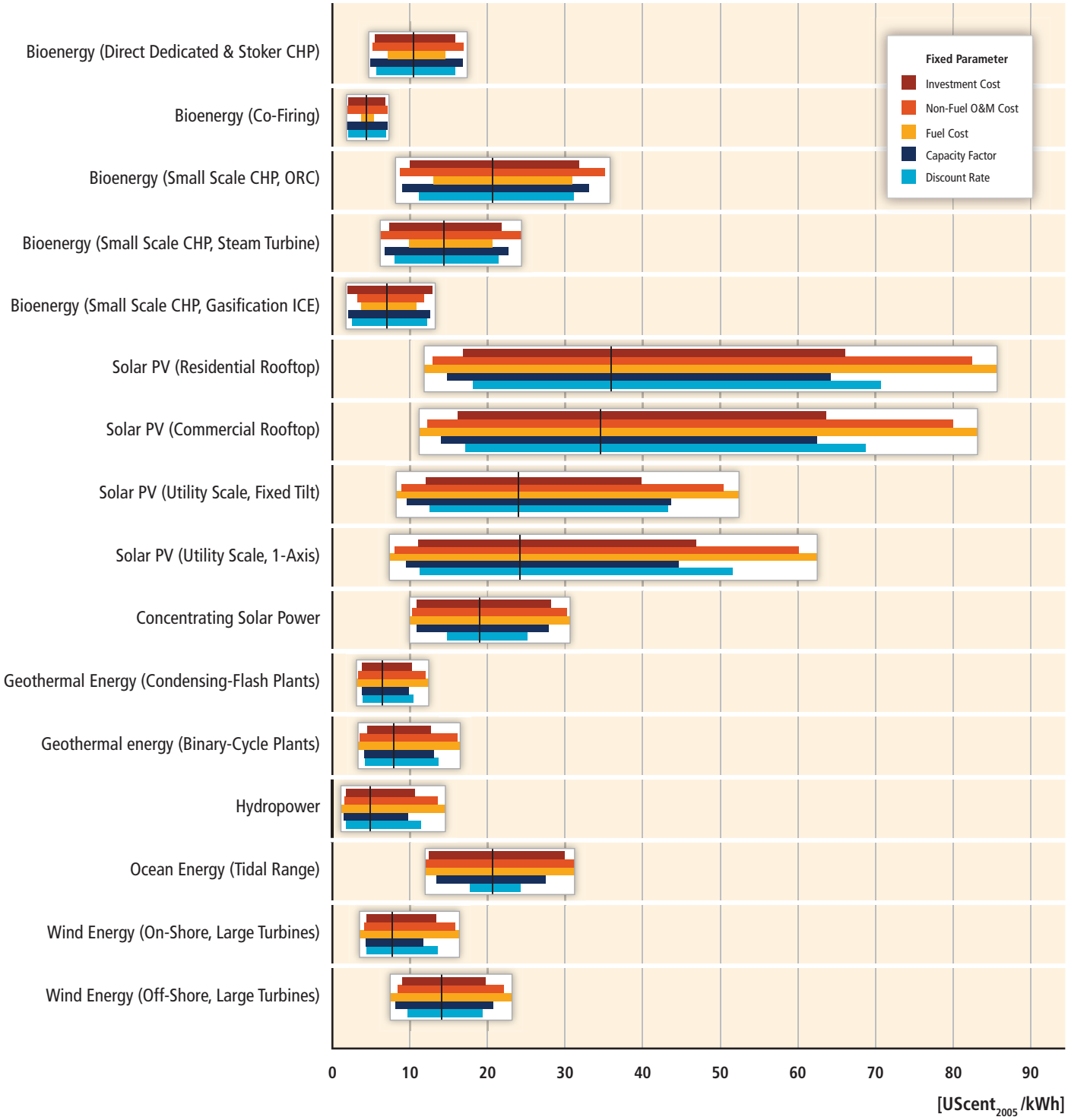

Figure A.III.2b | 'Negative' of tornado graph for renewable power technologies. For further explanation see Figure A.III.1b.

Note: The upper bounds of both geothermal energy technologies are calculated based on an assumed construction time of 4 years. In the simplified approach used for the sensitivity analysis shown here, this assumption was not taken into account, resulting in upper bounds that were below those based on the more accurate methodology. The ranges were rescaled, however, to yield the same results as the more accurate approach.

Table A.III.2 | Cost-performance parameters for RE heating technologies.[i]

		Input data									Output data		
Resource	Technology	Typical size of the device (MW_{th})	Investment cost (USD/kW_{th})	O&M cost, fixed annual (USD/kW) and/or variable (USD/GJ)	By-product revenue (USD/GJ_{feed})[ii]	Feedstock cost (USD/GJ_{feed})	(Feedstock) conversion efficiency (%)	Capacity factor (%)	Economic design lifetime (years)	References	LCOH[iii] (USD/GJ)		
											Discount rate		
											3%	7%	10%
Bioenergy	Biomass (DPH[iv])	0.005–0.1[v]	310–1,200[vi]	13–43 USD/kW[vii]	N/A[viii]	10–20	86–95	13–29	10–20	IEA (2007b)	14–70	15–77	16–84
	Biomass (MSW[ix], CHP[x])	1–10[xi]	370–3,000[xii, xiii]	15–130 USD/kW[vii]	N/A[viii]	0–3	20–40[xiv]	80–91	10–20		1.4–34	1.8–38	2.1–41
	Biomass (Steam Turbine, CHP)[xv]	12–14	370–1,000[xii]	1.2–2.5 USD/kW[vii]	N/A[viii]	3.7–6.2	10–40	63–74	10–20		10–69	11–70	11–72
	Biomass (Anaerobic Digestion, CHP)	0.5–5[xi]	170–1,000[xii,xvi]	37–140 USD/kW[vii]	N/A[viii]	2.5–3.7[xvii]	20–30[xviii]	68–91	15–25		10–29	10–30	10–32
Solar Energy	Solar Thermal Heating (DHW[xix], China)	0.0017–0.01[xx]	120–540[xxi]	1.5–10 USD/kW[xxii]	N/A[viii]	N/A[viii]	20–80[xxiii]	4.1–13[xxiv]	10–15[xxv]	see Section 3.8.2 and footnotes	2.8–56	3.6–67	4.2–75
	Solar Thermal Heating (DHW, Thermo-siphon, Combi-systems)	0.0017–0.07[xx]	530–1,800	5.6–22 USD/kW[xxii]	N/A[viii]	N/A[viii]	20–80[xxiii]	4.1–13[xxiv]	15–25	IEA (2007b)	8.8–134	12–170	16–200
Geothermal Energy	Geothermal (Building Heating)	0.1–1	1,600–3,900[xxvi]	8.3–11 USD/GJ[xxvii]	N/A[viii]	N/A[viii]	N/A[viii]	25–30	20	see Section 4.7.6	20–50	24–65	28–77
	Geothermal (District Heating)	3.8–35	600–1,600[xxvi]	8.3–11 USD/GJ[xxvii]	N/A[viii]	N/A[viii]	N/A[viii]	25–30	25		12–24	14–31	15–38
	Geothermal (Greenhouses)	2–5.5	500–1,000[xxvi]	5.6–8.3 USD/GJ[xxvii]	N/A[viii]	N/A[viii]	N/A[viii]	50	20		7.7–13	8.6–14	9.3–16
	Geothermal (Aquaculture Ponds, Uncovered)	5–14	50–100[xxvi]	8.3–11 USD/GJ[xxvii]	N/A[viii]	N/A[viii]	N/A[viii]	60	20		8.5–11	8.6–12	8.6–12
	Geothermal Heat Pumps (GHP)	0.01–0.35	900–3,800[xxvi]	7.8–8.9 USD/GJ[xxvii]	N/A[viii]	N/A[viii]	N/A[viii]	25–30	20		14–42	17–56	19–68

General remarks/notes:

i All data are rounded to 2 significant digits. Most technology chapters (Chapters 2 through 4) provide additional and/or more detailed cost and performance information in the respective chapters' sections on cost trends. The assumptions underlying some of the production cost estimates quoted directly from the literature may, however, not be as transparent as the data sets in this Annex and should therefore be considered with caution.

ii CHP plants produce both, heat and electricity. Calculating the levelized cost of one product only, that is, either heat or electricity, can be done in different ways. One way is to assign a (discounted) market value to the 'by-product' and subtract this additional income from the remaining expenses. This has been done in the calculation of the LCOE of bioenergy CHP plants. The calculation of LCOH has been done in a different way according to the methodology used in IEA (2007) which served as main reference for the input data: Instead of considering electricity as a 'by-product' and subtracting its value from the remaining expenses for the supply of heat, the total expenses over the lifetime of the investment project were split according to the average heat/electricity output ratio and only the heat shares of investment and O&M costs were taken into account. For this reason no by-product revenue is stated in the heat table. Both methodologies come with different advantages/disadvantages.

iii LCOH: Levelized cost of heat supply. The levelized cost does not include the cost of transmission and distribution in the case of district heating systems. Output subsidies for RE generation and tax credits are also excluded. However, indirect taxes and subsidies on inputs or commodities affecting the prices of inputs and, hence, private cost, cannot be fully excluded.

Continued next page →

Bioenergy:

iv DPH: Domestic pellet heating.

v This range is typical of a low-energy single family dwelling (5 kW) or an apartment building (100 kW).

vi Investment costs of a biomass pellet heating system for the combustion plant only (including controls) range from USD_{2005} 100 to 640/kW. The higher range stated above includes civil works and fuel and heat storage (IEA, 2007).

vii Fixed annual O&M costs include costs of auxiliary energy. Auxiliary energy needs are 10 to 20 kWh/kW_{th}/yr. Electricity prices are assumed to be USD_{2005} 0.1 to 0.3/kWh. O&M costs for CHP options include heat share only.

viii The abbreviation 'N/A' means here 'not applicable'.

ix MSW: Municipal solid waste.

x CHP: Combined heat and power.

xi Typical size based on expert judgment and cost data from IEA (2007).

xii Investment costs for CHP options include heat share only. The electricity data in Table A.III.1 provides examples of total investment cost (see Section 2.4.4).

xiii Investment costs of MSW installations are mainly determined by the cost of flue gas cleaning, which can be allocated to waste treatment rather than to heat production (IEA, 2007).

xiv Heat-only MSW incinerators (as used in Denmark and Sweden) could have a thermal efficiency of 70 to 80%, but are not considered (IEA, 2007).

xv The ranges provided in this category are mainly based on two plants in Denmark and Austria and have been taken from IEA (2007).

xvi Investment costs for anaerobic digestion are based on literature values provided relative to electric capacity. For conversion to thermal capacity an electric efficiency of 37% and a thermal efficiency of 55% were used (IEA, 2007).

xvii For anaerobic digestion, fuel prices are based on a mix of green crop maize and manure feedstock. Other biogas feedstocks include source-separated wastes and landfill gas, but are not considered here (IEA, 2007).

xviii Conversion efficiencies include auxiliary heat input (8 to 20% for process heat) as well as use of any co-substrate that might increase process efficiency. For source-separated wastes, the efficiency would be lower (IEA, 2007).

Solar Energy:

xix DHW: Domestic hot water.

xx 1 m^2 of collector area is converted into 0.7 kW_{th} of installed capacity (see Section 3.4.1).

xxi 70% of the 13.5 million m^2 sales volume in 2004 was sold below Yuan 1,500/m^2 (USD_{2005} ~190/kW) (Zhang et al., 2010). The lower bound is based on data collected during standardized interviews in the Zhejiang Province, China, in 2008 (Han et al., 2010). The higher bound is based on Chang et al. (2011).

xxii Fixed annual operating cost is assumed to be 1 to 3% of investment cost (IEA, 2007) plus annual cost of auxiliary energy. Annual auxiliary energy needs are 2 to 10 kWh/m^2. Electricity prices are assumed to be USD_{2005} 0.1 to 0.3/kWh.

xxiii The conversion efficiency of a solar thermal system tends to be larger in regions with lower solar irradiance. This partly offsets the negative effect of lower solar irradiance on cost as energy yields per m^2 of collector area will be similar (Harvey, 2006, p. 461). Conversion efficiencies, which affect the resulting capacity factor, have not been used in LCOH calculations directly.

xxiv Capacity factors are based on an assumed annual energy yield of 250 to 800 kWh/m^2 (IEA, 2007).

xxv Expected design lifetimes for Chinese solar water heaters are in the range of 10 to 15 years (Han et al., 2010).

Geothermal energy:

xxvi For geothermal heat pumps (GHP) the bounds of investment costs include residential and commercial or institutional installations. For commercial and institutional installations, costs are assumed to include drilling costs, but for residential installations drilling costs are not included.

xxvii Average O&M costs expressed in USD_{2005}/kWh_{th} are: 0.03 to 0.04 for building and district heating and for aquaculture uncovered ponds, 0.02 to 0.03 for greenhouses, and 0.028 to 0.032 for GHP.

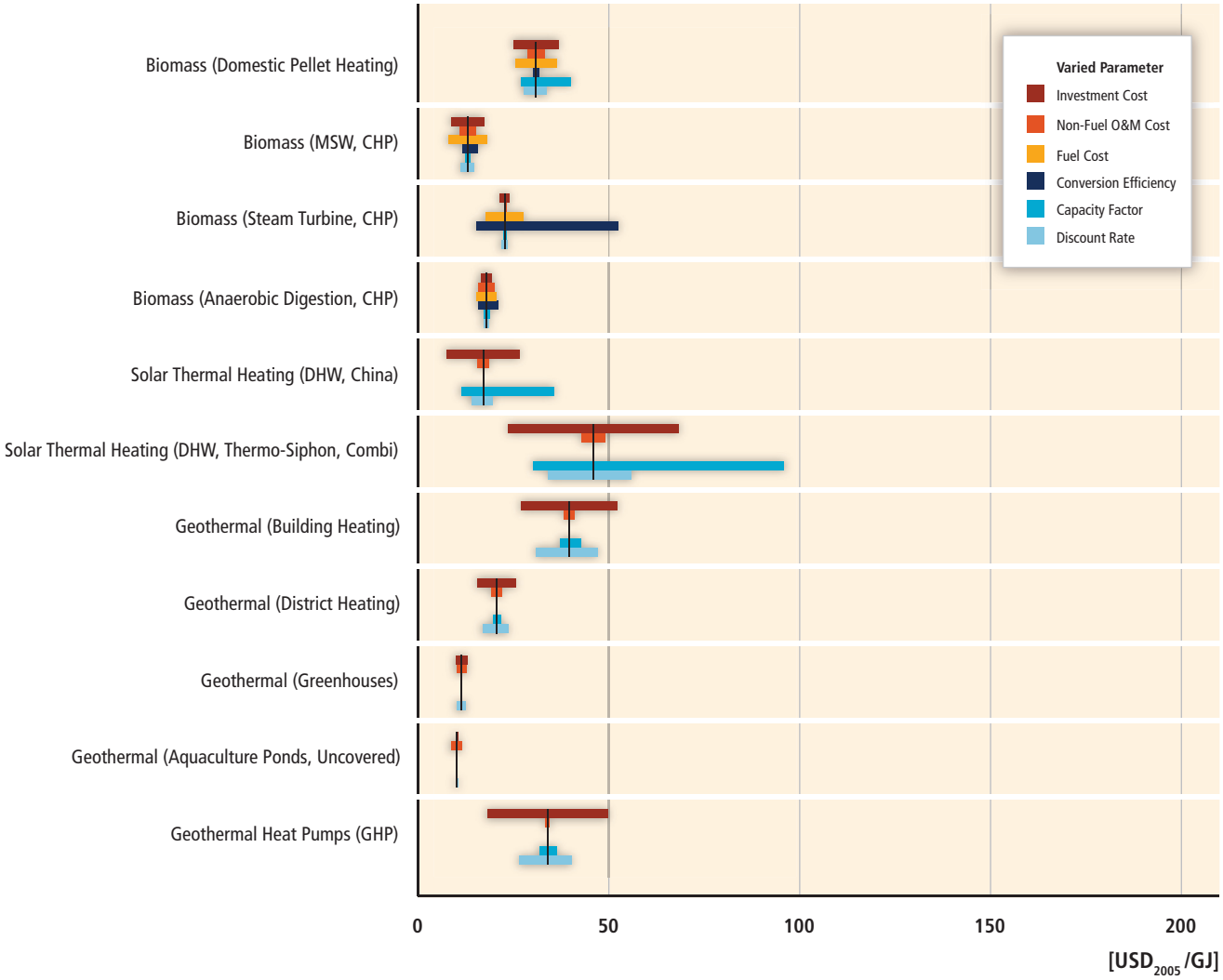

Figure A.III.3a | Tornado graph for renewable heat technologies. For further explanation see Figure A.III.1a.

Note: It may be somewhat misleading that solar thermal and geothermal heat applications do not show any sensitivity to variations in conversion efficiencies. This is due to the fact that the energy input for solar and geothermal has zero cost and that the effect of higher conversion efficiencies of the energy input on LCOH works solely via an increase in annual output. Variations in annual output, in turn, are fully captured by varying the capacity factor.

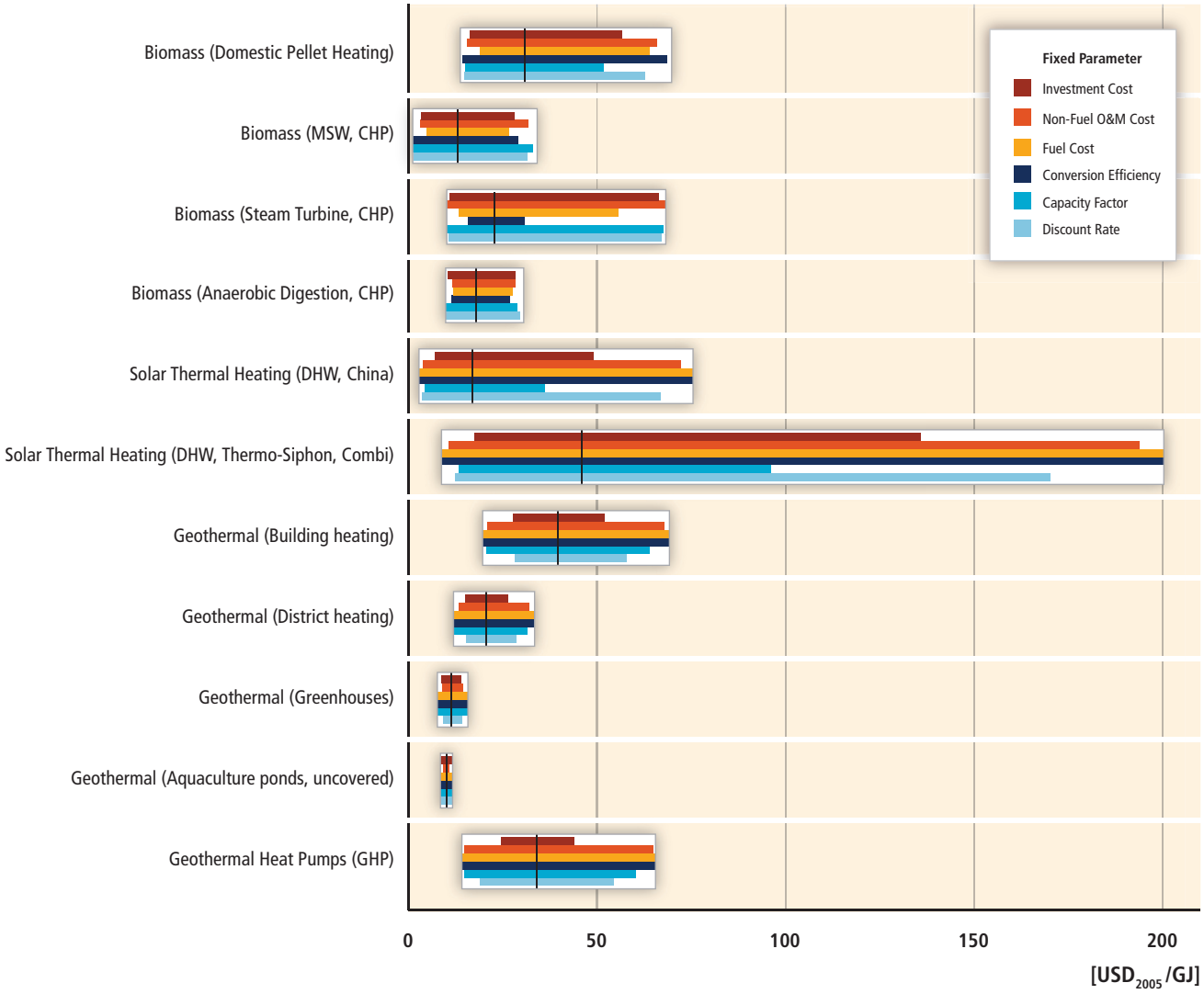

Figure A.III.3b | 'Negative' of tornado graph for renewable heat technologies. For further explanation see Figure A.III.1b.

Table A.III.3 | Cost-performance parameters for biofuels.[i]

		Input data									Output data		
Feedstock	Fuel, Region	Typical size of the device (MW_{th})	Investment cost (USD/kW_{th})[ii]	O&M cost, fixed annual (USD/kW_{th}) and non-feed variable (USD/GJ_{feed})	By-product Revenue (USD/GJ_{feed})	Feedstock cost (USD/GJ_{feed})	Feedstock conversion efficiency[iii] (%) Product only (product + by-product)	Capacity factor (%)	Economic design lifetime (years)	References	LCOF [iv] USD/GJ_{HHV} [v] Discount rate		
											3%	7%	10%
Sugarcane	Ethanol				Co-product: sugar[vi]								
	Overall	*170–1,000*	*83–360*	*16–35 USD/kW_{th} and 0.87 USD/GJ_{feed}*	*4.3*	*2.1–7.1*	*17 (39)*	*50%*	*20*	*Alfstad (2008), Bain (2007), Kline et al. (2007)*	*2.4–39*	*3.5–42*	*4.5–46*
	Brazil, Case A[vii]	See above	100–330	20–32 USD/kW_{th} and 0.87 USD/GJ_{feed}	See above	2.1–6.5[viii]	See above	See above	See above	Bohlmann and Cesar (2006), Oliverio (2006), van den Wall Bake et al. (2009)	2.4–38	3.5–41	4.5–44
	Argentina	See above	110–340	21–34 USD/kW_{th} and 0.87 USD/GJ_{feed}	See above	6.5[ix]	See above	See above	See above	Oliverio and Riberio (2006), see also row 'Overall' above	28–39	30–42	31–46
	Caribbean Basin[x, xi]	See above	110–360	22–35 USD/kW_{th} and 0.87 USD/GJ_{feed}	See above	2.6–6.2	See above	See above	See above	Rosillo-Calle et al. (2000) see also row 'Overall' above	6.4–38	7.7–42	8.8–46
	Colombia	See above	100–320	20–31 USD/kW_{th} and 0.87 USD/GJ_{feed}	See above	5.6	See above	See above	See above	McDonald and Schrattenholzer (2001), Goldemberg (1996), see also row 'Overall' above	23–32	24–36	25–39
	India	See above	110–340	21–33 USD/kW_{th} and 0.87 USD/GJ_{feed}	See above	2.6–6.2	See above	See above	See above	see row 'Overall' above	5.9–37	7.1–41	8.2–44
	Mexico	See above	83–260	16–25 USD/kW_{th} and 0.87 USD/GJ_{feed}	See above	5.2–7.1	See above	See above	See above	see row 'Overall' above	19–37	19–40	20–42
	USA	See above	100–320	20–31 USD/kW_{th} and 0.87 USD/GJ_{feed}	See above	6.2	See above	See above	See above	see row 'Overall' above	27–36	28–40	29–43

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		Input data									Output data		
Feedstock	Fuel, Region	Typical size of the device (MW_{th})	Investment cost (USD/kW_{th})[ii]	O&M cost, fixed annual (USD/kW_{th}) and non-feed variable (USD/GJ_{feed})	By-product Revenue (USD/GJ_{feed})	Feedstock cost (USD/GJ_{feed})	Feedstock conversion efficiency[iii] (%) Product only (product + by-product)	Capacity factor (%)	Economic design lifetime (years)	References	LCOF [iv] USD/GJ_{HHV} [v] Discount rate		
											3%	7%	10%
Corn	Ethanol				By-product: DDGS[xii]								
	Overall	*N/A*	*160–310*	*9–27 USD/kW_{th} and 1.98 USD/GJ_{feed}*	*1.56*	*4.2–10[xiii]*	*54 (91)*	*95%*	*20*	*Alfstad (2008), Bain (2007), Kline et al. (2007)*	*9.3–22*	*9.5–22*	*10–23*
	USA	140–550[xiv]	160–240	9–18 USD/kW_{th} and 1.98 USD/GJ_{feed}	See above	4.2–10[xv]	See above	See above	See above	Delta-T Corporation (1997), Ibsen et al. (2005), Jechura (2005), see also row 'Overall' above	9.3–22	9.5–22	10–23
	Argentina	See above	170–260	9–17 USD/kW_{th} and 1.98 USD/GJ_{feed}	See above	7.5	See above	See above	See above	McAloon et al. (2000). RFA (2011), University of Illinois (2011), see also row 'Overall' above	16–17	16–17	17–18
	Canada	See above	200–310	13–27 USD/kW_{th} and 1.98 USD/GJ_{feed}	See above	4.8–5.7	See above	See above	See above	see row 'Overall' above	11–15	12–15	12–16
Wheat	Ethanol				By-product: DDGS[xii]								
	Overall	*150–610*	*140–280[xvi]*	*8–25 USD/kW_{th} and 1.41 USD/GJ_{feed}*	*1.74*	*5.1–13*	*49 (91)*	*95%*	*20*	*Alfstad (2008), Bain (2007), Kline et al. (2007)*	*12–28*	*12–28*	*12-28*
	USA	See above	140–220	8–17 USD/kW_{th} and 1.41 USD/GJ_{feed}	See above	6.3–13	See above	See above	See above	OECD (2002), Shapouri and Salassi (2006), USDA (2007), see also 'Overall'	13–28	14–28	14–28
	Argentina	See above	150–230	8–16 USD/kW_{th} and 1.41 USD/GJ_{feed}	See above	6.5–7	See above	See above	See above	see row 'Overall' above	14–16	14–16	14–17
	Canada	See above	190–280	12–25 USD/kW_{th} and 1.41 USD/GJ_{feed}	See above	5.1–6.9	See above	See above	See above	see row 'Overall' above	12–16	12–17	12–17

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		Input data									Output data		
Feedstock	Fuel, Region	Typical size of the device (MW_{th})	Investment cost (USD/kW_{th})[ii]	O&M cost, fixed annual (USD/kW_{th}) and non-feed variable (USD/GJ_{feed})	By-product Revenue (USD/GJ_{feed})	Feedstock cost (USD/GJ_{feed})	Feedstock conversion efficiency[iii] (%) Product only (product + by-product)	Capacity factor (%)	Economic design lifetime (years)	References	LCOF[iv] USD/GJ_{HHV}[v] Discount rate		
											3%	7%	10%
Soy Oil	Biodiesel[xvii]				By-product: Glycerin[xviii]								
	Overall	*44–440*	*160–320*	*9–46 USD/kW_{th} and 2.58 USD/GJ_{feed}*	*0.58*	*7.0–24*	*103 (107)19*	*95%*	*20*	*Alfstad (2008), Bain (2007), Kline et al. (2007), Haas et al. (2006), Sheehan et al. (2006)*	*9.4–28*	*10–28*	*10–28*
	Argentina	See above	170–320	12–42 USD/kW_{th} and 2.58 USD/GJ_{feed}	See above	14–16[xx]	See above	See above	See above	Chicago Board of Trade (2006), see also row 'Overall' above	16–19	16–19	17–20
	Brazil	See above	160–310	9–27 USD/kW_{th} and 2.58 USD/GJ_{feed}	See above	7.0–18[xx]	See above	See above	See above	Chicago Board of Trade (2006), see also row 'Overall' above	9.4–21	10–21	10–21
	USA	See above	160–300	12–46 USD/kW_{th} and 2.58 USD/GJ_{feed}	See above	9.7–24	See above	See above	See above	USDA (2006), see also row 'Overall' above	12–28	12–28	12–28
Palm Oil	Biodiesel				By-product: Glycerin[xviii]								
	Overall	*44–440*	*160–340*	*10–46 USD/kWth and 2.58 USD/GJfeed*	*0.58*	*6.1–45*	*103 (107)*	*95%*	*20*	*Alfstad (2008), Bain (2007), Kline et al. (2007), Haas et al. (2006), Sheehan et al. (1998)*	*8.7–48*	*8.9–48*	*9.0–49*
	Colombia	See above	160–300	10–34 USD/kW_{th} and 2.58 USD/GJ_{feed}	See above	6.1–45	See above	See above	See above	see row 'Overall' above	8.7–48	8.8–48	9.0–49
	Caribbean Basin[x]	See above	180- 340	13–46 USD/kW_{th} and 2.58 USD/GJ_{feed}	See above	11–45	See above	See above	See above	see row 'Overall' above	14–48	14–48	14–48
Wood, Bagasse, other	Pyrolytic Fuel Oil				By-product: Electricity[xxi]								
	Overall	*110–440*	*160–240*	*12–44 USD/kWth and 0.42 USD/GJfeed*	*0.07*	*0.44–5.5[xxii]*	*67 (69)*	*95%*	*20*	*Ringer et al. (2006)*	*2.3–12*	*2.6–12*	*2.8–12*
	USA	See above	160–230	19–44 USD/kW_{th} and 0.42 USD/GJ_{feed}	See above	1.4–5.5	See above	See above	See above	see row 'Overall' above	4.0–12	4.3–12	4.5–12
	Brazil	See above	160–240	12–24 USD/kW_{th} and 0.42 USD/GJ_{feed}	See above	0.44–5.5	See above	See above	See above	see row 'Overall' above	2.3–11	2.5–11	2.8–11

Continued next page →

General remarks/notes:

i All data are rounded to two significant digits. Chapter 2 provides additional cost and performance information in the section on cost trends. The assumptions underlying some of the production cost estimates quoted directly from the literature may, however, not be as transparent as the data sets in this Annex and should therefore be considered with caution.

ii Investment cost is based on plant capacity factor and not at 100% stream factor, which is the normal convention.

iii The feedstock conversion efficiency measured in energy units of input relative to energy units of output is stated for biomass only. Conversion factors for a mixture of biomass and fossil inputs are generally lower.

iv LCOF: Levelized Cost of Transport Fuels. The levelized costs of transport fuels include all private costs that accrue upstream in the bioenergy system, but do not include the cost of transportation and distribution to the final customers. Output subsidies for RE generation and tax credits are also excluded. However, indirect taxes and subsidies on inputs or commodities affecting the prices of inputs and, hence, private cost, cannot be fully excluded.

v HHV: Higher heating value. LHV: Lower heating value.

vi Price of / revenue from sugar assumed to be USD_{2005} 22/GJ_{sugar} based on average 2005 to 2008 world refined sugar price.

vii A cane sucrose content of 14% is used in the calculations of case A with the additional assumption that 50% of the total sucrose is used for sugar production (97% extraction efficiency) and the other 50% of the total sucrose is used for ethanol production (90% conversion efficiency). The bagasse content of cane used is 16%. The HHVs used are bagasse: 18.6 GJ/t; sucrose: 17.0 GJ/t; and as received cane: 5.3 GJ/t.

viii Brazilian feedstock costs have declined by 60% in the time period of 1975 to 2005 (Hettinga et al, 2009). For a more detailed discussion of historical and future cost trends see also Sections 2.7.2, 2.7.3 and 2.7.4.

ix 55.2% of feed used is bagasse. More detailed information on feedstock characteristics can, for instance, be found in Section 2.3.1.

x Caribbean Basin Initiative Countries: Guatemala, Honduras, Nicaragua, Dominican Republic, Costa Rica, El Salvador, Guyana, and others.

xi Mixed ethanol/sugar mill: 50/50. More detailed information on sugar mills can be found in Section 2.3.4.

xii DDGS: Distillers dried grains plus solubles.

xiii For international feed range, supply curves from Kline et al. (2007) were used. For more information on feedstock supply curves and other economic considerations in biomass resource assessments see Chapter section 2.2.3.

xiv Plant size range (140-550 MW is the equivalent of 25-100 million gallons per year (mmgpy) of anhydrous ethanol) is representative of the US corn ethanol industry (RFA, 2011).

xv Corn prices in the USA have declined by 63% in the period from 1975 to 2005 (Hettinga et al., 2009). For a more detailed discussion of historical and future cost trends see also Sections 2.7.2, 2.7.3 and 2.7.4.

xvi Based on corn mill costs, corrected for HHV, and distillers dried grain (DDG) yields for wheat. More detailed information on milling can be found in Section 2.3.4.

xvii Installation basis is soy oil, not soybeans. Crush spread is used to convert from soybean prices to soy oil price. HHV soy oil = 39.6 GJ/t.

xviii Glycerine is also referred to as glycerol and is a simple polyol compound (1,2,3-propanetriol), and is central to all lipids known as triglycerides. Glycerine is a by-product of biodiesel production.

xix The yield is higher than 100% because methanol (or other alcohol) is incorporated into the product.

xx Soy oil prices are estimated from soybean prices (Kline et al., 2007) and crush spread (Chicago Board of Trade, 2006).

xxi Process-derived gas and residual solids (char) are used for process heat and power. Excess electricity is exported as a by-product.

xxii Feedstock cost range is based on bagasse residue and wood residue prices (Kline et al. 2007). High range is for wood-based pyrolysis, low range is typical of pyrolysis of bagasse. For more information on pyrolysis see Section 2.3.3.2. For a discussion of historical and future cost trends see also Sections 2.7.2, 2.7.3 and 2.7.4.

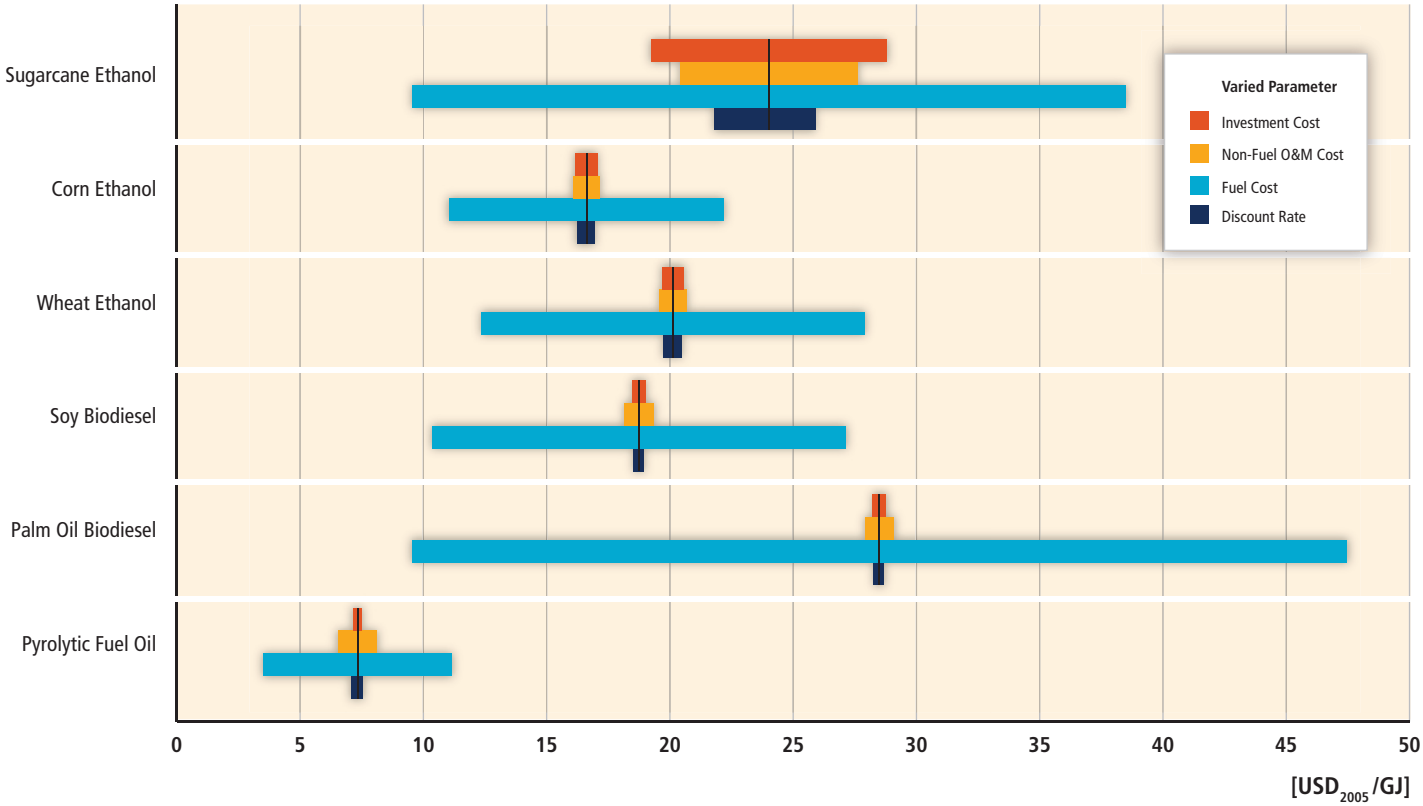

Figure A.III.4a | Tornado graph for biofuels. For further explanation see Figure A.III.1a.

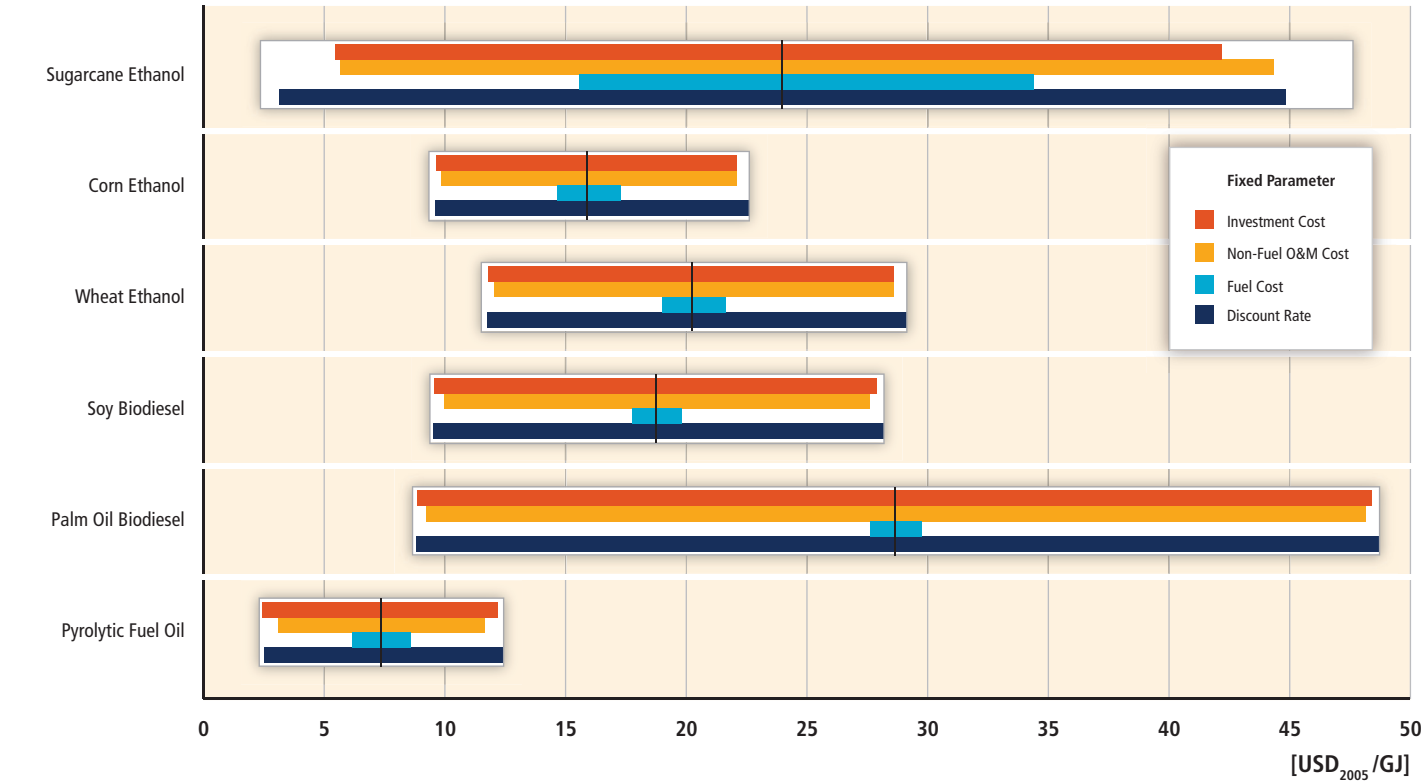

Figure A.III.4b | 'Negative' of tornado graph for biofuels. For further explanation see Figure A.III.1b.

Note: Aggregation of input data over various regions and subsequent LCOF calculations leads to slightly larger LCOF ranges than those obtained if region-specific LCOF values are calculated first and these regional LCOF values are subsequently aggregated. In order to allow for a broad sensitivity analysis the first approach was followed here. The broader ranges were, however, rescaled to yield the same results as the latter approach, which is more accurate and is used in the remainder of the report.

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The references in this list have been used in the assessment of the cost and performance data of the individual technologies summarized in the tables. Only some of them are quoted in the text of this Annex to support specific information included in the explanatory text. All references are sorted by energy type/carrier and by technology.

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"The Mitigation of Climate Change is one of the major challenges of the 21st century. The transition of our global energy system to one that supports a high share of renewable energy could be an integral part of humankind's answer to this challenge. This report provides important groundwork for such a transition."

– Hartmut Graßl, Former Director of the World Climate Research Programme, Max Planck Institute for Meteorology

"This report is a comprehensive and authoritative contribution to the debate about whether renewable energy can solve the climate problem in an economically attractive fashion. It's a blueprint for further development of the renewables sector and sets out clearly its role in climate change mitigation."

– Geoffrey Heal, Columbia Business School, Columbia University

"Renewable energy resources and the technologies to expand their use provide the key energy source to address multiple challenges of national and global sustainability for all. This report is invaluable for the 21st century."

– Thomas B. Johansson, Lund University, Sweden, and Global Energy Assessment, IIASA

"The IPCC has provided us with a well-researched, carefully-presented assessment of the costs, risks and opportunities of renewable energy sources. It provides a systematic analysis and scientific assessment of the current knowledge about one of the most promising options to cut emissions of greenhouse gases and to mitigate climate change."

– Lord Nicholas Stern, IG Patel Professor of Economics & Government, London School of Economics and Political Science

"Renewable energy can drive global sustainable development. The Special Report comes at the right time and offers insights and guidance to strongly facilitate the change of our industrial metabolism."

– Klaus Töpfer, IASS Potsdam – Institute for Advanced Sustainability Studies

"There may be a number of ways to achieve a low-carbon economy, but no pathway has been as thoroughly and comprehensively explored as the range of possible contributions of renewable energy sources towards achieving that goal contained in this IPCC Special Report."

– John P. Weyant, Stanford University

Climate change is one of the great challenges of the 21st century. Its most severe impacts may still be avoided if efforts are made to transform current energy systems. Renewable energy sources have a large potential to displace emissions of greenhouse gases from the combustion of fossil fuels and thereby to mitigate climate change. If implemented properly, renewable energy sources can contribute to social and economic development, to energy access, to a secure and sustainable energy supply, and to a reduction of negative impacts of energy provision on the environment and human health.

This Special Report on *Renewable Energy Sources and Climate Change Mitigation* (SRREN) impartially assesses the scientific literature on the potential role of renewable energy in the mitigation of climate change for policy makers, the private sector, academic researchers and civil society. It covers six renewable energy sources – bioenergy, direct solar energy, geothermal energy, hydropower, ocean energy and wind energy – as well as their integration into present and future energy systems. It considers the environmental and social consequences associated with the deployment of these technologies, and presents strategies to overcome technical as well as non-technical obstacles to their application and diffusion. The authors also compare the levelized cost of energy from renewable energy sources to recent non-renewable energy costs.

The Intergovernmental Panel on Climate Change (IPCC) is the leading international body for the assessment of climate change. It was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socioeconomic impacts.

The full Special Report is published by Cambridge University Press (www.cambridge.org) and the digital version can be accessed via the website of the IPCC Secretariat (www.ipcc.ch) or obtained on CDRom from the IPCC Secretariat. This brochure contains the Summary for Policymakers and the Technical Summary of the report.

RENEWABLE ENERGY SOURCES AND CLIMATE CHANGE MITIGATION

MANAGING THE RISKS OF EXTREME EVENTS AND DISASTERS TO ADVANCE CLIMATE CHANGE ADAPTATION

SUMMARY FOR POLICYMAKERS

SPECIAL REPORT OF THE
INTERGOVERNMENTAL PANEL
ON CLIMATE CHANGE

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SPM

Summary for Policymakers

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A. Context

This Summary for Policymakers presents key findings from the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX). The SREX approaches the topic by assessing the scientific literature on issues that range from the relationship between climate change and extreme weather and climate events ('climate extremes') to the implications of these events for society and sustainable development. The assessment concerns the interaction of climatic, environmental, and human factors that can lead to impacts and disasters, options for managing the risks posed by impacts and disasters, and the important role that non-climatic factors play in determining impacts. Box SPM.1 defines concepts central to the SREX.

The character and severity of impacts from climate extremes depend not only on the extremes themselves but also on exposure and vulnerability. In this report, adverse impacts are considered disasters when they produce widespread damage and cause severe alterations in the normal functioning of communities or societies. Climate extremes, exposure, and vulnerability are influenced by a wide range of factors, including anthropogenic climate change, natural climate variability, and socioeconomic development (Figure SPM.1). Disaster risk management and adaptation to climate change focus on reducing exposure and vulnerability and increasing resilience to the potential adverse impacts of climate extremes, even though risks cannot fully be eliminated (Figure SPM.2). Although mitigation of climate change is not the focus of this report, adaptation and mitigation can complement each other and together can significantly reduce the risks of climate change. [SYR AR4, 5.3]

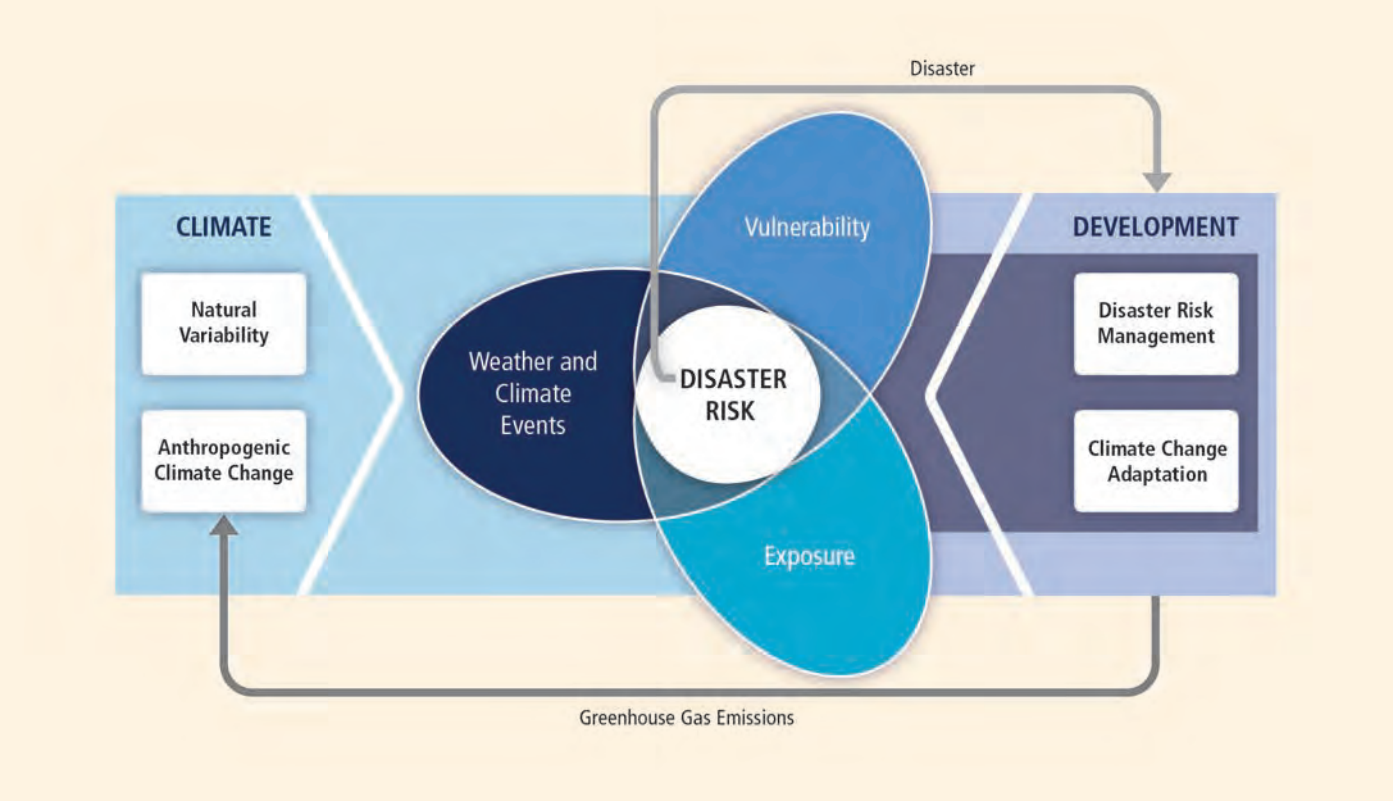

Figure SPM.1 | Illustration of the core concepts of SREX. The report assesses how exposure and vulnerability to weather and climate events determine impacts and the likelihood of disasters (disaster risk). It evaluates the influence of natural climate variability and anthropogenic climate change on climate extremes and other weather and climate events that can contribute to disasters, as well as the exposure and vulnerability of human society and natural ecosystems. It also considers the role of development in trends in exposure and vulnerability, implications for disaster risk, and interactions between disasters and development. The report examines how disaster risk management and adaptation to climate change can reduce exposure and vulnerability to weather and climate events and thus reduce disaster risk, as well as increase resilience to the risks that cannot be eliminated. Other important processes are largely outside the scope of this report, including the influence of development on greenhouse gas emissions and anthropogenic climate change, and the potential for mitigation of anthropogenic climate change. [1.1.2, Figure 1-1]

Box SPM.1 | Definitions Central to SREX

Core concepts defined in the SREX glossary[1] and used throughout the report include:

Climate Change: A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use.[2]

Climate Extreme (extreme weather or climate event): The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. For simplicity, both extreme weather events and extreme climate events are referred to collectively as 'climate extremes.' The full definition is provided in Section 3.1.2.

Exposure: The presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected.

Vulnerability: The propensity or predisposition to be adversely affected.

Disaster: Severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery.

Disaster Risk: The likelihood over a specified time period of severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery.

Disaster Risk Management: Processes for designing, implementing, and evaluating strategies, policies, and measures to improve the understanding of disaster risk, foster disaster risk reduction and transfer, and promote continuous improvement in disaster preparedness, response, and recovery practices, with the explicit purpose of increasing human security, well-being, quality of life, resilience, and sustainable development.

Adaptation: In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate.

Resilience: The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions.

Transformation: The altering of fundamental attributes of a system (including value systems; regulatory, legislative, or bureaucratic regimes; financial institutions; and technological or biological systems).

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[1] Reflecting the diversity of the communities involved in this assessment and progress in science, several of the definitions used in this Special Report differ in breadth or focus from those used in the Fourth Assessment Report and other IPCC reports.

[2] This definition differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), where climate change is defined as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes.

Figure SPM.2 | Adaptation and disaster risk management approaches for reducing and managing disaster risk in a changing climate. This report assesses a wide range of complementary adaptation and disaster risk management approaches that can reduce the risks of climate extremes and disasters and increase resilience to remaining risks as they change over time. These approaches can be overlapping and can be pursued simultaneously. [6.5, Figure 6-3, 8.6]

This report integrates perspectives from several historically distinct research communities studying climate science, climate impacts, adaptation to climate change, and disaster risk management. Each community brings different viewpoints, vocabularies, approaches, and goals, and all provide important insights into the status of the knowledge base and its gaps. Many of the key assessment findings come from the interfaces among these communities. These interfaces are also illustrated in Table SPM.1. To accurately convey the degree of certainty in key findings, the report relies on the consistent use of calibrated uncertainty language, introduced in Box SPM.2. The basis for substantive paragraphs in this Summary for Policymakers can be found in the chapter sections specified in square brackets.

Exposure and vulnerability are key determinants of disaster risk and of impacts when risk is realized. [1.1.2, 1.2.3, 1.3, 2.2.1, 2.3, 2.5] For example, a tropical cyclone can have very different impacts depending on where and when it makes landfall. [2.5.1, 3.1, 4.4.6] Similarly, a heat wave can have very different impacts on different populations depending on their vulnerability. [Box 4-4, 9.2.1] Extreme impacts on human, ecological, or physical systems can result from individual extreme weather or climate events. Extreme impacts can also result from non-extreme events where exposure and vulnerability are high [2.2.1, 2.3, 2.5] or from a compounding of events or their impacts. [1.1.2, 1.2.3, 3.1.3] For example, drought, coupled with extreme heat and low humidity, can increase the risk of wildfire. [Box 4-1, 9.2.2]

Extreme and non-extreme weather or climate events affect vulnerability to future extreme events by modifying resilience, coping capacity, and adaptive capacity. [2.4.3] In particular, the cumulative effects of disasters at local

or sub-national levels can substantially affect livelihood options and resources and the capacity of societies and communities to prepare for and respond to future disasters. [2.2, 2.7]

A changing climate leads to changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events, and can result in unprecedented extreme weather and climate events. Changes in extremes can be linked to changes in the mean, variance, or shape of probability distributions, or all of these (Figure SPM.3). Some climate extremes (e.g., droughts) may be the result of an accumulation of weather or climate events that are not extreme when considered independently. Many extreme weather and climate events continue to be the result of natural climate variability. Natural variability will be an important factor in shaping future extremes in addition to the effect of anthropogenic changes in climate. [3.1]

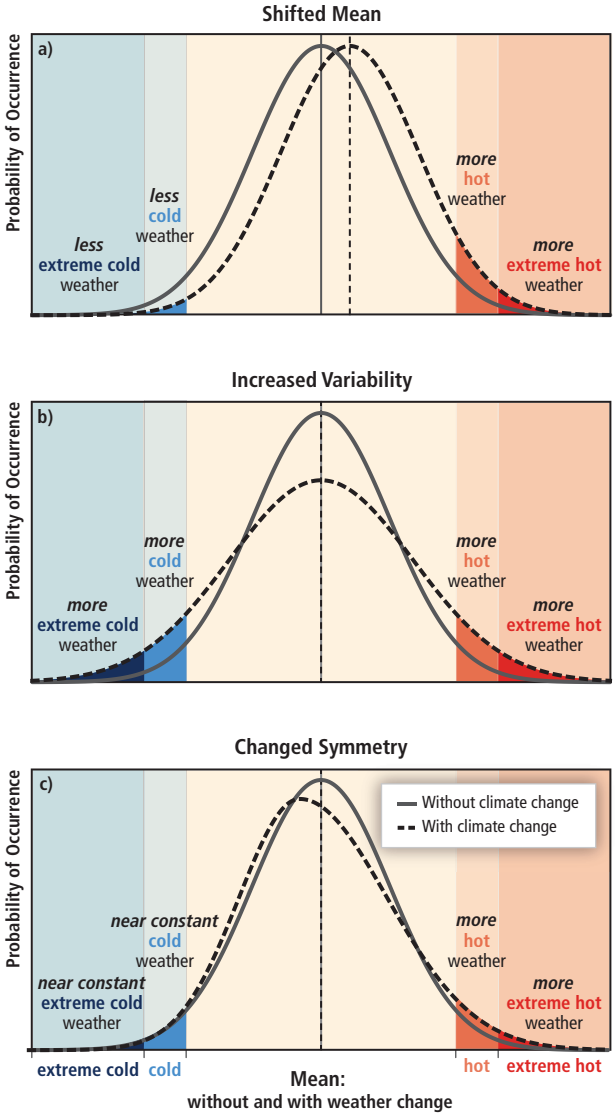


Figure SPM.3 | The effect of changes in temperature distribution on extremes. Different changes in temperature distributions between present and future climate and their effects on extreme values of the distributions: (a) effects of a simple shift of the entire distribution toward a warmer climate; (b) effects of an increase in temperature variability with no shift in the mean; (c) effects of an altered shape of the distribution, in this example a change in asymmetry toward the hotter part of the distribution. [Figure 1-2, 1.2.2]

B. Observations of Exposure, Vulnerability, Climate Extremes, Impacts, and Disaster Losses

The impacts of climate extremes and the potential for disasters result from the climate extremes themselves and from the exposure and vulnerability of human and natural systems. Observed changes in climate extremes reflect the influence of anthropogenic climate change in addition to natural climate variability, with changes in exposure and vulnerability influenced by both climatic and non-climatic factors.

Exposure and Vulnerability

Exposure and vulnerability are dynamic, varying across temporal and spatial scales, and depend on economic, social, geographic, demographic, cultural, institutional, governance, and environmental factors (*high confidence*). [2.2, 2.3, 2.5] Individuals and communities are differentially exposed and vulnerable based on inequalities expressed through levels of wealth and education, disability, and health status, as well as gender, age, class, and other social and cultural characteristics. [2.5]

Settlement patterns, urbanization, and changes in socioeconomic conditions have all influenced observed trends in exposure and vulnerability to climate extremes (*high confidence*). [4.2, 4.3.5] For example, coastal

settlements, including in small islands and megadeltas, and mountain settlements are exposed and vulnerable to climate extremes in both developed and developing countries, but with differences among regions and countries. [4.3.5, 4.4.3, 4.4.6, 4.4.9, 4.4.10] Rapid urbanization and the growth of megacities, especially in developing countries, have led to the emergence of highly vulnerable urban communities, particularly through informal settlements and inadequate land management (*high agreement, robust evidence*). [5.5.1] See also Case Studies 9.2.8 and 9.2.9. Vulnerable populations also include refugees, internally displaced people, and those living in marginal areas. [4.2, 4.3.5]

Climate Extremes and Impacts

There is evidence from observations gathered since 1950 of change in some extremes. Confidence in observed changes in extremes depends on the quality and quantity of data and the availability of studies analyzing these data, which vary across regions and for different extremes. Assigning 'low confidence' in observed changes in a specific extreme on regional or global scales neither implies nor excludes the possibility of changes in this extreme. Extreme events are rare, which means there are few data available to make assessments regarding changes in their frequency or intensity. The more rare the event the more difficult it is to identify long-term changes. Global-scale trends in a specific extreme may be either more reliable (e.g., for temperature extremes) or less reliable (e.g., for droughts) than some regional-scale trends, depending on the geographical uniformity of the trends in the specific extreme. The following paragraphs provide further details for specific climate extremes from observations since 1950. [3.1.5, 3.1.6, 3.2.1]

It is *very likely* that there has been an overall decrease in the number of cold days and nights,[3] and an overall increase in the number of warm days and nights,[3] at the global scale, that is, for most land areas with sufficient data. It is *likely* that these changes have also occurred at the continental scale in North America, Europe, and Australia. There is *medium confidence* in a warming trend in daily temperature extremes in much of Asia. Confidence in observed trends in daily temperature extremes in Africa and South America generally varies from *low* to *medium* depending on the region. In many (but not all) regions over the globe with sufficient data, there is *medium confidence* that the length or number of warm spells or heat waves[3] has increased. [3.3.1, Table 3-2]

There have been statistically significant trends in the number of heavy precipitation events in some regions. It is *likely* that more of these regions have experienced increases than decreases, although there are strong regional and subregional variations in these trends. [3.3.2]

There is *low confidence* in any observed long-term (i.e., 40 years or more) increases in tropical cyclone activity (i.e., intensity, frequency, duration), after accounting for past changes in observing capabilities. It is *likely* that there has been a poleward shift in the main Northern and Southern Hemisphere extratropical storm tracks. There is *low confidence* in observed trends in small spatial-scale phenomena such as tornadoes and hail because of data inhomogeneities and inadequacies in monitoring systems. [3.3.2, 3.3.3, 3.4.4, 3.4.5]

There is *medium confidence* that some regions of the world have experienced more intense and longer droughts, in particular in southern Europe and West Africa, but in some regions droughts have become less frequent, less intense, or shorter, for example, in central North America and northwestern Australia. [3.5.1]

There is *limited* to *medium evidence* available to assess climate-driven observed changes in the magnitude and frequency of floods at regional scales because the available instrumental records of floods at gauge stations are limited in space and time, and because of confounding effects of changes in land use and engineering. Furthermore, there is *low agreement* in this evidence, and thus overall *low confidence* at the global scale regarding even the sign of these changes. [3.5.2]

[3] See SREX Glossary for definition of these terms: cold days / cold nights, warm days / warm nights, and warm spell – heat wave.

It is *likely* that there has been an increase in extreme coastal high water related to increases in mean sea level. [3.5.3]

There is evidence that some extremes have changed as a result of anthropogenic influences, including increases in atmospheric concentrations of greenhouse gases. It is *likely* that anthropogenic influences have led to warming of extreme daily minimum and maximum temperatures at the global scale. There is *medium confidence* that anthropogenic influences have contributed to intensification of extreme precipitation at the global scale. It is *likely* that there has been an anthropogenic influence on increasing extreme coastal high water due to an increase in mean sea level. The uncertainties in the historical tropical cyclone records, the incomplete understanding of the physical mechanisms linking tropical cyclone metrics to climate change, and the degree of tropical cyclone variability provide only *low confidence* for the attribution of any detectable changes in tropical cyclone activity to anthropogenic influences. Attribution of single extreme events to anthropogenic climate change is challenging. [3.2.2, 3.3.1, 3.3.2, 3.4.4, 3.5.3, Table 3-1]

Disaster Losses

Economic losses from weather- and climate-related disasters have increased, but with large spatial and interannual variability (*high confidence*, based on *high agreement*, *medium evidence*). Global weather- and climate-related disaster losses reported over the last few decades reflect mainly monetized direct damages to assets, and are unequally distributed. Estimates of annual losses have ranged since 1980 from a few US$ billion to above 200 billion (in 2010 dollars), with the highest value for 2005 (the year of Hurricane Katrina). Loss estimates are lower-bound estimates because many impacts, such as loss of human lives, cultural heritage, and ecosystem services, are difficult to value and monetize, and thus they are poorly reflected in estimates of losses. Impacts on the informal or undocumented economy as well as indirect economic effects can be very important in some areas and sectors, but are generally not counted in reported estimates of losses. [4.5.1, 4.5.3, 4.5.4]

Economic, including insured, disaster losses associated with weather, climate, and geophysical events[4] are higher in developed countries. Fatality rates and economic losses expressed as a proportion of gross domestic product (GDP) are higher in developing countries (*high confidence*). During the period from 1970 to 2008, over 95% of deaths from natural disasters occurred in developing countries. Middle-income countries with rapidly expanding asset bases have borne the largest burden. During the period from 2001 to 2006, losses amounted to about 1% of GDP for middle-income countries, while this ratio has been about 0.3% of GDP for low-income countries and less than 0.1% of GDP for high-income countries, based on *limited evidence*. In small exposed countries, particularly small island developing states, losses expressed as a percentage of GDP have been particularly high, exceeding 1% in many cases and 8% in the most extreme cases, averaged over both disaster and non-disaster years for the period from 1970 to 2010. [4.5.2, 4.5.4]

Increasing exposure of people and economic assets has been the major cause of long-term increases in economic losses from weather- and climate-related disasters (*high confidence*). Long-term trends in economic disaster losses adjusted for wealth and population increases have not been attributed to climate change, but a role for climate change has not been excluded (*high agreement, medium evidence*). These conclusions are subject to a number of limitations in studies to date. Vulnerability is a key factor in disaster losses, yet it is not well accounted for. Other limitations are: (i) data availability, as most data are available for standard economic sectors in developed countries; and (ii) type of hazards studied, as most studies focus on cyclones, where confidence in observed trends and attribution of changes to human influence is *low*. The second conclusion is subject to additional limitations: (iii) the processes used to adjust loss data over time, and (iv) record length. [4.5.3]

[4] Economic losses and fatalities described in this paragraph pertain to all disasters associated with weather, climate, and geophysical events.

C. Disaster Risk Management and Adaptation to Climate Change: Past Experience with Climate Extremes

Past experience with climate extremes contributes to understanding of effective disaster risk management and adaptation approaches to manage risks.

The severity of the impacts of climate extremes depends strongly on the level of the exposure and vulnerability to these extremes (*high confidence*). [2.1.1, 2.3, 2.5]

Trends in exposure and vulnerability are major drivers of changes in disaster risk (*high confidence*). [2.5] Understanding the multi-faceted nature of both exposure and vulnerability is a prerequisite for determining how weather and climate events contribute to the occurrence of disasters, and for designing and implementing effective adaptation and disaster risk management strategies. [2.2, 2.6] Vulnerability reduction is a core common element of adaptation and disaster risk management. [2.2, 2.3]

Development practice, policy, and outcomes are critical to shaping disaster risk, which may be increased by shortcomings in development (*high confidence*). [1.1.2, 1.1.3] High exposure and vulnerability are generally the outcome of skewed development processes such as those associated with environmental degradation, rapid and unplanned urbanization in hazardous areas, failures of governance, and the scarcity of livelihood options for the poor. [2.2.2, 2.5] Increasing global interconnectivity and the mutual interdependence of economic and ecological systems can have sometimes contrasting effects, reducing or amplifying vulnerability and disaster risk. [7.2.1] Countries more effectively manage disaster risk if they include considerations of disaster risk in national development and sector plans and if they adopt climate change adaptation strategies, translating these plans and strategies into actions targeting vulnerable areas and groups. [6.2, 6.5.2]

Data on disasters and disaster risk reduction are lacking at the local level, which can constrain improvements in local vulnerability reduction (*high agreement, medium evidence*). [5.7] There are few examples of national disaster risk management systems and associated risk management measures explicitly integrating knowledge of and uncertainties in projected changes in exposure, vulnerability, and climate extremes. [6.6.2, 6.6.4]

Inequalities influence local coping and adaptive capacity, and pose disaster risk management and adaptation challenges from the local to national levels (*high agreement, robust evidence*). These inequalities reflect socioeconomic, demographic, and health-related differences and differences in governance, access to livelihoods, entitlements, and other factors. [5.5.1, 6.2] Inequalities also exist across countries: developed countries are often better equipped financially and institutionally to adopt explicit measures to effectively respond and adapt to projected changes in exposure, vulnerability, and climate extremes than are developing countries. Nonetheless, all countries face challenges in assessing, understanding, and responding to such projected changes. [6.3.2, 6.6]

Humanitarian relief is often required when disaster risk reduction measures are absent or inadequate (*high agreement, robust evidence*). [5.2.1] Smaller or economically less-diversified countries face particular challenges in providing the public goods associated with disaster risk management, in absorbing the losses caused by climate extremes and disasters, and in providing relief and reconstruction assistance. [6.4.3]

Post-disaster recovery and reconstruction provide an opportunity for reducing weather- and climate-related disaster risk and for improving adaptive capacity (*high agreement, robust evidence*). An emphasis on rapidly rebuilding houses, reconstructing infrastructure, and rehabilitating livelihoods often leads to recovering in ways that recreate or even increase existing vulnerabilities, and that preclude longer-term planning and policy changes for enhancing resilience and sustainable development. [5.2.3] See also assessment in Sections 8.4.1 and 8.5.2.

Risk sharing and transfer mechanisms at local, national, regional, and global scales can increase resilience to climate extremes (*medium confidence*). Mechanisms include informal and traditional risk sharing mechanisms,

micro-insurance, insurance, reinsurance, and national, regional, and global risk pools. [5.6.3, 6.4.3, 6.5.3, 7.4] These mechanisms are linked to disaster risk reduction and climate change adaptation by providing means to finance relief, recovery of livelihoods, and reconstruction; reducing vulnerability; and providing knowledge and incentives for reducing risk. [5.5.2, 6.2.2] Under certain conditions, however, such mechanisms can provide disincentives for reducing disaster risk. [5.6.3, 6.5.3, 7.4.4] Uptake of formal risk sharing and transfer mechanisms is unequally distributed across regions and hazards. [6.5.3] See also Case Study 9.2.13.

Attention to the temporal and spatial dynamics of exposure and vulnerability is particularly important given that the design and implementation of adaptation and disaster risk management strategies and policies can reduce risk in the short term, but may increase exposure and vulnerability over the longer term (*high agreement, medium evidence*). For instance, dike systems can reduce flood exposure by offering immediate protection, but also encourage settlement patterns that may increase risk in the long term. [2.4.2, 2.5.4, 2.6.2] See also assessment in Sections 1.4.3, 5.3.2, and 8.3.1.

National systems are at the core of countries' capacity to meet the challenges of observed and projected trends in exposure, vulnerability, and weather and climate extremes (*high agreement, robust evidence*). Effective national systems comprise multiple actors from national and sub-national governments, the private sector, research bodies, and civil society including community-based organizations, playing differential but complementary roles to manage risk, according to their accepted functions and capacities. [6.2]

Closer integration of disaster risk management and climate change adaptation, along with the incorporation of both into local, sub-national, national, and international development policies and practices, could provide benefits at all scales (*high agreement, medium evidence*). [5.4, 5.5, 5.6, 6.3.1, 6.3.2, 6.4.2, 6.6, 7.4] Addressing social welfare, quality of life, infrastructure, and livelihoods, and incorporating a multi-hazards approach into planning and action for disasters in the short term, facilitates adaptation to climate extremes in the longer term, as is increasingly recognized internationally. [5.4, 5.5, 5.6, 7.3] Strategies and policies are more effective when they acknowledge multiple stressors, different prioritized values, and competing policy goals. [8.2, 8.3, 8.7]

D. Future Climate Extremes, Impacts, and Disaster Losses

Future changes in exposure, vulnerability, and climate extremes resulting from natural climate variability, anthropogenic climate change, and socioeconomic development can alter the impacts of climate extremes on natural and human systems and the potential for disasters.

Climate Extremes and Impacts

Confidence in projecting changes in the direction and magnitude of climate extremes depends on many factors, including the type of extreme, the region and season, the amount and quality of observational data, the level of understanding of the underlying processes, and the reliability of their simulation in models. Projected changes in climate extremes under different emissions scenarios[5] generally do not strongly diverge in the coming two to three decades, but these signals are relatively small compared to natural climate variability over this time frame. Even the sign of projected changes in some climate extremes over this time frame is uncertain. For projected changes by the end of the 21st century, either model uncertainty or uncertainties associated with emissions scenarios used becomes dominant, depending on the extreme. Low-probability, high-impact changes associated with

[5] Emissions scenarios for radiatively important substances result from pathways of socioeconomic and technological development. This report uses a subset (B1, A1B, A2) of the 40 scenarios extending to the year 2100 that are described in the IPCC Special Report on Emissions Scenarios (SRES) and that did not include additional climate initiatives. These scenarios have been widely used in climate change projections and encompass a substantial range of carbon dioxide equivalent concentrations, but not the entire range of the scenarios included in the SRES.

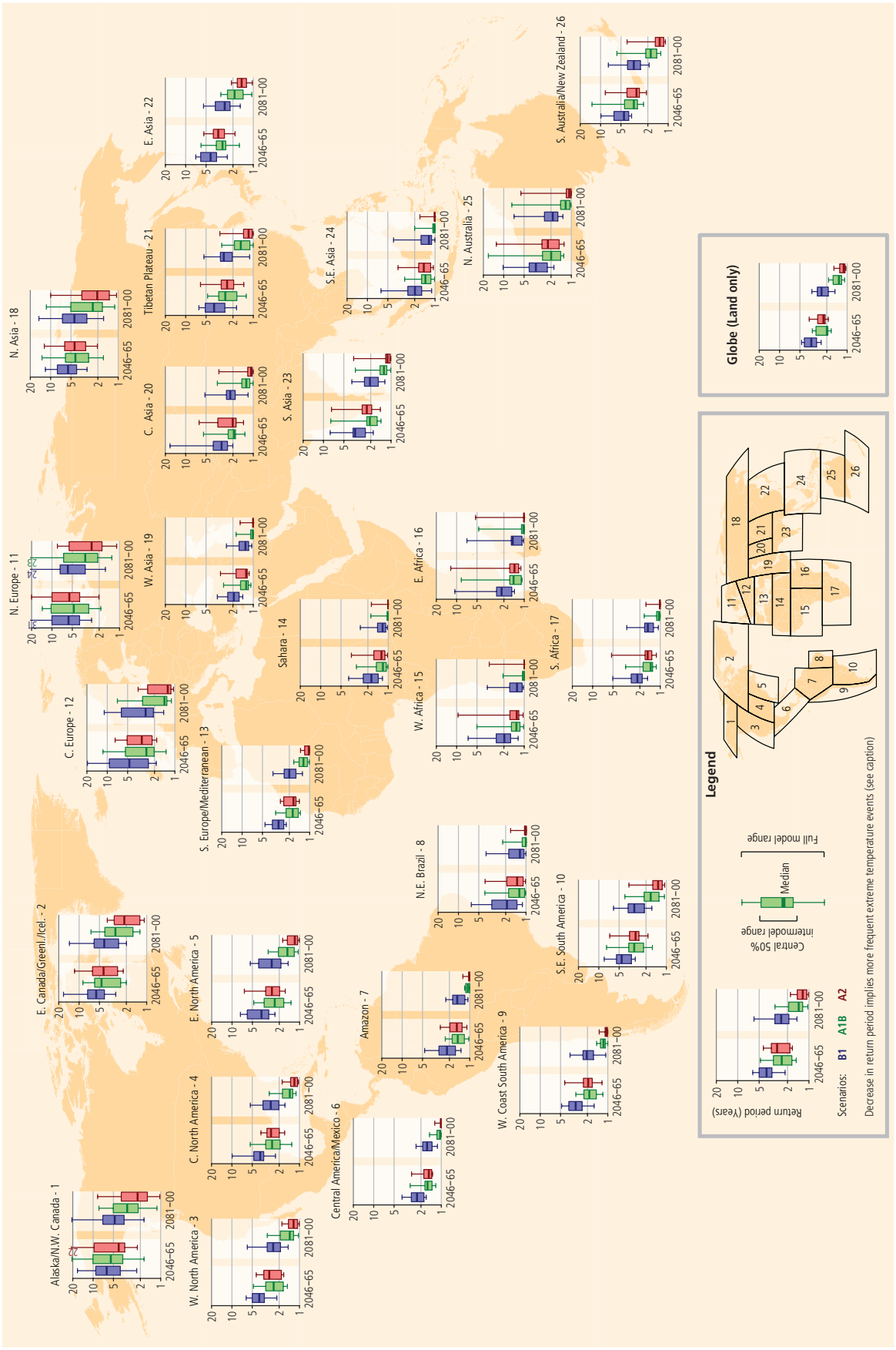


Figure SPM.4A | Projected return periods for the maximum daily temperature that was exceeded on average once during a 20-year period in the late 20th century (1981–2000). A decrease in return period implies more frequent extreme temperature events (i.e., less time between events on average). The box plots show results for regionally averaged projections for two time horizons, 2046 to 2065 and 2081 to 2100, as compared to the late 20th century, and for three different SRES emissions scenarios (B1, A1B, A2) (see legend). Results are based on 12 global climate models (GCMs) contributing to the third phase of the Coupled Model Intercomparison Project (CMIP3). The level of agreement among the models is indicated by the size of the colored boxes (in which 50% of the model projections are contained), and the length of the whiskers (indicating the maximum and minimum projections from all models). See legend for defined extent of regions. Values are computed for land points only. The 'Globe' inset box displays the values computed using all land grid points. [3.3.1, Figure 3-1, Figure 3-5]

the crossing of poorly understood climate thresholds cannot be excluded, given the transient and complex nature of the climate system. Assigning 'low confidence' for projections of a specific extreme neither implies nor excludes the possibility of changes in this extreme. The following assessments of the likelihood and/or confidence of projections are generally for the end of the 21st century and relative to the climate at the end of the 20th century. [3.1.5, 3.1.7, 3.2.3, Box 3-2]

Models project substantial warming in temperature extremes by the end of the 21st century. It is *virtually certain* that increases in the frequency and magnitude of warm daily temperature extremes and decreases in cold extremes will occur in the 21st century at the global scale. It is *very likely* that the length, frequency, and/or intensity of warm spells or heat waves will increase over most land areas. Based on the A1B and A2 emissions scenarios, a 1-in-20 year hottest day is *likely* to become a 1-in-2 year event by the end of the 21st century in most regions, except in the high latitudes of the Northern Hemisphere, where it is *likely* to become a 1-in-5 year event (see Figure SPM.4A). Under the B1 scenario, a 1-in-20 year event would *likely* become a 1-in-5 year event (and a 1-in-10 year event in Northern Hemisphere high latitudes). The 1-in-20 year extreme daily maximum temperature (i.e., a value that was exceeded on average only once during the period 1981–2000) will *likely* increase by about 1°C to 3°C by the mid-21st century and by about 2°C to 5°C by the late 21st century, depending on the region and emissions scenario (based on the B1, A1B, and A2 scenarios). [3.3.1, 3.1.6, Table 3-3, Figure 3-5]

It is *likely* that the frequency of heavy precipitation or the proportion of total rainfall from heavy falls will increase in the 21st century over many areas of the globe. This is particularly the case in the high latitudes and tropical regions, and in winter in the northern mid-latitudes. Heavy rainfalls associated with tropical cyclones are *likely* to increase with continued warming. There is *medium confidence* that, in some regions, increases in heavy precipitation will occur despite projected decreases in total precipitation in those regions. Based on a range of emissions scenarios (B1, A1B, A2), a 1-in-20 year annual maximum daily precipitation amount is *likely* to become a 1-in-5 to 1-in-15 year event by the end of the 21st century in many regions, and in most regions the higher emissions scenarios (A1B and A2) lead to a stronger projected decrease in return period. See Figure SPM.4B. [3.3.2, 3.4.4, Table 3-3, Figure 3-7]

Average tropical cyclone maximum wind speed is *likely* to increase, although increases may not occur in all ocean basins. It is *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged. [3.4.4]

There is *medium confidence* that there will be a reduction in the number of extratropical cyclones averaged over each hemisphere. While there is *low confidence* in the detailed geographical projections of extratropical cyclone activity, there is *medium confidence* in a projected poleward shift of extratropical storm tracks. There is *low confidence* in projections of small spatial-scale phenomena such as tornadoes and hail because competing physical processes may affect future trends and because current climate models do not simulate such phenomena. [3.3.2, 3.3.3, 3.4.5]

There is *medium confidence* that droughts will intensify in the 21st century in some seasons and areas, due to reduced precipitation and/or increased evapotranspiration. This applies to regions including southern Europe and the Mediterranean region, central Europe, central North America, Central America and Mexico, northeast Brazil, and southern Africa. Elsewhere there is overall *low confidence* because of inconsistent projections of drought changes (dependent both on model and dryness index). Definitional issues, lack of observational data, and the inability of models to include all the factors that influence droughts preclude stronger confidence than *medium* in drought projections. See Figure SPM.5. [3.5.1, Table 3-3, Box 3-3]

Projected precipitation and temperature changes imply possible changes in floods, although overall there is *low confidence* in projections of changes in fluvial floods. Confidence is *low* due to *limited evidence* and because the causes of regional changes are complex, although there are exceptions to this statement. There is *medium confidence* (based on physical reasoning) that projected increases in heavy rainfall would contribute to increases in local flooding in some catchments or regions. [3.5.2]

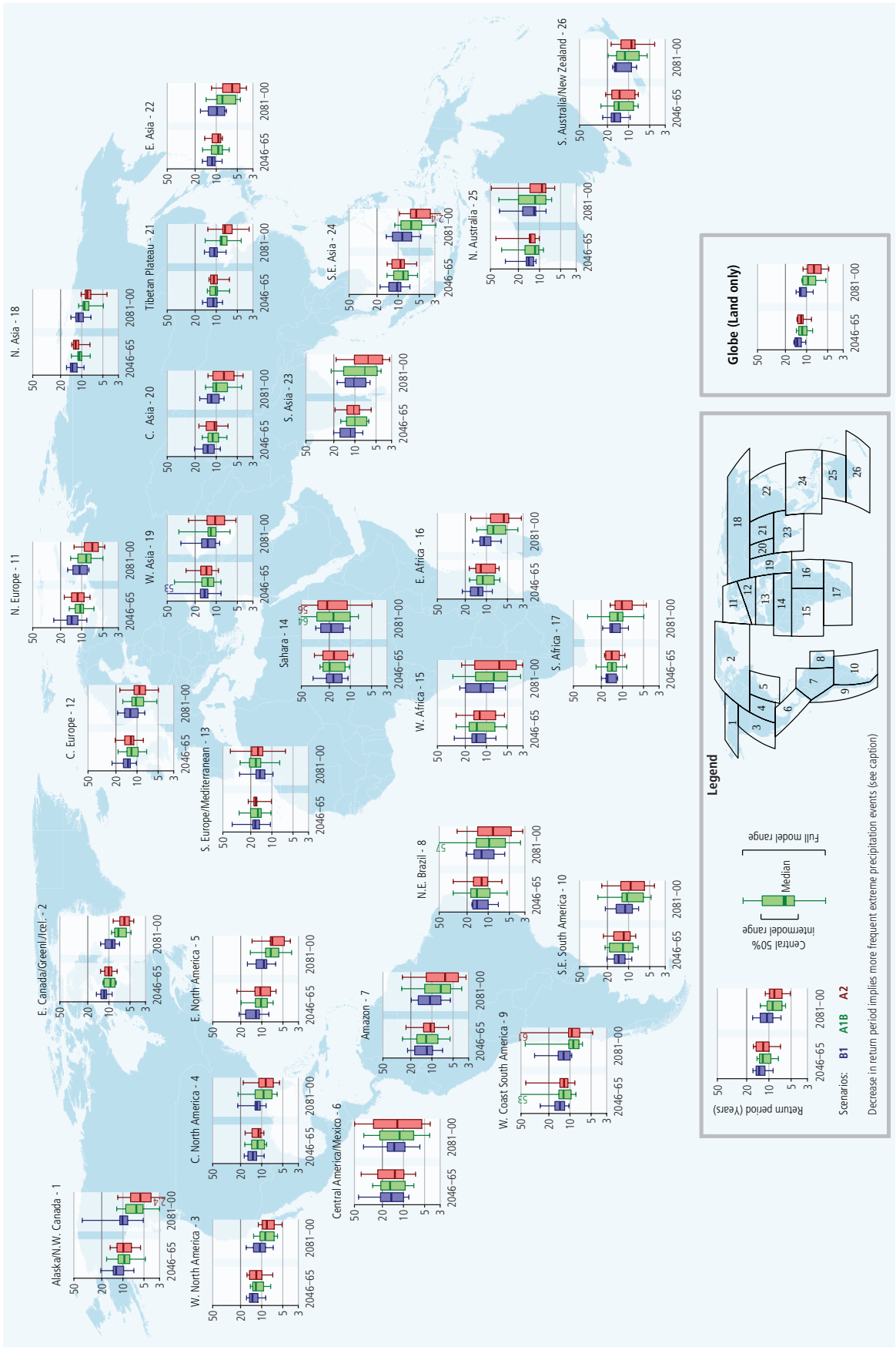


Figure SPM.4B | Projected return periods for a daily precipitation event that was exceeded in the late 20th century on average once during a 20-year period (1981–2000). A decrease in return period implies more frequent extreme precipitation events (i.e., less time between events on average). The box plots show results for regionally averaged projections for two time horizons, 2046 to 2065 and 2081 to 2100, as compared to the late 20th century, and for three different SRES emissions scenarios (B1, A1B, A2) (see legend). Results are based on 14 GCMs contributing to the CMIP3. The level of agreement among the models is indicated by the size of the colored boxes (in which 50% of the model projections are contained), and the length of the whiskers (indicating the maximum and minimum projections from all models). See legend for defined extent of regions. Values are computed for land points only. The 'Globe' inset box displays the values computed using all land grid points. [3.3.2, Figure 3-1, Figure 3-7]

It is *very likely* that mean sea level rise will contribute to upward trends in extreme coastal high water levels in the future. There is *high confidence* that locations currently experiencing adverse impacts such as coastal erosion and inundation will continue to do so in the future due to increasing sea levels, all other contributing factors being equal. The *very likely* contribution of mean sea level rise to increased extreme coastal high water levels, coupled with the *likely* increase in tropical cyclone maximum wind speed, is a specific issue for tropical small island states. [3.5.3, 3.5.5, Box 3-4]

There is *high confidence* that changes in heat waves, glacial retreat, and/or permafrost degradation will affect high mountain phenomena such as slope instabilities, movements of mass, and glacial lake outburst floods. There is also *high confidence* that changes in heavy precipitation will affect landslides in some regions. [3.5.6]

There is *low confidence* in projections of changes in large-scale patterns of natural climate variability. Confidence is *low* in projections of changes in monsoons (rainfall, circulation) because there is little consensus in climate models regarding the sign of future change in the monsoons. Model projections of changes in El Niño–Southern

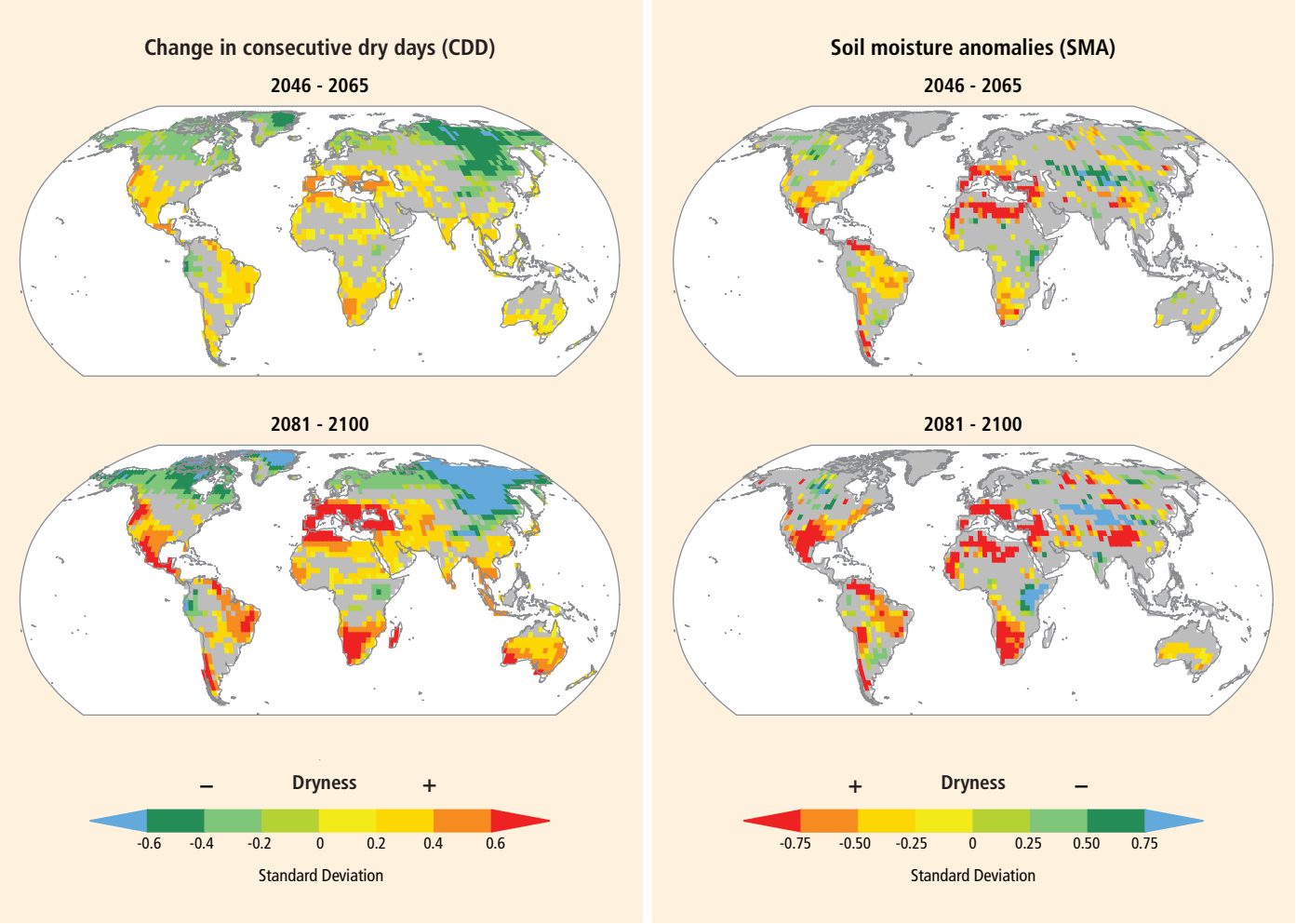


Figure SPM.5 | Projected annual changes in dryness assessed from two indices. Left column: Change in annual maximum number of consecutive dry days (CDD: days with precipitation <1 mm). Right column: Changes in soil moisture (soil moisture anomalies, SMA). Increased dryness is indicated with yellow to red colors; decreased dryness with green to blue. Projected changes are expressed in units of standard deviation of the interannual variability in the three 20-year periods 1980–1999, 2046–2065, and 2081–2100. The figures show changes for two time horizons, 2046–2065 and 2081–2100, as compared to late 20th-century values (1980–1999), based on GCM simulations under emissions scenario SRES A2 relative to corresponding simulations for the late 20th century. Results are based on 17 (CDD) and 15 (SMA) GCMs contributing to the CMIP3. Colored shading is applied for areas where at least 66% (12 out of 17 for CDD, 10 out of 15 for SMA) of the models agree on the sign of the change; stippling is added for regions where at least 90% (16 out of 17 for CDD, 14 out of 15 for SMA) of all models agree on the sign of the change. Grey shading indicates where there is insufficient model agreement (<66%). [3.5.1, Figure 3-9]

Oscillation variability and the frequency of El Niño episodes are not consistent, and so there is *low confidence* in projections of changes in this phenomenon. [3.4.1, 3.4.2, 3.4.3]

Human Impacts and Disaster Losses

Extreme events will have greater impacts on sectors with closer links to climate, such as water, agriculture and food security, forestry, health, and tourism. For example, while it is not currently possible to reliably project specific changes at the catchment scale, there is *high confidence* that changes in climate have the potential to seriously affect water management systems. However, climate change is in many instances only one of the drivers of future changes, and is not necessarily the most important driver at the local scale. Climate-related extremes are also expected to produce large impacts on infrastructure, although detailed analysis of potential and projected damages are limited to a few countries, infrastructure types, and sectors. [4.3.2, 4.3.5]

In many regions, the main drivers of future increases in economic losses due to some climate extremes will be socioeconomic in nature (*medium confidence*, based on *medium agreement*, *limited evidence*). Climate extremes are only one of the factors that affect risks, but few studies have specifically quantified the effects of changes in population, exposure of people and assets, and vulnerability as determinants of loss. However, the few studies available generally underline the important role of projected changes (increases) in population and capital at risk. [4.5.4]

Increases in exposure will result in higher direct economic losses from tropical cyclones. Losses will also depend on future changes in tropical cyclone frequency and intensity (*high confidence*). Overall losses due to extratropical cyclones will also increase, with possible decreases or no change in some areas (*medium confidence*). Although future flood losses in many locations will increase in the absence of additional protection measures (*high agreement, medium evidence*), the size of the estimated change is highly variable, depending on location, climate scenarios used, and methods used to assess impacts on river flow and flood occurrence. [4.5.4]

Disasters associated with climate extremes influence population mobility and relocation, affecting host and origin communities (*medium agreement, medium evidence*). If disasters occur more frequently and/or with greater magnitude, some local areas will become increasingly marginal as places to live or in which to maintain livelihoods. In such cases, migration and displacement could become permanent and could introduce new pressures in areas of relocation. For locations such as atolls, in some cases it is possible that many residents will have to relocate. [5.2.2]

E. Managing Changing Risks of Climate Extremes and Disasters

Adaptation to climate change and disaster risk management provide a range of complementary approaches for managing the risks of climate extremes and disasters (Figure SPM.2). Effectively applying and combining approaches may benefit from considering the broader challenge of sustainable development.

Measures that provide benefits under current climate and a range of future climate change scenarios, called low-regrets measures, are available starting points for addressing projected trends in exposure, vulnerability, and climate extremes. They have the potential to offer benefits now and lay the foundation for addressing projected changes (*high agreement, medium evidence*). Many of these low-regrets strategies produce co-benefits, help address other development goals, such as improvements in livelihoods, human well-being, and biodiversity conservation, and help minimize the scope for maladaptation. [6.3.1, Table 6-1]

Potential low-regrets measures include early warning systems; risk communication between decisionmakers and local citizens; sustainable land management, including land use planning; and ecosystem management and restoration.

Other low-regrets measures include improvements to health surveillance, water supply, sanitation, and irrigation and drainage systems; climate-proofing of infrastructure; development and enforcement of building codes; and better education and awareness. [5.3.1, 5.3.3, 6.3.1, 6.5.1, 6.5.2] See also Case Studies 9.2.11 and 9.2.14, and assessment in Section 7.4.3.

Effective risk management generally involves a portfolio of actions to reduce and transfer risk and to respond to events and disasters, as opposed to a singular focus on any one action or type of action (*high confidence*). [1.1.2, 1.1.4, 1.3.3] Such integrated approaches are more effective when they are informed by and customized to specific local circumstances (*high agreement, robust evidence*). [5.1] Successful strategies include a combination of hard infrastructure-based responses and soft solutions such as individual and institutional capacity building and ecosystem-based responses. [6.5.2]

Multi-hazard risk management approaches provide opportunities to reduce complex and compound hazards (*high agreement, robust evidence*). Considering multiple types of hazards reduces the likelihood that risk reduction efforts targeting one type of hazard will increase exposure and vulnerability to other hazards, in the present and future. [8.2.5, 8.5.2, 8.7]

Opportunities exist to create synergies in international finance for disaster risk management and adaptation to climate change, but these have not yet been fully realized (*high confidence*). International funding for disaster risk reduction remains relatively low as compared to the scale of spending on international humanitarian response. [7.4.2] Technology transfer and cooperation to advance disaster risk reduction and climate change adaptation are important. Coordination on technology transfer and cooperation between these two fields has been lacking, which has led to fragmented implementation. [7.4.3]

Stronger efforts at the international level do not necessarily lead to substantive and rapid results at the local level (*high confidence*). There is room for improved integration across scales from international to local. [7.6]

Integration of local knowledge with additional scientific and technical knowledge can improve disaster risk reduction and climate change adaptation (*high agreement, robust evidence*). Local populations document their experiences with the changing climate, particularly extreme weather events, in many different ways, and this self-generated knowledge can uncover existing capacity within the community and important current shortcomings. [5.4.4] Local participation supports community-based adaptation to benefit management of disaster risk and climate extremes. However, improvements in the availability of human and financial capital and of disaster risk and climate information customized for local stakeholders can enhance community-based adaptation (*medium agreement, medium evidence)*. [5.6]

Appropriate and timely risk communication is critical for effective adaptation and disaster risk management (*high confidence*). Explicit characterization of uncertainty and complexity strengthens risk communication. [2.6.3] Effective risk communication builds on exchanging, sharing, and integrating knowledge about climate-related risks among all stakeholder groups. Among individual stakeholders and groups, perceptions of risk are driven by psychological and cultural factors, values, and beliefs. [1.1.4, 1.3.1, 1.4.2] See also assessment in Section 7.4.5.

An iterative process of monitoring, research, evaluation, learning, and innovation can reduce disaster risk and promote adaptive management in the context of climate extremes (*high agreement, robust evidence*). [8.6.3, 8.7] Adaptation efforts benefit from iterative risk management strategies because of the complexity, uncertainties, and long time frame associated with climate change (*high confidence*). [1.3.2] Addressing knowledge gaps through enhanced observation and research can reduce uncertainty and help in designing effective adaptation and risk management strategies. [3.2, 6.2.5, Table 6-3, 7.5, 8.6.3] See also assessment in Section 6.6.

Table SPM.1 presents examples of how observed and projected trends in exposure, vulnerability, and climate extremes can inform risk management and adaptation strategies, policies, and measures. The

Table SPM.1 | Illustrative examples of options for risk management and adaptation in the context of changes in exposure, vulnerability, and climate extremes. In each example, information is characterized at the scale directly relevant to decisionmaking. Observed and projected changes in climate extremes at global and regional scales illustrate that the direction of, magnitude of, and/or degree of certainty for changes may differ across scales.

The examples were selected based on availability of evidence in the underlying chapters, including on exposure, vulnerability, climate information, and risk management and adaptation options. They are intended to reflect relevant risk management themes and scales, rather than to provide comprehensive information by region. The examples are not intended to reflect any regional differences in exposure and vulnerability, or in experience in risk management.

The confidence in projected changes in climate extremes at local scales is often more limited than the confidence in projected regional and global changes. This limited confidence in changes places a focus on low-regrets risk management options that aim to reduce exposure and vulnerability and to increase resilience and preparedness for risks that cannot be entirely eliminated. Higher-confidence projected changes in climate extremes, at a scale relevant to adaptation and risk management decisions, can inform more targeted adjustments in strategies, policies, and measures. [3.1.6, Box 3-2, 6.3.1, 6.5.2]

Example	Exposure and vulnerability at scale of risk management in the example	Information on Climate Extreme Across Spatial Scales			Options for risk management and adaptation in the example
		GLOBAL Observed (since 1950) and projected (to 2100) global changes	**REGIONAL** Observed (since 1950) and projected (to 2100) changes in the example	**SCALE OF RISK MANAGEMENT** Available information for the example	
Inundation related to **extreme sea levels** in tropical small island developing states	Small island states in the Pacific, Indian, and Atlantic Oceans, often with low elevation, are particularly vulnerable to rising sea levels and impacts such as erosion, inundation, shoreline change, and saltwater intrusion into coastal aquifers. These impacts can result in ecosystem disruption, decreased agricultural productivity, changes in disease patterns, economic losses such as in tourism industries, and population displacement – all of which reinforce vulnerability to extreme weather events. [3.5.5, Box 3-4, 4.3.5, 4.4.10, 9.2.9]	**Observed:** *Likely* increase in extreme coastal high water worldwide related to increases in mean sea level. **Projected:** *Very likely* that mean sea level rise will contribute to upward trends in extreme coastal high water levels. *High confidence* that locations currently experiencing coastal erosion and inundation will continue to do so due to increasing sea level, in the absence of changes in other contributing factors. *Likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged. *Likely* increase in average tropical cyclone maximum wind speed, although increases may not occur in all ocean basins. [Table 3-1, 3.4.4, 3.5.3, 3.5.5]	**Observed:** Tides and El Niño–Southern Oscillation have contributed to the more frequent occurrence of extreme coastal high water levels and associated flooding experienced on some Pacific Islands in recent years. **Projected:** The *very likely* contribution of mean sea level rise to increased extreme coastal high water levels, coupled with the *likely* increase in tropical cyclone maximum wind speed, is a specific issue for tropical small island states. See global changes column for information on global projections for tropical cyclones. [Box 3-4, 3.4.4, 3.5.3]	Sparse regional and temporal coverage of terrestrial-based observation networks and limited in situ ocean observing network, but with improved satellite-based observations in recent decades. While changes in storminess may contribute to changes in extreme coastal high water levels, the limited geographical coverage of studies to date and the uncertainties associated with storminess changes overall mean that a general assessment of the effects of storminess changes on storm surge is not possible at this time. [Box 3-4, 3.5.3]	Low-regrets options that reduce exposure and vulnerability across a range of hazard trends: • Maintenance of drainage systems • Well technologies to limit saltwater contamination of groundwater • Improved early warning systems • Regional risk pooling • Mangrove conservation, restoration, and replanting Specific adaptation options include, for instance, rendering national economies more climate-independent and adaptive management involving iterative learning. In some cases there may be a need to consider relocation, for example, for atolls where storm surges may completely inundate them. [4.3.5, 4.4.10, 5.2.2, 6.3.2, 6.5.2, 6.6.2, 7.4.4, 9.2.9, 9.2.11, 9.2.13]
Flash floods in informal settlements in Nairobi, Kenya	Rapid expansion of poor people living in informal settlements around Nairobi has led to houses of weak building materials being constructed immediately adjacent to rivers and to blockage of natural drainage areas, increasing exposure and vulnerability. [6.4.2, Box 6-2]	**Observed:** *Low confidence* at global scale regarding (climate-driven) observed changes in the magnitude and frequency of floods. **Projected:** *Low confidence* in projections of changes in floods because of limited evidence and because the causes of regional changes are complex. However, *medium confidence* (based on physical reasoning) that projected increases in heavy precipitation will contribute to rain-generated local flooding in some catchments or regions. [Table 3-1, 3.5.2]	**Observed:** *Low confidence* regarding trends in heavy precipitation in East Africa, because of insufficient evidence. **Projected:** *Likely* increase in heavy precipitation indicators in East Africa. [Table 3-2, Table 3-3, 3.3.2]	Limited ability to provide local flash flood projections. [3.5.2]	Low-regrets options that reduce exposure and vulnerability across a range of hazard trends: • Strengthening building design and regulation • Poverty reduction schemes • City-wide drainage and sewerage improvements The Nairobi Rivers Rehabilitation and Restoration Programme includes installation of riparian buffers, canals, and drainage channels and clearance of existing channels; attention to climate variability and change in the location and design of wastewater infrastructure; and environmental monitoring for flood early warning. [6.3, 6.4.2, Box 6-2, Box 6-6]

Continued next page →

Table SPM.1 (continued)

Example	Exposure and vulnerability at scale of risk management in the example	Information on Climate Extreme Across Spatial Scales			Options for risk management and adaptation in the example
		GLOBAL Observed (since 1950) and projected (to 2100) global changes	REGIONAL Observed (since 1950) and projected (to 2100) changes in the example	SCALE OF RISK MANAGEMENT Available information for the example	
Impacts of **heat waves** in urban areas in Europe	Factors affecting exposure and vulnerability include age, pre-existing health status, level of outdoor activity, socioeconomic factors including poverty and social isolation, access to and use of cooling, physiological and behavioral adaptation of the population, and urban infrastructure. [2.5.2, 4.3.5, 4.3.6, 4.4.5, 9.2.1]	**Observed:** *Medium confidence* that the length or number of warm spells or heat waves has increased since the middle of the 20th century, in many (but not all) regions over the globe. *Very likely* increase in number of warm days and nights at the global scale. **Projected:** *Very likely* increase in length, frequency, and/or intensity of warm spells or heat waves over most land areas. *Virtually certain* increase in frequency and magnitude of warm days and nights at the global scale. [Table 3-1, 3.3.1]	**Observed:** *Medium confidence* in increase in heat waves or warm spells in Europe. *Likely* overall increase in warm days and nights over most of the continent. **Projected:** *Likely* more frequent, longer, and/or more intense heat waves or warm spells in Europe. *Very likely* increase in warm days and nights. [Table 3-2, Table 3-3, 3.3.1]	Observations and projections can provide information for specific urban areas in the region, with increased heat waves expected due to regional trends and urban heat island effects. [3.3.1, 4.4.5]	Low-regrets options that reduce exposure and vulnerability across a range of hazard trends: • Early warning systems that reach particularly vulnerable groups (e.g., the elderly) • Vulnerability mapping and corresponding measures • Public information on what to do during heat waves, including behavioral advice • Use of social care networks to reach vulnerable groups Specific adjustments in strategies, policies, and measures informed by trends in heat waves include awareness raising of heat waves as a public health concern; changes in urban infrastructure and land use planning, for example, increasing urban green space; changes in approaches to cooling for public facilities; and adjustments in energy generation and transmission infrastructure. [Table 6-1, 9.2.1]
Increasing losses from **hurricanes** in the USA and the Caribbean	Exposure and vulnerability are increasing due to growth in population and increase in property values, particularly along the Gulf and Atlantic coasts of the United States. Some of this increase has been offset by improved building codes. [4.4.6]	**Observed:** *Low confidence* in any observed long-term (i.e., 40 years or more) increases in tropical cyclone activity, after accounting for past changes in observing capabilities. **Projected:** *Likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged. *Likely* increase in average tropical cyclone maximum wind speed, although increases may not occur in all ocean basins. Heavy rainfalls associated with tropical cyclones are *likely* to increase. Projected sea level rise is expected to further compound tropical cyclone surge impacts. [Table 3-1, 3.4.4]	See global changes column for global projections.	Limited model capability to project changes relevant to specific settlements or other locations, due to the inability of global models to accurately simulate factors relevant to tropical cyclone genesis, track, and intensity evolution. [3.4.4]	Low-regrets options that reduce exposure and vulnerability across a range of hazard trends: • Adoption and enforcement of improved building codes • Improved forecasting capacity and implementation of improved early warning systems (including evacuation plans and infrastructures) • Regional risk pooling In the context of high underlying variability and uncertainty regarding trends, options can include emphasizing adaptive management involving learning and flexibility (e.g., Cayman Islands National Hurricane Committee). [5.5.3, 6.5.2, 6.6.2, Box 6-7, Table 6-1, 7.4.4, 9.2.5, 9.2.11, 9.2.13]
Droughts in the context of food security in West Africa	Less advanced agricultural practices render region vulnerable to increasing variability in seasonal rainfall, drought, and weather extremes. Vulnerability is exacerbated by population growth, degradation of ecosystems, and overuse of natural resources, as well as poor standards for health, education, and governance. [2.2.2, 2.3, 2.5, 4.4.2, 9.2.3]	**Observed:** *Medium confidence* that some regions of the world have experienced more intense and longer droughts, but in some regions droughts have become less frequent, less intense, or shorter. **Projected:** *Medium confidence* in projected intensification of drought in some seasons and areas. Elsewhere there is overall *low confidence* because of inconsistent projections. [Table 3-1, 3.5.1]	**Observed:** *Medium confidence* in an increase in dryness. Recent years characterized by greater interannual variability than previous 40 years, with the western Sahel remaining dry and the eastern Sahel returning to wetter conditions. **Projected:** *Low confidence* due to inconsistent signal in model projections. [Table 3-2, Table 3-3, 3.5.1]	Sub-seasonal, seasonal, and interannual forecasts with increasing uncertainty over longer time scales. Improved monitoring, instrumentation, and data associated with early warning systems, but with limited participation and dissemination to at-risk populations. [5.3.1, 5.5.3, 7.3.1, 9.2.3, 9.2.11]	Low-regrets options that reduce exposure and vulnerability across a range of hazard trends: • Traditional rain and groundwater harvesting and storage systems • Water demand management and improved irrigation efficiency measures • Conservation agriculture, crop rotation, and livelihood diversification • Increasing use of drought-resistant crop varieties • Early warning systems integrating seasonal forecasts with drought projections, with improved communication involving extension services • Risk pooling at the regional or national level [2.5.4, 5.3.1, 5.3.3, 6.5, Table 6-3, 9.2.3, 9.2.11]

importance of these trends for decisionmaking depends on their magnitude and degree of certainty at the temporal and spatial scale of the risk being managed and on the available capacity to implement risk management options (see Table SPM.1).

Implications for Sustainable Development

Actions that range from incremental steps to transformational changes are essential for reducing risk from climate extremes (*high agreement, robust evidence*). Incremental steps aim to improve efficiency within existing technological, governance, and value systems, whereas transformation may involve alterations of fundamental attributes of those systems. Transformations, where they are required, are also facilitated through increased emphasis on adaptive management and learning. Where vulnerability is high and adaptive capacity low, changes in climate extremes can make it difficult for systems to adapt sustainably without transformational changes. Vulnerability is often concentrated in lower-income countries or groups, although higher-income countries or groups can also be vulnerable to climate extremes. [8.6, 8.6.3, 8.7]

Social, economic, and environmental sustainability can be enhanced by disaster risk management and adaptation approaches. A prerequisite for sustainability in the context of climate change is addressing the underlying causes of vulnerability, including the structural inequalities that create and sustain poverty and constrain access to resources (*medium agreement, robust evidence*). This involves integrating disaster risk management and adaptation into all social, economic, and environmental policy domains. [8.6.2, 8.7]

The most effective adaptation and disaster risk reduction actions are those that offer development benefits in the relatively near term, as well as reductions in vulnerability over the longer term (*high agreement, medium evidence*). There are tradeoffs between current decisions and long-term goals linked to diverse values, interests, and priorities for the future. Short- and long-term perspectives on disaster risk management and adaptation to climate change thus can be difficult to reconcile. Such reconciliation involves overcoming the disconnect between local risk management practices and national institutional and legal frameworks, policy, and planning. [8.2.1, 8.3.1, 8.3.2, 8.6.1]

Progress toward resilient and sustainable development in the context of changing climate extremes can benefit from questioning assumptions and paradigms and stimulating innovation to encourage new patterns of response (*medium agreement, robust evidence*). Successfully addressing disaster risk, climate change, and other stressors often involves embracing broad participation in strategy development, the capacity to combine multiple perspectives, and contrasting ways of organizing social relations. [8.2.5, 8.6.3, 8.7]

The interactions among climate change mitigation, adaptation, and disaster risk management may have a major influence on resilient and sustainable pathways (*high agreement, limited evidence*). Interactions between the goals of mitigation and adaptation in particular will play out locally, but have global consequences. [8.2.5, 8.5.2]

There are many approaches and pathways to a sustainable and resilient future. [8.2.3, 8.4.1, 8.6.1, 8.7] However, limits to resilience are faced when thresholds or tipping points associated with social and/or natural systems are exceeded, posing severe challenges for adaptation. [8.5.1] Choices and outcomes for adaptive actions to climate events must reflect divergent capacities and resources and multiple interacting processes. Actions are framed by tradeoffs between competing prioritized values and objectives, and different visions of development that can change over time. Iterative approaches allow development pathways to integrate risk management so that diverse policy solutions can be considered, as risk and its measurement, perception, and understanding evolve over time. [8.2.3, 8.4.1, 8.6.1, 8.7]

Box SPM.2 | Treatment of Uncertainty

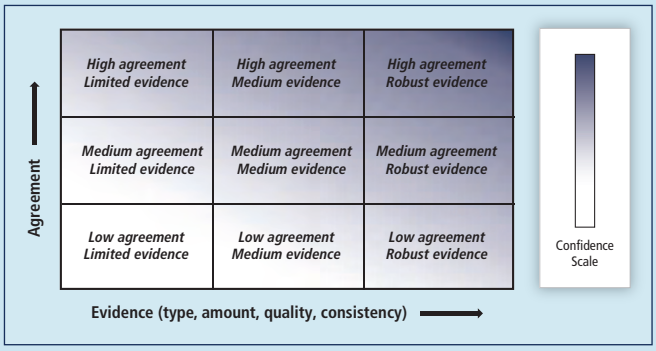
Based on the Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties,[6] this Summary for Policymakers relies on two metrics for communicating the degree of certainty in key findings, which is based on author teams' evaluations of underlying scientific understanding:

- Confidence in the validity of a finding, based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and the degree of agreement. Confidence is expressed qualitatively.
- Quantified measures of uncertainty in a finding expressed probabilistically (based on statistical analysis of observations or model results, or expert judgment).

This Guidance Note refines the guidance provided to support the IPCC Third and Fourth Assessment Reports. Direct comparisons between assessment of uncertainties in findings in this report and those in the IPCC Fourth Assessment Report are difficult if not impossible, because of the application of the revised guidance note on uncertainties, as well as the availability of new information, improved scientific understanding, continued analyses of data and models, and specific differences in methodologies applied in the assessed studies. For some extremes, different aspects have been assessed and therefore a direct comparison would be inappropriate.

Each key finding is based on an author team's evaluation of associated evidence and agreement. The confidence metric provides a qualitative synthesis of an author team's judgment about the validity of a finding, as determined through evaluation of evidence and agreement. If uncertainties can be quantified probabilistically, an author team can characterize a finding using the calibrated likelihood language or a more precise presentation of probability. Unless otherwise indicated, *high* or *very high confidence* is associated with findings for which an author team has assigned a likelihood term.

The following summary terms are used to describe the available evidence: *limited*, *medium*, or *robust*; and for the degree of agreement: *low*, *medium*, or *high*. A level of confidence is expressed using five qualifiers: *very low*, *low*, *medium*, *high*, and *very high*. The accompanying figure depicts summary statements for evidence and agreement and their relationship to confidence. There is flexibility in this relationship; for a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.



A depiction of evidence and agreement statements and their relationship to confidence. Confidence increases toward the top-right corner as suggested by the increasing strength of shading. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality evidence.

The following terms indicate the assessed likelihood:

Term*	Likelihood of the Outcome
Virtually certain	99–100% probability
Very likely	90–100% probability
Likely	66–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Exceptionally unlikely	0–1% probability

* Additional terms that were used in limited circumstances in the Fourth Assessment Report (*extremely likely:* 95–100% probability, *more likely than not:* >50–100% probability, and *extremely unlikely:* 0–5% probability) may also be used when appropriate.

[6] Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, G.-K. Plattner, G.W. Yohe, and F.W. Zwiers, 2010: *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*. Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, www.ipcc.ch.

Summary for Policymakers

SPM

Summary for Policymakers

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Introduction

This Report responds to the invitation for IPCC '... to provide a Special Report in 2018 on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways' contained in the Decision of the 21st Conference of Parties of the United Nations Framework Convention on Climate Change to adopt the Paris Agreement.[1]

The IPCC accepted the invitation in April 2016, deciding to prepare this Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

This Summary for Policymakers (SPM) presents the key findings of the Special Report, based on the assessment of the available scientific, technical and socio-economic literature[2] relevant to global warming of 1.5°C and for the comparison between global warming of 1.5°C and 2°C above pre-industrial levels. The level of confidence associated with each key finding is reported using the IPCC calibrated language.[3] The underlying scientific basis of each key finding is indicated by references provided to chapter elements. In the SPM, knowledge gaps are identified associated with the underlying chapters of the Report.

A. Understanding Global Warming of 1.5°C[4]

A.1 Human activities are estimated to have caused approximately 1.0°C of global warming[5] above pre-industrial levels, with a *likely* range of 0.8°C to 1.2°C. Global warming is *likely* to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. (*high confidence*) (Figure SPM.1) {1.2}

A.1.1 Reflecting the long-term warming trend since pre-industrial times, observed global mean surface temperature (GMST) for the decade 2006–2015 was 0.87°C (*likely* between 0.75°C and 0.99°C)[6] higher than the average over the 1850–1900 period (*very high confidence*). Estimated anthropogenic global warming matches the level of observed warming to within ±20% (*likely range*). Estimated anthropogenic global warming is currently increasing at 0.2°C (*likely* between 0.1°C and 0.3°C) per decade due to past and ongoing emissions (*high confidence*). {1.2.1, Table 1.1, 1.2.4}

A.1.2 Warming greater than the global annual average is being experienced in many land regions and seasons, including two to three times higher in the Arctic. Warming is generally higher over land than over the ocean. (*high confidence*) {1.2.1, 1.2.2, Figure 1.1, Figure 1.3, 3.3.1, 3.3.2}

A.1.3 Trends in intensity and frequency of some climate and weather extremes have been detected over time spans during which about 0.5°C of global warming occurred (*medium confidence*). This assessment is based on several lines of evidence, including attribution studies for changes in extremes since 1950. {3.3.1, 3.3.2, 3.3.3}

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1 Decision 1/CP.21, paragraph 21.

2 The assessment covers literature accepted for publication by 15 May 2018.

3 Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not >50–100%, more unlikely than likely 0–<50%, extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, for example, *very likely*. This is consistent with AR5.

4 See also Box SPM.1: Core Concepts Central to this Special Report.

5 Present level of global warming is defined as the average of a 30-year period centred on 2017 assuming the recent rate of warming continues.

6 This range spans the four available peer-reviewed estimates of the observed GMST change and also accounts for additional uncertainty due to possible short-term natural variability. {1.2.1, Table 1.1}

A.2 Warming from anthropogenic emissions from the pre-industrial period to the present will persist for centuries to millennia and will continue to cause further long-term changes in the climate system, such as sea level rise, with associated impacts (*high confidence*), but these emissions alone are *unlikely* to cause global warming of 1.5°C (*medium confidence*). (Figure SPM.1) {1.2, 3.3, Figure 1.5}

A.2.1 Anthropogenic emissions (including greenhouse gases, aerosols and their precursors) up to the present are *unlikely* to cause further warming of more than 0.5°C over the next two to three decades (*high confidence*) or on a century time scale (*medium confidence*). {1.2.4, Figure 1.5}

A.2.2 Reaching and sustaining net zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal time scales (*high confidence*). The maximum temperature reached is then determined by cumulative net global anthropogenic CO_2 emissions up to the time of net zero CO_2 emissions (*high confidence*) and the level of non-CO_2 radiative forcing in the decades prior to the time that maximum temperatures are reached (*medium confidence*). On longer time scales, sustained net negative global anthropogenic CO_2 emissions and/or further reductions in non-CO_2 radiative forcing may still be required to prevent further warming due to Earth system feedbacks and to reverse ocean acidification (*medium confidence*) and will be required to minimize sea level rise (*high confidence*). {Cross-Chapter Box 2 in Chapter 1, 1.2.3, 1.2.4, Figure 1.4, 2.2.1, 2.2.2, 3.4.4.8, 3.4.5.1, 3.6.3.2}

A.3 Climate-related risks for natural and human systems are higher for global warming of 1.5°C than at present, but lower than at 2°C (*high confidence*). These risks depend on the magnitude and rate of warming, geographic location, levels of development and vulnerability, and on the choices and implementation of adaptation and mitigation options (*high confidence*). (Figure SPM.2) {1.3, 3.3, 3.4, 5.6}

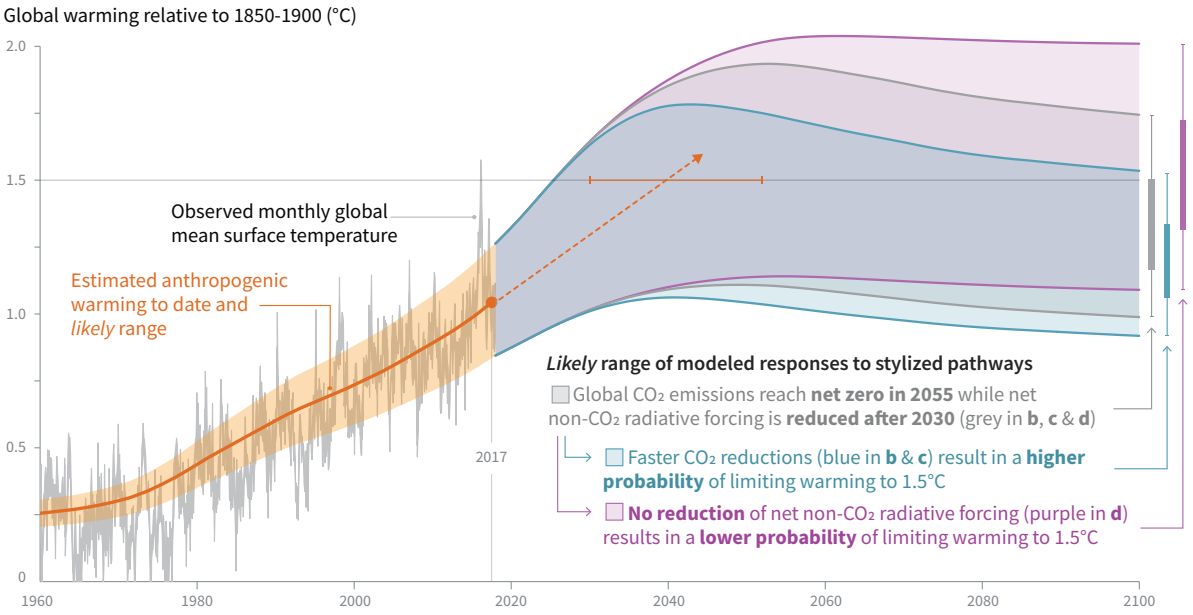
A.3.1 Impacts on natural and human systems from global warming have already been observed (*high confidence*). Many land and ocean ecosystems and some of the services they provide have already changed due to global warming (*high confidence*). (Figure SPM.2) {1.4, 3.4, 3.5}

A.3.2 Future climate-related risks depend on the rate, peak and duration of warming. In the aggregate, they are larger if global warming exceeds 1.5°C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5°C, especially if the peak temperature is high (e.g., about 2°C) (*high confidence*). Some impacts may be long-lasting or irreversible, such as the loss of some ecosystems (*high confidence*). {3.2, 3.4.4, 3.6.3, Cross-Chapter Box 8 in Chapter 3}

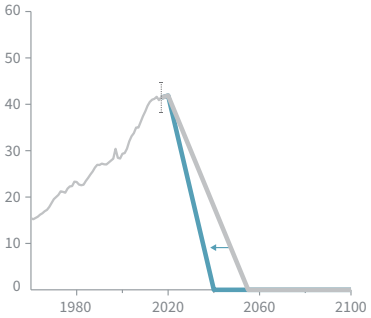
A.3.3 Adaptation and mitigation are already occurring (*high confidence*). Future climate-related risks would be reduced by the upscaling and acceleration of far-reaching, multilevel and cross-sectoral climate mitigation and by both incremental and transformational adaptation (*high confidence*). {1.2, 1.3, Table 3.5, 4.2.2, Cross-Chapter Box 9 in Chapter 4, Box 4.2, Box 4.3, Box 4.6, 4.3.1, 4.3.2, 4.3.3, 4.3.4, 4.3.5, 4.4.1, 4.4.4, 4.4.5, 4.5.3}

Cumulative emissions of CO_2 and future non-CO_2 radiative forcing determine the probability of limiting warming to 1.5°C

a) Observed global temperature change and modeled responses to stylized anthropogenic emission and forcing pathways

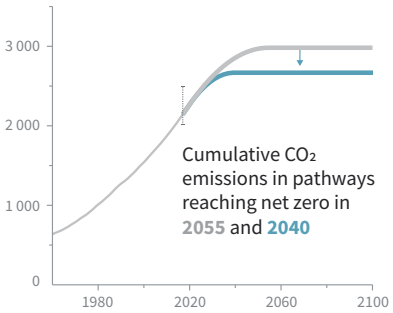


b) Stylized net global CO_2 emission pathways
Billion tonnes CO_2 per year ($GtCO_2$/yr)

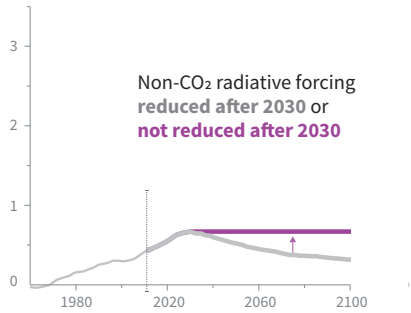


Faster immediate CO_2 emission reductions limit cumulative CO_2 emissions shown in panel **(c)**.

c) Cumulative net CO_2 emissions
Billion tonnes CO_2 ($GtCO_2$)



d) Non-CO_2 radiative forcing pathways
Watts per square metre (W/m^2)



Maximum temperature rise is determined by cumulative net CO_2 emissions and net non-CO_2 radiative forcing due to methane, nitrous oxide, aerosols and other anthropogenic forcing agents.

Figure SPM.1 | Panel a: Observed monthly global mean surface temperature (GMST, grey line up to 2017, from the HadCRUT4, GISTEMP, Cowtan–Way, and NOAA datasets) change and estimated anthropogenic global warming (solid orange line up to 2017, with orange shading indicating assessed *likely* range). Orange dashed arrow and horizontal orange error bar show respectively the central estimate and *likely* range of the time at which 1.5°C is reached if the current rate of warming continues. The grey plume on the right of panel a shows the *likely* range of warming responses, computed with a simple climate model, to a stylized pathway (hypothetical future) in which net CO_2 emissions (grey line in panels b and c) decline in a straight line from 2020 to reach net zero in 2055 and net non-CO_2 radiative forcing (grey line in panel d) increases to 2030 and then declines. The blue plume in panel a) shows the response to faster CO_2 emissions reductions (blue line in panel b), reaching net zero in 2040, reducing cumulative CO_2 emissions (panel c). The purple plume shows the response to net CO_2 emissions declining to zero in 2055, with net non-CO_2 forcing remaining constant after 2030. The vertical error bars on right of panel a) show the *likely* ranges (thin lines) and central terciles (33rd – 66th percentiles, thick lines) of the estimated distribution of warming in 2100 under these three stylized pathways. Vertical dotted error bars in panels b, c and d show the *likely* range of historical annual and cumulative global net CO_2 emissions in 2017 (data from the Global Carbon Project) and of net non-CO_2 radiative forcing in 2011 from AR5, respectively. Vertical axes in panels c and d are scaled to represent approximately equal effects on GMST. {1.2.1, 1.2.3, 1.2.4, 2.3, Figure 1.2 and Chapter 1 Supplementary Material, Cross-Chapter Box 2 in Chapter 1}

B. Projected Climate Change, Potential Impacts and Associated Risks

B.1 Climate models project robust[7] differences in regional climate characteristics between present-day and global warming of 1.5°C,[8] and between 1.5°C and 2°C.[8] These differences include increases in: mean temperature in most land and ocean regions (*high confidence*), hot extremes in most inhabited regions (*high confidence*), heavy precipitation in several regions (*medium confidence*), and the probability of drought and precipitation deficits in some regions (*medium confidence*). {3.3}

B.1.1 Evidence from attributed changes in some climate and weather extremes for a global warming of about 0.5°C supports the assessment that an additional 0.5°C of warming compared to present is associated with further detectable changes in these extremes (*medium confidence*). Several regional changes in climate are assessed to occur with global warming up to 1.5°C compared to pre-industrial levels, including warming of extreme temperatures in many regions (*high confidence*), increases in frequency, intensity, and/or amount of heavy precipitation in several regions (*high confidence*), and an increase in intensity or frequency of droughts in some regions (*medium confidence*). {3.2, 3.3.1, 3.3.2, 3.3.3, 3.3.4, Table 3.2}

B.1.2 Temperature extremes on land are projected to warm more than GMST (*high confidence*): extreme hot days in mid-latitudes warm by up to about 3°C at global warming of 1.5°C and about 4°C at 2°C, and extreme cold nights in high latitudes warm by up to about 4.5°C at 1.5°C and about 6°C at 2°C (*high confidence*). The number of hot days is projected to increase in most land regions, with highest increases in the tropics (*high confidence*). {3.3.1, 3.3.2, Cross-Chapter Box 8 in Chapter 3}

B.1.3 Risks from droughts and precipitation deficits are projected to be higher at 2°C compared to 1.5°C of global warming in some regions (*medium confidence*). Risks from heavy precipitation events are projected to be higher at 2°C compared to 1.5°C of global warming in several northern hemisphere high-latitude and/or high-elevation regions, eastern Asia and eastern North America (*medium confidence)*. Heavy precipitation associated with tropical cyclones is projected to be higher at 2°C compared to 1.5°C global warming (*medium confidence*). There is generally *low confidence* in projected changes in heavy precipitation at 2°C compared to 1.5°C in other regions. Heavy precipitation when aggregated at global scale is projected to be higher at 2°C than at 1.5°C of global warming (*medium confidence*). As a consequence of heavy precipitation, the fraction of the global land area affected by flood hazards is projected to be larger at 2°C compared to 1.5°C of global warming (*medium confidence*). {3.3.1, 3.3.3, 3.3.4, 3.3.5, 3.3.6}

B.2 By 2100, global mean sea level rise is projected to be around 0.1 metre lower with global warming of 1.5°C compared to 2°C (*medium confidence*). Sea level will continue to rise well beyond 2100 (*high confidence*), and the magnitude and rate of this rise depend on future emission pathways. A slower rate of sea level rise enables greater opportunities for adaptation in the human and ecological systems of small islands, low-lying coastal areas and deltas (*medium confidence*). {3.3, 3.4, 3.6}

B.2.1 Model-based projections of global mean sea level rise (relative to 1986–2005) suggest an indicative range of 0.26 to 0.77 m by 2100 for 1.5°C of global warming, 0.1 m (0.04–0.16 m) less than for a global warming of 2°C (*medium confidence*). A reduction of 0.1 m in global sea level rise implies that up to 10 million fewer people would be exposed to related risks, based on population in the year 2010 and assuming no adaptation (*medium confidence*). {3.4.4, 3.4.5, 4.3.2}

B.2.2 Sea level rise will continue beyond 2100 even if global warming is limited to 1.5°C in the 21st century (*high confidence*). Marine ice sheet instability in Antarctica and/or irreversible loss of the Greenland ice sheet could result in multi-metre rise in sea level over hundreds to thousands of years. These instabilities could be triggered at around 1.5°C to 2°C of global warming (*medium confidence*). (Figure SPM.2) {3.3.9, 3.4.5, 3.5.2, 3.6.3, Box 3.3}

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7 Robust is here used to mean that at least two thirds of climate models show the same sign of changes at the grid point scale, and that differences in large regions are statistically significant.

8 Projected changes in impacts between different levels of global warming are determined with respect to changes in global mean surface air temperature.

B.2.3 Increasing warming amplifies the exposure of small islands, low-lying coastal areas and deltas to the risks associated with sea level rise for many human and ecological systems, including increased saltwater intrusion, flooding and damage to infrastructure (*high confidence*). Risks associated with sea level rise are higher at 2°C compared to 1.5°C. The slower rate of sea level rise at global warming of 1.5°C reduces these risks, enabling greater opportunities for adaptation including managing and restoring natural coastal ecosystems and infrastructure reinforcement (*medium confidence*). (Figure SPM.2) {3.4.5, Box 3.5}

B.3 On land, impacts on biodiversity and ecosystems, including species loss and extinction, are projected to be lower at 1.5°C of global warming compared to 2°C. Limiting global warming to 1.5°C compared to 2°C is projected to lower the impacts on terrestrial, freshwater and coastal ecosystems and to retain more of their services to humans (*high confidence*). (Figure SPM.2) {3.4, 3.5, Box 3.4, Box 4.2, Cross-Chapter Box 8 in Chapter 3}

B.3.1 Of 105,000 species studied,[9] 6% of insects, 8% of plants and 4% of vertebrates are projected to lose over half of their climatically determined geographic range for global warming of 1.5°C, compared with 18% of insects, 16% of plants and 8% of vertebrates for global warming of 2°C (*medium confidence*). Impacts associated with other biodiversity-related risks such as forest fires and the spread of invasive species are lower at 1.5°C compared to 2°C of global warming (*high confidence*). {3.4.3, 3.5.2}

B.3.2 Approximately 4% (interquartile range 2–7%) of the global terrestrial land area is projected to undergo a transformation of ecosystems from one type to another at 1°C of global warming, compared with 13% (interquartile range 8–20%) at 2°C (*medium confidence*). This indicates that the area at risk is projected to be approximately 50% lower at 1.5°C compared to 2°C (*medium confidence*). {3.4.3.1, 3.4.3.5}

B.3.3 High-latitude tundra and boreal forests are particularly at risk of climate change-induced degradation and loss, with woody shrubs already encroaching into the tundra (*high confidence*) and this will proceed with further warming. Limiting global warming to 1.5°C rather than 2°C is projected to prevent the thawing over centuries of a permafrost area in the range of 1.5 to 2.5 million km^2 (*medium confidence*). {3.3.2, 3.4.3, 3.5.5}

B.4 Limiting global warming to 1.5°C compared to 2°C is projected to reduce increases in ocean temperature as well as associated increases in ocean acidity and decreases in ocean oxygen levels (*high confidence*). Consequently, limiting global warming to 1.5°C is projected to reduce risks to marine biodiversity, fisheries, and ecosystems, and their functions and services to humans, as illustrated by recent changes to Arctic sea ice and warm-water coral reef ecosystems (*high confidence*). {3.3, 3.4, 3.5, Box 3.4, Box 3.5}

B.4.1 There is *high confidence* that the probability of a sea ice-free Arctic Ocean during summer is substantially lower at global warming of 1.5°C when compared to 2°C. With 1.5°C of global warming, one sea ice-free Arctic summer is projected per century. This likelihood is increased to at least one per decade with 2°C global warming. Effects of a temporary overshoot are reversible for Arctic sea ice cover on decadal time scales (*high confidence*). {3.3.8, 3.4.4.7}

B.4.2 Global warming of 1.5°C is projected to shift the ranges of many marine species to higher latitudes as well as increase the amount of damage to many ecosystems. It is also expected to drive the loss of coastal resources and reduce the productivity of fisheries and aquaculture (especially at low latitudes). The risks of climate-induced impacts are projected to be higher at 2°C than those at global warming of 1.5°C (*high confidence*). Coral reefs, for example, are projected to decline by a further 70–90% at 1.5°C (*high confidence*) with larger losses (>99%) at 2°C (*very high confidence*). The risk of irreversible loss of many marine and coastal ecosystems increases with global warming, especially at 2°C or more (*high confidence*). {3.4.4, Box 3.4}

9 Consistent with earlier studies, illustrative numbers were adopted from one recent meta-study.

B.4.3 The level of ocean acidification due to increasing CO_2 concentrations associated with global warming of 1.5°C is projected to amplify the adverse effects of warming, and even further at 2°C, impacting the growth, development, calcification, survival, and thus abundance of a broad range of species, for example, from algae to fish (*high confidence*). {3.3.10, 3.4.4}

B.4.4 Impacts of climate change in the ocean are increasing risks to fisheries and aquaculture via impacts on the physiology, survivorship, habitat, reproduction, disease incidence, and risk of invasive species (*medium confidence*) but are projected to be less at 1.5°C of global warming than at 2°C. One global fishery model, for example, projected a decrease in global annual catch for marine fisheries of about 1.5 million tonnes for 1.5°C of global warming compared to a loss of more than 3 million tonnes for 2°C of global warming (*medium confidence*). {3.4.4, Box 3.4}

B.5 Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C. (Figure SPM.2) {3.4, 3.5, 5.2, Box 3.2, Box 3.3, Box 3.5, Box 3.6, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5, 5.2}

B.5.1 Populations at disproportionately higher risk of adverse consequences with global warming of 1.5°C and beyond include disadvantaged and vulnerable populations, some indigenous peoples, and local communities dependent on agricultural or coastal livelihoods (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small island developing states, and Least Developed Countries (*high confidence*). Poverty and disadvantage are expected to increase in some populations as global warming increases; limiting global warming to 1.5°C, compared with 2°C, could reduce the number of people both exposed to climate-related risks and susceptible to poverty by up to several hundred million by 2050 (*medium confidence*). {3.4.10, 3.4.11, Box 3.5, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5, 4.2.2.2, 5.2.1, 5.2.2, 5.2.3, 5.6.3}

B.5.2 Any increase in global warming is projected to affect human health, with primarily negative consequences (*high confidence*). Lower risks are projected at 1.5°C than at 2°C for heat-related morbidity and mortality (*very high confidence*) and for ozone-related mortality if emissions needed for ozone formation remain high (*high confidence*). Urban heat islands often amplify the impacts of heatwaves in cities (*high confidence*). Risks from some vector-borne diseases, such as malaria and dengue fever, are projected to increase with warming from 1.5°C to 2°C, including potential shifts in their geographic range (*high confidence*). {3.4.7, 3.4.8, 3.5.5.8}

B.5.3 Limiting warming to 1.5°C compared with 2°C is projected to result in smaller net reductions in yields of maize, rice, wheat, and potentially other cereal crops, particularly in sub-Saharan Africa, Southeast Asia, and Central and South America, and in the CO_2-dependent nutritional quality of rice and wheat (*high confidence*). Reductions in projected food availability are larger at 2°C than at 1.5°C of global warming in the Sahel, southern Africa, the Mediterranean, central Europe, and the Amazon (*medium confidence*). Livestock are projected to be adversely affected with rising temperatures, depending on the extent of changes in feed quality, spread of diseases, and water resource availability (*high confidence*). {3.4.6, 3.5.4, 3.5.5, Box 3.1, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4}

B.5.4 Depending on future socio-economic conditions, limiting global warming to 1.5°C compared to 2°C may reduce the proportion of the world population exposed to a climate change-induced increase in water stress by up to 50%, although there is considerable variability between regions (*medium confidence*). Many small island developing states could experience lower water stress as a result of projected changes in aridity when global warming is limited to 1.5°C, as compared to 2°C (*medium confidence*). {3.3.5, 3.4.2, 3.4.8, 3.5.5, Box 3.2, Box 3.5, Cross-Chapter Box 9 in Chapter 4}

B.5.5 Risks to global aggregated economic growth due to climate change impacts are projected to be lower at 1.5°C than at 2°C by the end of this century[10] (*medium confidence*). This excludes the costs of mitigation, adaptation investments and the benefits of adaptation. Countries in the tropics and Southern Hemisphere subtropics are projected to experience the largest impacts on economic growth due to climate change should global warming increase from 1.5°C to 2°C (*medium confidence*). {3.5.2, 3.5.3}

10 Here, impacts on economic growth refer to changes in gross domestic product (GDP). Many impacts, such as loss of human lives, cultural heritage and ecosystem services, are difficult to value and monetize.

B.5.6 Exposure to multiple and compound climate-related risks increases between 1.5°C and 2°C of global warming, with greater proportions of people both so exposed and susceptible to poverty in Africa and Asia (*high confidence*). For global warming from 1.5°C to 2°C, risks across energy, food, and water sectors could overlap spatially and temporally, creating new and exacerbating current hazards, exposures, and vulnerabilities that could affect increasing numbers of people and regions (*medium confidence*). {Box 3.5, 3.3.1, 3.4.5.3, 3.4.5.6, 3.4.11, 3.5.4.9}

B.5.7 There are multiple lines of evidence that since AR5 the assessed levels of risk increased for four of the five Reasons for Concern (RFCs) for global warming to 2°C (*high confidence*). The risk transitions by degrees of global warming are now: from high to very high risk between 1.5°C and 2°C for RFC1 (Unique and threatened systems) (*high confidence*); from moderate to high risk between 1°C and 1.5°C for RFC2 (Extreme weather events) (*medium confidence*); from moderate to high risk between 1.5°C and 2°C for RFC3 (Distribution of impacts) (*high confidence*); from moderate to high risk between 1.5°C and 2.5°C for RFC4 (Global aggregate impacts) (*medium confidence*); and from moderate to high risk between 1°C and 2.5°C for RFC5 (Large-scale singular events) (*medium confidence*). (Figure SPM.2) {3.4.13; 3.5, 3.5.2}

B.6 Most adaptation needs will be lower for global warming of 1.5°C compared to 2°C (*high confidence*). There are a wide range of adaptation options that can reduce the risks of climate change (*high confidence*). There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5°C, with associated losses (*medium confidence*). The number and availability of adaptation options vary by sector (*medium confidence*). {Table 3.5, 4.3, 4.5, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5}

B.6.1 A wide range of adaptation options are available to reduce the risks to natural and managed ecosystems (e.g., ecosystem-based adaptation, ecosystem restoration and avoided degradation and deforestation, biodiversity management, sustainable aquaculture, and local knowledge and indigenous knowledge), the risks of sea level rise (e.g., coastal defence and hardening), and the risks to health, livelihoods, food, water, and economic growth, especially in rural landscapes (e.g., efficient irrigation, social safety nets, disaster risk management, risk spreading and sharing, and community-based adaptation) and urban areas (e.g., green infrastructure, sustainable land use and planning, and sustainable water management) (*medium confidence*). {4.3.1, 4.3.2, 4.3.3, 4.3.5, 4.5.3, 4.5.4, 5.3.2, Box 4.2, Box 4.3, Box 4.6, Cross-Chapter Box 9 in Chapter 4}.

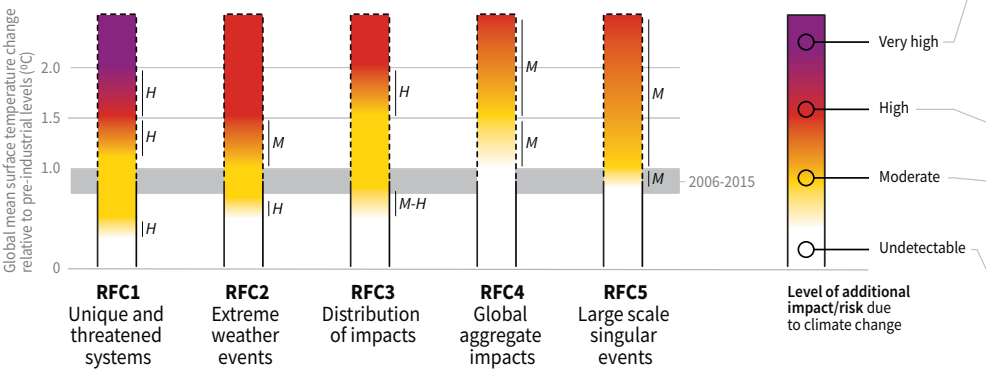
B.6.2 Adaptation is expected to be more challenging for ecosystems, food and health systems at 2°C of global warming than for 1.5°C (*medium confidence*). Some vulnerable regions, including small islands and Least Developed Countries, are projected to experience high multiple interrelated climate risks even at global warming of 1.5°C (*high confidence*). {3.3.1, 3.4.5, Box 3.5, Table 3.5, Cross-Chapter Box 9 in Chapter 4, 5.6, Cross-Chapter Box 12 in Chapter 5, Box 5.3}

B.6.3 Limits to adaptive capacity exist at 1.5°C of global warming, become more pronounced at higher levels of warming and vary by sector, with site-specific implications for vulnerable regions, ecosystems and human health (*medium confidence*). {Cross-Chapter Box 12 in Chapter 5, Box 3.5, Table 3.5}

How the level of global warming affects impacts and/or risks associated with the Reasons for Concern (RFCs) and selected natural, managed and human systems

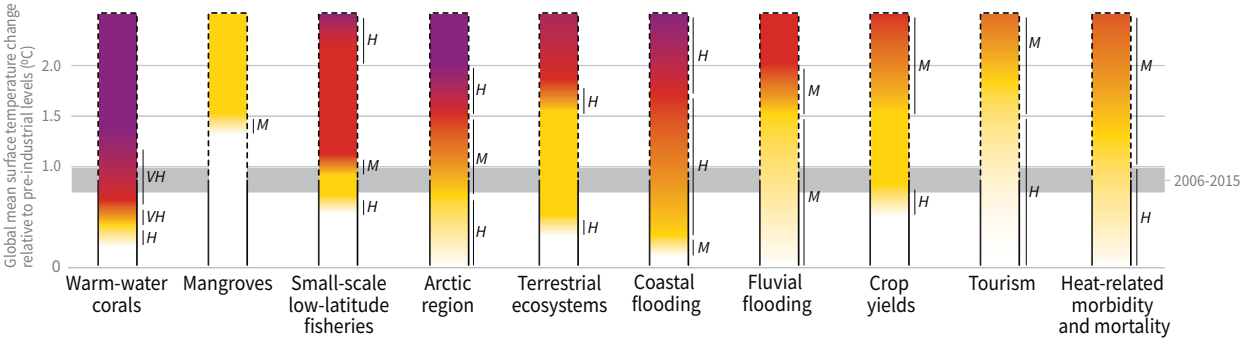
Five Reasons For Concern (RFCs) illustrate the impacts and risks of different levels of global warming for people, economies and ecosystems across sectors and regions.

Impacts and risks associated with the Reasons for Concern (RFCs)



Purple indicates very high risks of severe impacts/risks and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks.
Red indicates severe and widespread impacts/risks.
Yellow indicates that impacts/risks are detectable and attributable to climate change with at least medium confidence.
White indicates that no impacts are detectable and attributable to climate change.

Impacts and risks for selected natural, managed and human systems



Confidence level for transition: *L*=Low, *M*=Medium, *H*=High and *VH*=Very high

Figure SPM.2 | Five integrative reasons for concern (RFCs) provide a framework for summarizing key impacts and risks across sectors and regions, and were introduced in the IPCC Third Assessment Report. RFCs illustrate the implications of global warming for people, economies and ecosystems. Impacts and/or risks for each RFC are based on assessment of the new literature that has appeared. As in AR5, this literature was used to make expert judgments to assess the levels of global warming at which levels of impact and/or risk are undetectable, moderate, high or very high. The selection of impacts and risks to natural, managed and human systems in the lower panel is illustrative and is not intended to be fully comprehensive. {3.4, 3.5, 3.5.2.1, 3.5.2.2, 3.5.2.3, 3.5.2.4, 3.5.2.5, 5.4.1, 5.5.3, 5.6.1, Box 3.4}

RFC1 Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its indigenous people, mountain glaciers and biodiversity hotspots.
RFC2 Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heat waves, heavy rain, drought and associated wildfires, and coastal flooding.
RFC3 Distribution of impacts: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability.
RFC4 Global aggregate impacts: global monetary damage, global-scale degradation and loss of ecosystems and biodiversity.
RFC5 Large-scale singular events: are relatively large, abrupt and sometimes irreversible changes in systems that are caused by global warming. Examples include disintegration of the Greenland and Antarctic ice sheets.

C. Emission Pathways and System Transitions Consistent with 1.5°C Global Warming

C.1 In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range). For limiting global warming to below 2°C[11] CO_2 emissions are projected to decline by about 25% by 2030 in most pathways (10–30% interquartile range) and reach net zero around 2070 (2065–2080 interquartile range). Non-CO_2 emissions in pathways that limit global warming to 1.5°C show deep reductions that are similar to those in pathways limiting warming to 2°C. (*high confidence*) (Figure SPM.3a) {2.1, 2.3, Table 2.4}

C.1.1 CO_2 emissions reductions that limit global warming to 1.5°C with no or limited overshoot can involve different portfolios of mitigation measures, striking different balances between lowering energy and resource intensity, rate of decarbonization, and the reliance on carbon dioxide removal. Different portfolios face different implementation challenges and potential synergies and trade-offs with sustainable development. (*high confidence*) (Figure SPM.3b) {2.3.2, 2.3.4, 2.4, 2.5.3}

C.1.2 Modelled pathways that limit global warming to 1.5°C with no or limited overshoot involve deep reductions in emissions of methane and black carbon (35% or more of both by 2050 relative to 2010). These pathways also reduce most of the cooling aerosols, which partially offsets mitigation effects for two to three decades. Non-CO_2 emissions[12] can be reduced as a result of broad mitigation measures in the energy sector. In addition, targeted non-CO_2 mitigation measures can reduce nitrous oxide and methane from agriculture, methane from the waste sector, some sources of black carbon, and hydrofluorocarbons. High bioenergy demand can increase emissions of nitrous oxide in some 1.5°C pathways, highlighting the importance of appropriate management approaches. Improved air quality resulting from projected reductions in many non-CO_2 emissions provide direct and immediate population health benefits in all 1.5°C model pathways. (*high confidence*) (Figure SPM.3a) {2.2.1, 2.3.3, 2.4.4, 2.5.3, 4.3.6, 5.4.2}

C.1.3 Limiting global warming requires limiting the total cumulative global anthropogenic emissions of CO_2 since the pre-industrial period, that is, staying within a total carbon budget (*high confidence*).[13] By the end of 2017, anthropogenic CO_2 emissions since the pre-industrial period are estimated to have reduced the total carbon budget for 1.5°C by approximately 2200 ± 320 $GtCO_2$ (*medium confidence*). The associated remaining budget is being depleted by current emissions of 42 ± 3 $GtCO_2$ per year (*high confidence*). The choice of the measure of global temperature affects the estimated remaining carbon budget. Using global mean surface air temperature, as in AR5, gives an estimate of the remaining carbon budget of 580 $GtCO_2$ for a 50% probability of limiting warming to 1.5°C, and 420 $GtCO_2$ for a 66% probability (*medium confidence*).[14] Alternatively, using GMST gives estimates of 770 and 570 $GtCO_2$, for 50% and 66% probabilities,[15] respectively (*medium confidence*). Uncertainties in the size of these estimated remaining carbon budgets are substantial and depend on several factors. Uncertainties in the climate response to CO_2 and non-CO_2 emissions contribute ±400 $GtCO_2$ and the level of historic warming contributes ±250 $GtCO_2$ (*medium confidence*). Potential additional carbon release from future permafrost thawing and methane release from wetlands would reduce budgets by up to 100 $GtCO_2$ over the course of this century and more thereafter (*medium confidence*). In addition, the level of non-CO_2 mitigation in the future could alter the remaining carbon budget by 250 $GtCO_2$ in either direction (*medium confidence*). {1.2.4, 2.2.2, 2.6.1, Table 2.2, Chapter 2 Supplementary Material}

C.1.4 Solar radiation modification (SRM) measures are not included in any of the available assessed pathways. Although some SRM measures may be theoretically effective in reducing an overshoot, they face large uncertainties and knowledge gaps

11 References to pathways limiting global warming to 2°C are based on a 66% probability of staying below 2°C.

12 Non-CO_2 emissions included in this Report are all anthropogenic emissions other than CO_2 that result in radiative forcing. These include short-lived climate forcers, such as methane, some fluorinated gases, ozone precursors, aerosols or aerosol precursors, such as black carbon and sulphur dioxide, respectively, as well as long-lived greenhouse gases, such as nitrous oxide or some fluorinated gases. The radiative forcing associated with non-CO_2 emissions and changes in surface albedo is referred to as non-CO_2 radiative forcing. {2.2.1}

13 There is a clear scientific basis for a total carbon budget consistent with limiting global warming to 1.5°C. However, neither this total carbon budget nor the fraction of this budget taken up by past emissions were assessed in this Report.

14 Irrespective of the measure of global temperature used, updated understanding and further advances in methods have led to an increase in the estimated remaining carbon budget of about 300 $GtCO_2$ compared to AR5. (*medium confidence*) {2.2.2}

15 These estimates use observed GMST to 2006–2015 and estimate future temperature changes using near surface air temperatures.

as well as substantial risks and institutional and social constraints to deployment related to governance, ethics, and impacts on sustainable development. They also do not mitigate ocean acidification. (*medium confidence*) {4.3.8, Cross-Chapter Box 10 in Chapter 4}

Global emissions pathway characteristics

General characteristics of the evolution of anthropogenic net emissions of CO_2, and total emissions of methane, black carbon, and nitrous oxide in model pathways that limit global warming to 1.5°C with no or limited overshoot. Net emissions are defined as anthropogenic emissions reduced by anthropogenic removals. Reductions in net emissions can be achieved through different portfolios of mitigation measures illustrated in Figure SPM.3b.

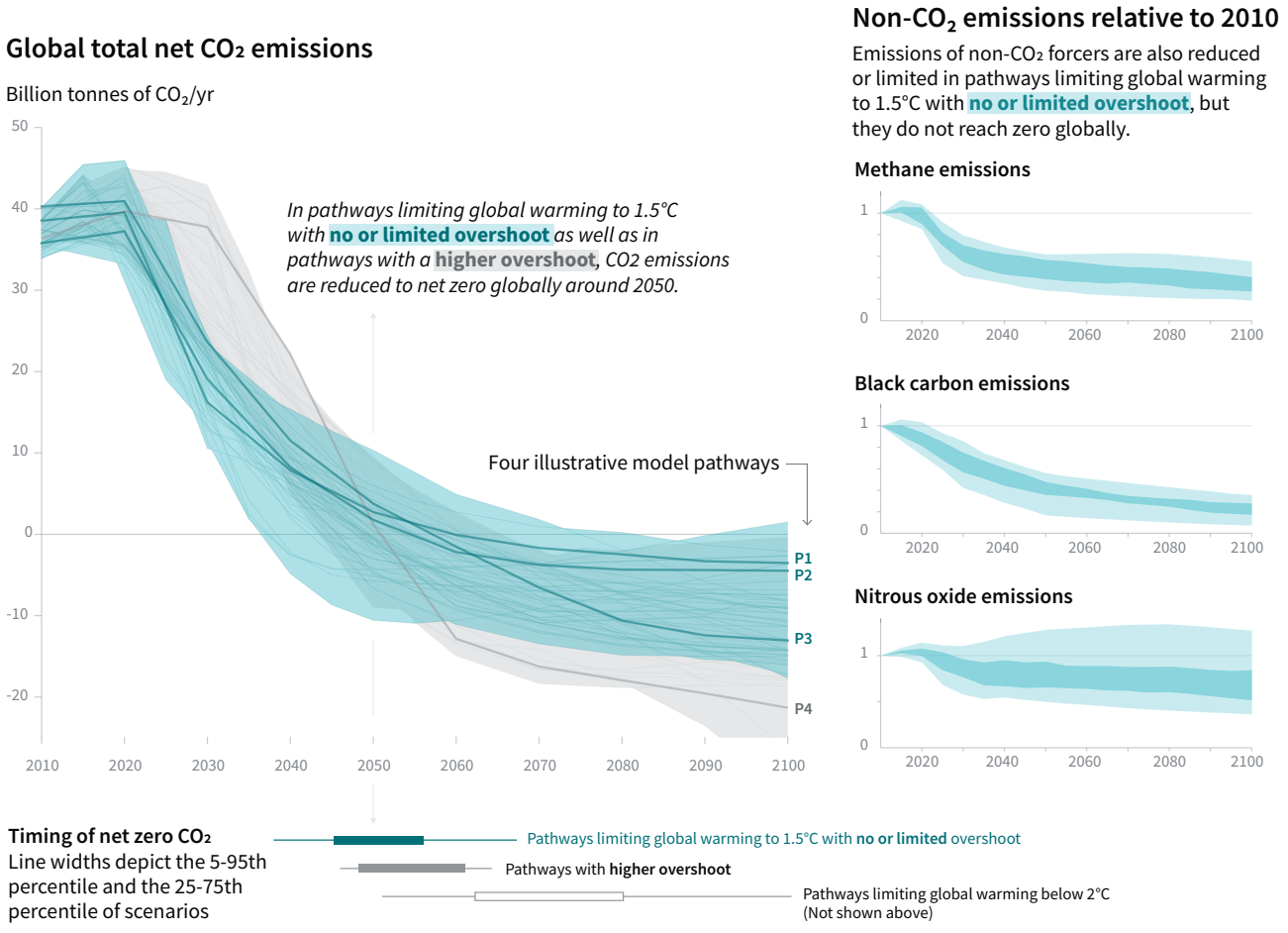
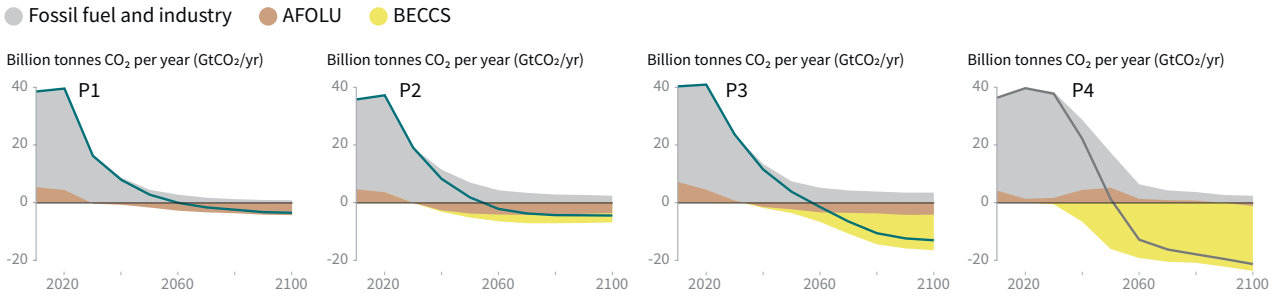


Figure SPM.3a | Global emissions pathway characteristics. The main panel shows global net anthropogenic CO_2 emissions in pathways limiting global warming to 1.5°C with no or limited (less than 0.1°C) overshoot and pathways with higher overshoot. The shaded area shows the full range for pathways analysed in this Report. The panels on the right show non-CO_2 emissions ranges for three compounds with large historical forcing and a substantial portion of emissions coming from sources distinct from those central to CO_2 mitigation. Shaded areas in these panels show the 5–95% (light shading) and interquartile (dark shading) ranges of pathways limiting global warming to 1.5°C with no or limited overshoot. Box and whiskers at the bottom of the figure show the timing of pathways reaching global net zero CO_2 emission levels, and a comparison with pathways limiting global warming to 2°C with at least 66% probability. Four illustrative model pathways are highlighted in the main panel and are labelled P1, P2, P3 and P4, corresponding to the LED, S1, S2, and S5 pathways assessed in Chapter 2. Descriptions and characteristics of these pathways are available in Figure SPM.3b. {2.1, 2.2, 2.3, Figure 2.5, Figure 2.10, Figure 2.11}

Characteristics of four illustrative model pathways

Different mitigation strategies can achieve the net emissions reductions that would be required to follow a pathway that limits global warming to 1.5°C with no or limited overshoot. All pathways use Carbon Dioxide Removal (CDR), but the amount varies across pathways, as do the relative contributions of Bioenergy with Carbon Capture and Storage (BECCS) and removals in the Agriculture, Forestry and Other Land Use (AFOLU) sector. This has implications for emissions and several other pathway characteristics.

Breakdown of contributions to global net CO_2 emissions in four illustrative model pathways



P1: A scenario in which social, business and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A downsized energy system enables rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource- and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas-intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

Global indicators	P1	P2	P3	P4	**Interquartile range**
Pathway classification	No or limited overshoot	No or limited overshoot	No or limited overshoot	Higher overshoot	No or limited overshoot
CO_2 emission change in 2030 (% rel to 2010)	-58	-47	-41	4	(-58,-40)
↳ in 2050 (% rel to 2010)	-93	-95	-91	-97	(-107,-94)
Kyoto-GHG emissions in 2030 (% rel to 2010)*	-50	-49	-35	-2	(-51,-39)
↳ in 2050 (% rel to 2010)	-82	-89	-78	-80	(-93,-81)
*Final energy demand** in 2030 (% rel to 2010)*	-15	-5	17	39	(-12,7)
↳ in 2050 (% rel to 2010)	-32	2	21	44	(-11,22)
Renewable share in electricity in 2030 (%)	60	58	48	25	(47,65)
↳ in 2050 (%)	77	81	63	70	(69,86)
Primary energy from coal in 2030 (% rel to 2010)	-78	-61	-75	-59	(-78, -59)
↳ in 2050 (% rel to 2010)	-97	-77	-73	-97	(-95, -74)
from oil in 2030 (% rel to 2010)	-37	-13	-3	86	(-34,3)
↳ in 2050 (% rel to 2010)	-87	-50	-81	-32	(-78,-31)
from gas in 2030 (% rel to 2010)	-25	-20	33	37	(-26,21)
↳ in 2050 (% rel to 2010)	-74	-53	21	-48	(-56,6)
from nuclear in 2030 (% rel to 2010)	59	83	98	106	(44,102)
↳ in 2050 (% rel to 2010)	150	98	501	468	(91,190)
from biomass in 2030 (% rel to 2010)	-11	0	36	-1	(29,80)
↳ in 2050 (% rel to 2010)	-16	49	121	418	(123,261)
from non-biomass renewables in 2030 (% rel to 2010)	430	470	315	110	(245,436)
↳ in 2050 (% rel to 2010)	833	1327	878	1137	(576,1299)
Cumulative CCS until 2100 ($GtCO_2$)	0	348	687	1218	(550,1017)
↳ of which BECCS ($GtCO_2$)	0	151	414	1191	(364,662)
Land area of bioenergy crops in 2050 (million km^2)	0.2	0.9	2.8	7.2	(1.5,3.2)
Agricultural CH_4 emissions in 2030 (% rel to 2010)	-24	-48	1	14	(-30,-11)
in 2050 (% rel to 2010)	-33	-69	-23	2	(-47,-24)
Agricultural N_2O emissions in 2030 (% rel to 2010)	5	-26	15	3	(-21,3)
in 2050 (% rel to 2010)	6	-26	0	39	(-26,1)

NOTE: Indicators have been selected to show global trends identified by the Chapter 2 assessment. National and sectoral characteristics can differ substantially from the global trends shown above.

** Kyoto-gas emissions are based on IPCC Second Assessment Report GWP-100*
*** Changes in energy demand are associated with improvements in energy efficiency and behaviour change*

Figure SPM.3b | Characteristics of four illustrative model pathways in relation to global warming of 1.5°C introduced in Figure SPM.3a. These pathways were selected to show a range of potential mitigation approaches and vary widely in their projected energy and land use, as well as their assumptions about future socio-economic developments, including economic and population growth, equity and sustainability. A breakdown of the global net anthropogenic CO_2 emissions into the contributions in terms of CO_2 emissions from fossil fuel and industry; agriculture, forestry and other land use (AFOLU); and bioenergy with carbon capture and storage (BECCS) is shown. AFOLU estimates reported here are not necessarily comparable with countries' estimates. Further characteristics for each of these pathways are listed below each pathway. These pathways illustrate relative global differences in mitigation strategies, but do not represent central estimates, national strategies, and do not indicate requirements. For comparison, the right-most column shows the interquartile ranges across pathways with no or limited overshoot of 1.5°C. Pathways P1, P2, P3 and P4 correspond to the LED, S1, S2 and S5 pathways assessed in Chapter 2 (Figure SPM.3a). {2.2.1, 2.3.1, 2.3.2, 2.3.3, 2.3.4, 2.4.1, 2.4.2, 2.4.4, 2.5.3, Figure 2.5, Figure 2.6, Figure 2.9, Figure 2.10, Figure 2.11, Figure 2.14, Figure 2.15, Figure 2.16, Figure 2.17, Figure 2.24, Figure 2.25, Table 2.4, Table 2.6, Table 2.7, Table 2.9, Table 4.1}

C.2 Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (*high confidence*). These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (*medium confidence*). {2.3, 2.4, 2.5, 4.2, 4.3, 4.4, 4.5}

C.2.1 Pathways that limit global warming to 1.5°C with no or limited overshoot show system changes that are more rapid and pronounced over the next two decades than in 2°C pathways (*high confidence*). The rates of system changes associated with limiting global warming to 1.5°C with no or limited overshoot have occurred in the past within specific sectors, technologies and spatial contexts, but there is no documented historic precedent for their scale (*medium confidence*). {2.3.3, 2.3.4, 2.4, 2.5, 4.2.1, 4.2.2, Cross-Chapter Box 11 in Chapter 4}

C.2.2 In energy systems, modelled global pathways (considered in the literature) limiting global warming to 1.5°C with no or limited overshoot (for more details see Figure SPM.3b) generally meet energy service demand with lower energy use, including through enhanced energy efficiency, and show faster electrification of energy end use compared to 2°C (*high confidence*). In 1.5°C pathways with no or limited overshoot, low-emission energy sources are projected to have a higher share, compared with 2°C pathways, particularly before 2050 (*high confidence*). In 1.5°C pathways with no or limited overshoot, renewables are projected to supply 70–85% (interquartile range) of electricity in 2050 (*high confidence*). In electricity generation, shares of nuclear and fossil fuels with carbon dioxide capture and storage (CCS) are modelled to increase in most 1.5°C pathways with no or limited overshoot. In modelled 1.5°C pathways with limited or no overshoot, the use of CCS would allow the electricity generation share of gas to be approximately 8% (3–11% interquartile range) of global electricity in 2050, while the use of coal shows a steep reduction in all pathways and would be reduced to close to 0% (0–2% interquartile range) of electricity (*high confidence*). While acknowledging the challenges, and differences between the options and national circumstances, political, economic, social and technical feasibility of solar energy, wind energy and electricity storage technologies have substantially improved over the past few years (*high confidence*). These improvements signal a potential system transition in electricity generation. (Figure SPM.3b) {2.4.1, 2.4.2, Figure 2.1, Table 2.6, Table 2.7, Cross-Chapter Box 6 in Chapter 3, 4.2.1, 4.3.1, 4.3.3, 4.5.2}

C.2.3 CO_2 emissions from industry in pathways limiting global warming to 1.5°C with no or limited overshoot are projected to be about 65–90% (interquartile range) lower in 2050 relative to 2010, as compared to 50–80% for global warming of 2°C (*medium confidence*). Such reductions can be achieved through combinations of new and existing technologies and practices, including electrification, hydrogen, sustainable bio-based feedstocks, product substitution, and carbon capture, utilization and storage (CCUS). These options are technically proven at various scales but their large-scale deployment may be limited by economic, financial, human capacity and institutional constraints in specific contexts, and specific characteristics of large-scale industrial installations. In industry, emissions reductions by energy and process efficiency by themselves are insufficient for limiting warming to 1.5°C with no or limited overshoot (*high confidence*). {2.4.3, 4.2.1, Table 4.1, Table 4.3, 4.3.3, 4.3.4, 4.5.2}

C.2.4 The urban and infrastructure system transition consistent with limiting global warming to 1.5°C with no or limited overshoot would imply, for example, changes in land and urban planning practices, as well as deeper emissions reductions in transport and buildings compared to pathways that limit global warming below 2°C (*medium confidence*). Technical measures

and practices enabling deep emissions reductions include various energy efficiency options. In pathways limiting global warming to 1.5°C with no or limited overshoot, the electricity share of energy demand in buildings would be about 55–75% in 2050 compared to 50–70% in 2050 for 2°C global warming (*medium confidence*). In the transport sector, the share of low-emission final energy would rise from less than 5% in 2020 to about 35–65% in 2050 compared to 25–45% for 2°C of global warming (*medium confidence*). Economic, institutional and socio-cultural barriers may inhibit these urban and infrastructure system transitions, depending on national, regional and local circumstances, capabilities and the availability of capital (*high confidence*). {2.3.4, 2.4.3, 4.2.1, Table 4.1, 4.3.3, 4.5.2}

C.2.5 Transitions in global and regional land use are found in all pathways limiting global warming to 1.5°C with no or limited overshoot, but their scale depends on the pursued mitigation portfolio. Model pathways that limit global warming to 1.5°C with no or limited overshoot project a 4 million km^2 reduction to a 2.5 million km^2 increase of non-pasture agricultural land for food and feed crops and a 0.5–11 million km^2 reduction of pasture land, to be converted into a 0–6 million km^2 increase of agricultural land for energy crops and a 2 million km^2 reduction to 9.5 million km^2 increase in forests by 2050 relative to 2010 (*medium confidence*).[16] Land-use transitions of similar magnitude can be observed in modelled 2°C pathways (*medium confidence*). Such large transitions pose profound challenges for sustainable management of the various demands on land for human settlements, food, livestock feed, fibre, bioenergy, carbon storage, biodiversity and other ecosystem services (*high confidence*). Mitigation options limiting the demand for land include sustainable intensification of land-use practices, ecosystem restoration and changes towards less resource-intensive diets (*high confidence*). The implementation of land-based mitigation options would require overcoming socio-economic, institutional, technological, financing and environmental barriers that differ across regions (*high confidence*). {2.4.4, Figure 2.24, 4.3.2, 4.3.7, 4.5.2, Cross-Chapter Box 7 in Chapter 3}

C.2.6 Additional annual average energy-related investments for the period 2016 to 2050 in pathways limiting warming to 1.5°C compared to pathways without new climate policies beyond those in place today are estimated to be around 830 billion USD2010 (range of 150 billion to 1700 billion USD2010 across six models[17]). This compares to total annual average energy supply investments in 1.5°C pathways of 1460 to 3510 billion USD2010 and total annual average energy demand investments of 640 to 910 billion USD2010 for the period 2016 to 2050. Total energy-related investments increase by about 12% (range of 3% to 24%) in 1.5°C pathways relative to 2°C pathways. Annual investments in low-carbon energy technologies and energy efficiency are upscaled by roughly a factor of six (range of factor of 4 to 10) by 2050 compared to 2015 (*medium confidence*). {2.5.2, Box 4.8, Figure 2.27}

C.2.7 Modelled pathways limiting global warming to 1.5°C with no or limited overshoot project a wide range of global average discounted marginal abatement costs over the 21st century. They are roughly 3-4 times higher than in pathways limiting global warming to below 2°C (*high confidence*). The economic literature distinguishes marginal abatement costs from total mitigation costs in the economy. The literature on total mitigation costs of 1.5°C mitigation pathways is limited and was not assessed in this Report. Knowledge gaps remain in the integrated assessment of the economy-wide costs and benefits of mitigation in line with pathways limiting warming to 1.5°C. {2.5.2; 2.6; Figure 2.26}

16 The projected land-use changes presented are not deployed to their upper limits simultaneously in a single pathway.

17 Including two pathways limiting warming to 1.5°C with no or limited overshoot and four pathways with higher overshoot.

C.3 All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the 21st century. CDR would be used to compensate for residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5°C following a peak (*high confidence*). CDR deployment of several hundreds of $GtCO_2$ is subject to multiple feasibility and sustainability constraints (*high confidence*). Significant near-term emissions reductions and measures to lower energy and land demand can limit CDR deployment to a few hundred $GtCO_2$ without reliance on bioenergy with carbon capture and storage (BECCS) (*high confidence*). {2.3, 2.4, 3.6.2, 4.3, 5.4}

C.3.1 Existing and potential CDR measures include afforestation and reforestation, land restoration and soil carbon sequestration, BECCS, direct air carbon capture and storage (DACCS), enhanced weathering and ocean alkalinization. These differ widely in terms of maturity, potentials, costs, risks, co-benefits and trade-offs (*high confidence*). To date, only a few published pathways include CDR measures other than afforestation and BECCS. {2.3.4, 3.6.2, 4.3.2, 4.3.7}

C.3.2 In pathways limiting global warming to 1.5°C with limited or no overshoot, BECCS deployment is projected to range from 0–1, 0–8, and 0–16 $GtCO_2\ yr^{-1}$ in 2030, 2050, and 2100, respectively, while agriculture, forestry and land-use (AFOLU) related CDR measures are projected to remove 0–5, 1–11, and 1–5 $GtCO_2\ yr^{-1}$ in these years (*medium confidence*). The upper end of these deployment ranges by mid-century exceeds the BECCS potential of up to 5 $GtCO_2\ yr^{-1}$ and afforestation potential of up to 3.6 $GtCO_2\ yr^{-1}$ assessed based on recent literature (*medium confidence*). Some pathways avoid BECCS deployment completely through demand-side measures and greater reliance on AFOLU-related CDR measures (*medium confidence*). The use of bioenergy can be as high or even higher when BECCS is excluded compared to when it is included due to its potential for replacing fossil fuels across sectors (*high confidence*). (Figure SPM.3b) {2.3.3, 2.3.4, 2.4.2, 3.6.2, 4.3.1, 4.2.3, 4.3.2, 4.3.7, 4.4.3, Table 2.4}

C.3.3 Pathways that overshoot 1.5°C of global warming rely on CDR exceeding residual CO_2 emissions later in the century to return to below 1.5°C by 2100, with larger overshoots requiring greater amounts of CDR (Figure SPM.3b) (*high confidence*). Limitations on the speed, scale, and societal acceptability of CDR deployment hence determine the ability to return global warming to below 1.5°C following an overshoot. Carbon cycle and climate system understanding is still limited about the effectiveness of net negative emissions to reduce temperatures after they peak (*high confidence*). {2.2, 2.3.4, 2.3.5, 2.6, 4.3.7, 4.5.2, Table 4.11}

C.3.4 Most current and potential CDR measures could have significant impacts on land, energy, water or nutrients if deployed at large scale (*high confidence*). Afforestation and bioenergy may compete with other land uses and may have significant impacts on agricultural and food systems, biodiversity, and other ecosystem functions and services (*high confidence*). Effective governance is needed to limit such trade-offs and ensure permanence of carbon removal in terrestrial, geological and ocean reservoirs (*high confidence*). Feasibility and sustainability of CDR use could be enhanced by a portfolio of options deployed at substantial, but lesser scales, rather than a single option at very large scale (*high confidence*). (Figure SPM.3b) {2.3.4, 2.4.4, 2.5.3, 2.6, 3.6.2, 4.3.2, 4.3.7, 4.5.2, 5.4.1, 5.4.2; Cross-Chapter Boxes 7 and 8 in Chapter 3, Table 4.11, Table 5.3, Figure 5.3}

C.3.5 Some AFOLU-related CDR measures such as restoration of natural ecosystems and soil carbon sequestration could provide co-benefits such as improved biodiversity, soil quality, and local food security. If deployed at large scale, they would require governance systems enabling sustainable land management to conserve and protect land carbon stocks and other ecosystem functions and services (*medium confidence*). (Figure SPM.4) {2.3.3, 2.3.4, 2.4.2, 2.4.4, 3.6.2, 5.4.1, Cross-Chapter Boxes 3 in Chapter 1 and 7 in Chapter 3, 4.3.2, 4.3.7, 4.4.1, 4.5.2, Table 2.4}

D. Strengthening the Global Response in the Context of Sustainable Development and Efforts to Eradicate Poverty

D.1 Estimates of the global emissions outcome of current nationally stated mitigation ambitions as submitted under the Paris Agreement would lead to global greenhouse gas emissions[18] in 2030 of 52–58 $GtCO_2eq\ yr^{-1}$ (*medium confidence*). Pathways reflecting these ambitions would not limit global warming to 1.5°C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030 (*high confidence*). Avoiding overshoot and reliance on future large-scale deployment of carbon dioxide removal (CDR) can only be achieved if global CO_2 emissions start to decline well before 2030 (*high confidence*). {1.2, 2.3, 3.3, 3.4, 4.2, 4.4, Cross-Chapter Box 11 in Chapter 4}

D.1.1 Pathways that limit global warming to 1.5°C with no or limited overshoot show clear emission reductions by 2030 (*high confidence*). All but one show a decline in global greenhouse gas emissions to below 35 $GtCO_2eq\ yr^{-1}$ in 2030, and half of available pathways fall within the 25–30 $GtCO_2eq\ yr^{-1}$ range (interquartile range), a 40–50% reduction from 2010 levels (*high confidence*). Pathways reflecting current nationally stated mitigation ambition until 2030 are broadly consistent with cost-effective pathways that result in a global warming of about 3°C by 2100, with warming continuing afterwards (*medium confidence*). {2.3.3, 2.3.5, Cross-Chapter Box 11 in Chapter 4, 5.5.3.2}

D.1.2 Overshoot trajectories result in higher impacts and associated challenges compared to pathways that limit global warming to 1.5°C with no or limited overshoot (*high confidence*). Reversing warming after an overshoot of 0.2°C or larger during this century would require upscaling and deployment of CDR at rates and volumes that might not be achievable given considerable implementation challenges (*medium confidence*). {1.3.3, 2.3.4, 2.3.5, 2.5.1, 3.3, 4.3.7, Cross-Chapter Box 8 in Chapter 3, Cross-Chapter Box 11 in Chapter 4}

D.1.3 The lower the emissions in 2030, the lower the challenge in limiting global warming to 1.5°C after 2030 with no or limited overshoot (*high confidence*). The challenges from delayed actions to reduce greenhouse gas emissions include the risk of cost escalation, lock-in in carbon-emitting infrastructure, stranded assets, and reduced flexibility in future response options in the medium to long term (*high confidence*). These may increase uneven distributional impacts between countries at different stages of development (*medium confidence*). {2.3.5, 4.4.5, 5.4.2}

D.2 The avoided climate change impacts on sustainable development, eradication of poverty and reducing inequalities would be greater if global warming were limited to 1.5°C rather than 2°C, if mitigation and adaptation synergies are maximized while trade-offs are minimized (*high confidence*). {1.1, 1.4, 2.5, 3.3, 3.4, 5.2, Table 5.1}

D.2.1 Climate change impacts and responses are closely linked to sustainable development which balances social well-being, economic prosperity and environmental protection. The United Nations Sustainable Development Goals (SDGs), adopted in 2015, provide an established framework for assessing the links between global warming of 1.5°C or 2°C and development goals that include poverty eradication, reducing inequalities, and climate action. (*high confidence*) {Cross-Chapter Box 4 in Chapter 1, 1.4, 5.1}

D.2.2 The consideration of ethics and equity can help address the uneven distribution of adverse impacts associated with 1.5°C and higher levels of global warming, as well as those from mitigation and adaptation, particularly for poor and disadvantaged populations, in all societies (*high confidence*). {1.1.1, 1.1.2, 1.4.3, 2.5.3, 3.4.10, 5.1, 5.2, 5.3. 5.4, Cross-Chapter Box 4 in Chapter 1, Cross-Chapter Boxes 6 and 8 in Chapter 3, and Cross-Chapter Box 12 in Chapter 5}

D.2.3 Mitigation and adaptation consistent with limiting global warming to 1.5°C are underpinned by enabling conditions, assessed in this Report across the geophysical, environmental-ecological, technological, economic, socio-cultural and institutional

18 GHG emissions have been aggregated with 100-year GWP values as introduced in the IPCC Second Assessment Report.

dimensions of feasibility. Strengthened multilevel governance, institutional capacity, policy instruments, technological innovation and transfer and mobilization of finance, and changes in human behaviour and lifestyles are enabling conditions that enhance the feasibility of mitigation and adaptation options for 1.5°C-consistent systems transitions. (*high confidence*) {1.4, Cross-Chapter Box 3 in Chapter 1, 2.5.1, 4.4, 4.5, 5.6}

D.3 Adaptation options specific to national contexts, if carefully selected together with enabling conditions, will have benefits for sustainable development and poverty reduction with global warming of 1.5°C, although trade-offs are possible (*high confidence*). {1.4, 4.3, 4.5}

D.3.1 Adaptation options that reduce the vulnerability of human and natural systems have many synergies with sustainable development, if well managed, such as ensuring food and water security, reducing disaster risks, improving health conditions, maintaining ecosystem services and reducing poverty and inequality (*high confidence*). Increasing investment in physical and social infrastructure is a key enabling condition to enhance the resilience and the adaptive capacities of societies. These benefits can occur in most regions with adaptation to 1.5°C of global warming (*high confidence*). {1.4.3, 4.2.2, 4.3.1, 4.3.2, 4.3.3, 4.3.5, 4.4.1, 4.4.3, 4.5.3, 5.3.1, 5.3.2}

D.3.2 Adaptation to 1.5°C global warming can also result in trade-offs or maladaptations with adverse impacts for sustainable development. For example, if poorly designed or implemented, adaptation projects in a range of sectors can increase greenhouse gas emissions and water use, increase gender and social inequality, undermine health conditions, and encroach on natural ecosystems (*high confidence*). These trade-offs can be reduced by adaptations that include attention to poverty and sustainable development (*high confidence*). {4.3.2, 4.3.3, 4.5.4, 5.3.2; Cross-Chapter Boxes 6 and 7 in Chapter 3}

D.3.3 A mix of adaptation and mitigation options to limit global warming to 1.5°C, implemented in a participatory and integrated manner, can enable rapid, systemic transitions in urban and rural areas (*high confidence*). These are most effective when aligned with economic and sustainable development, and when local and regional governments and decision makers are supported by national governments (*medium confidence*). {4.3.2, 4.3.3, 4.4.1, 4.4.2}

D.3.4 Adaptation options that also mitigate emissions can provide synergies and cost savings in most sectors and system transitions, such as when land management reduces emissions and disaster risk, or when low-carbon buildings are also designed for efficient cooling. Trade-offs between mitigation and adaptation, when limiting global warming to 1.5°C, such as when bioenergy crops, reforestation or afforestation encroach on land needed for agricultural adaptation, can undermine food security, livelihoods, ecosystem functions and services and other aspects of sustainable development. (*high confidence*) {3.4.3, 4.3.2, 4.3.4, 4.4.1, 4.5.2, 4.5.3, 4.5.4}

D.4 Mitigation options consistent with 1.5°C pathways are associated with multiple synergies and trade-offs across the Sustainable Development Goals (SDGs). While the total number of possible synergies exceeds the number of trade-offs, their net effect will depend on the pace and magnitude of changes, the composition of the mitigation portfolio and the management of the transition. (*high confidence*) (Figure SPM.4) {2.5, 4.5, 5.4}

D.4.1 1.5°C pathways have robust synergies particularly for the SDGs 3 (health), 7 (clean energy), 11 (cities and communities), 12 (responsible consumption and production) and 14 (oceans) (*very high confidence*). Some 1.5°C pathways show potential trade-offs with mitigation for SDGs 1 (poverty), 2 (hunger), 6 (water) and 7 (energy access), if not managed carefully (*high confidence*). (Figure SPM.4) {5.4.2; Figure 5.4, Cross-Chapter Boxes 7 and 8 in Chapter 3}

D.4.2 1.5°C pathways that include low energy demand (e.g., see P1 in Figure SPM.3a and SPM.3b), low material consumption, and low GHG-intensive food consumption have the most pronounced synergies and the lowest number of trade-offs with respect to sustainable development and the SDGs (*high confidence*). Such pathways would reduce dependence on CDR. In modelled pathways, sustainable development, eradicating poverty and reducing inequality can support limiting warming to 1.5°C (*high confidence*). (Figure SPM.3b, Figure SPM.4) {2.4.3, 2.5.1, 2.5.3, Figure 2.4, Figure 2.28, 5.4.1, 5.4.2, Figure 5.4}

Indicative linkages between mitigation options and sustainable development using SDGs (The linkages do not show costs and benefits)

Mitigation options deployed in each sector can be associated with potential positive effects (synergies) or negative effects (trade-offs) with the Sustainable Development Goals (SDGs). The degree to which this potential is realized will depend on the selected portfolio of mitigation options, mitigation policy design, and local circumstances and context. Particularly in the energy-demand sector, the potential for synergies is larger than for trade-offs. The bars group individually assessed options by level of confidence and take into account the relative strength of the assessed mitigation-SDG connections.

Length shows strength of connection

The overall **size of the coloured bars** depict **the relative potential** for synergies and trade-offs between the sectoral mitigation options and the SDGs.

Shades show level of confidence

The shades depict **the level of confidence** of the assessed potential for **Trade-offs**/**Synergies**.

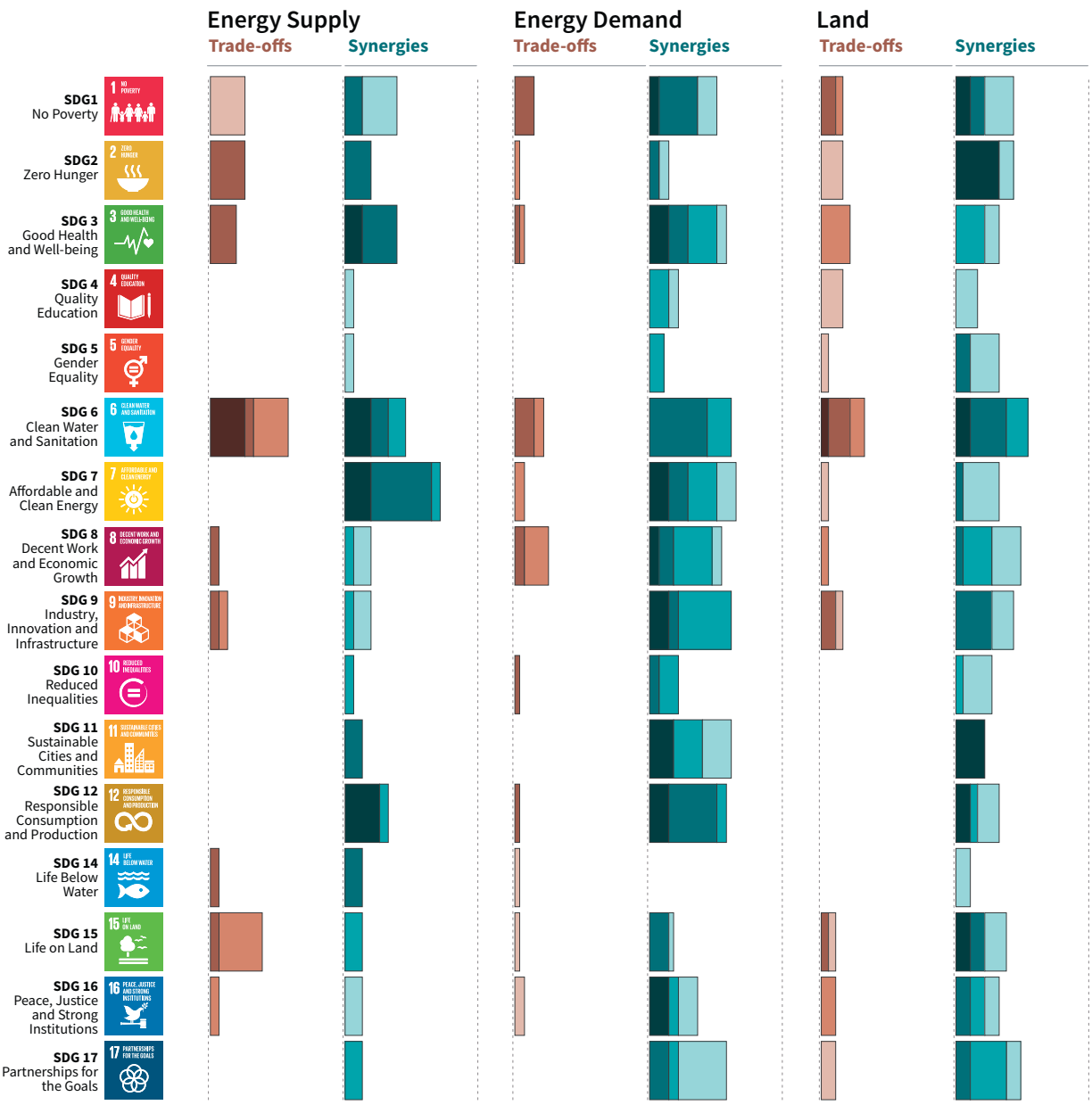


Figure SPM.4 | Potential synergies and trade-offs between the sectoral portfolio of climate change mitigation options and the Sustainable Development Goals (SDGs). The SDGs serve as an analytical framework for the assessment of the different sustainable development dimensions, which extend beyond the time frame of the 2030 SDG targets. The assessment is based on literature on mitigation options that are considered relevant for 1.5°C. The assessed strength of the SDG interactions is based on the qualitative and quantitative assessment of individual mitigation options listed in Table 5.2. For each mitigation option, the strength of the SDG-connection as well as the associated confidence of the underlying literature (shades of green and red) was assessed. The strength of positive connections (synergies) and negative connections (trade-offs) across all individual options within a sector (see Table 5.2) are aggregated into sectoral potentials for the whole mitigation portfolio. The (white) areas outside the bars, which indicate no interactions, have *low confidence* due to the uncertainty and limited number of studies exploring indirect effects. The strength of the connection considers only the effect of mitigation and does not include benefits of avoided impacts. SDG 13 (climate action) is not listed because mitigation is being considered in terms of interactions with SDGs and not vice versa. The bars denote the strength of the connection, and do not consider the strength of the impact on the SDGs. The energy demand sector comprises behavioural responses, fuel switching and efficiency options in the transport, industry and building sector as well as carbon capture options in the industry sector. Options assessed in the energy supply sector comprise biomass and non-biomass renewables, nuclear, carbon capture and storage (CCS) with bioenergy, and CCS with fossil fuels. Options in the land sector comprise agricultural and forest options, sustainable diets and reduced food waste, soil sequestration, livestock and manure management, reduced deforestation, afforestation and reforestation, and responsible sourcing. In addition to this figure, options in the ocean sector are discussed in the underlying report. {5.4, Table 5.2, Figure 5.2}

Information about the net impacts of mitigation on sustainable development in 1.5°C pathways is available only for a limited number of SDGs and mitigation options. Only a limited number of studies have assessed the benefits of avoided climate change impacts of 1.5°C pathways for the SDGs, and the co-effects of adaptation for mitigation and the SDGs. The assessment of the indicative mitigation potentials in Figure SPM.4 is a step further from AR5 towards a more comprehensive and integrated assessment in the future.

D.4.3 1.5°C and 2°C modelled pathways often rely on the deployment of large-scale land-related measures like afforestation and bioenergy supply, which, if poorly managed, can compete with food production and hence raise food security concerns (*high confidence*). The impacts of carbon dioxide removal (CDR) options on SDGs depend on the type of options and the scale of deployment (*high confidence*). If poorly implemented, CDR options such as BECCS and AFOLU options would lead to trade-offs. Context-relevant design and implementation requires considering people's needs, biodiversity, and other sustainable development dimensions (*very high confidence*). (Figure SPM.4) {5.4.1.3, Cross-Chapter Box 7 in Chapter 3}

D.4.4 Mitigation consistent with 1.5°C pathways creates risks for sustainable development in regions with high dependency on fossil fuels for revenue and employment generation (*high confidence*). Policies that promote diversification of the economy and the energy sector can address the associated challenges (*high confidence*). {5.4.1.2, Box 5.2}

D.4.5 Redistributive policies across sectors and populations that shield the poor and vulnerable can resolve trade-offs for a range of SDGs, particularly hunger, poverty and energy access. Investment needs for such complementary policies are only a small fraction of the overall mitigation investments in 1.5°C pathways. (*high confidence*) {2.4.3, 5.4.2, Figure 5.5}

D.5 Limiting the risks from global warming of 1.5°C in the context of sustainable development and poverty eradication implies system transitions that can be enabled by an increase of adaptation and mitigation investments, policy instruments, the acceleration of technological innovation and behaviour changes (*high confidence*). {2.3, 2.4, 2.5, 3.2, 4.2, 4.4, 4.5, 5.2, 5.5, 5.6}

D.5.1 Directing finance towards investment in infrastructure for mitigation and adaptation could provide additional resources. This could involve the mobilization of private funds by institutional investors, asset managers and development or investment banks, as well as the provision of public funds. Government policies that lower the risk of low-emission and adaptation investments can facilitate the mobilization of private funds and enhance the effectiveness of other public policies. Studies indicate a number of challenges, including access to finance and mobilization of funds. (*high confidence*) {2.5.1, 2.5.2, 4.4.5}

D.5.2 Adaptation finance consistent with global warming of 1.5°C is difficult to quantify and compare with 2°C. Knowledge gaps include insufficient data to calculate specific climate resilience-enhancing investments from the provision of currently underinvested basic infrastructure. Estimates of the costs of adaptation might be lower at global warming of 1.5°C than for 2°C. Adaptation needs have typically been supported by public sector sources such as national and subnational government budgets, and in developing countries together with support from development assistance, multilateral development banks, and United Nations Framework Convention on Climate Change channels (*medium confidence*). More recently there is a

growing understanding of the scale and increase in non-governmental organizations and private funding in some regions (*medium confidence*). Barriers include the scale of adaptation financing, limited capacity and access to adaptation finance (*medium confidence*). {4.4.5, 4.6}

D.5.3 Global model pathways limiting global warming to 1.5°C are projected to involve the annual average investment needs in the energy system of around 2.4 trillion USD2010 between 2016 and 2035, representing about 2.5% of the world GDP (*medium confidence*). {4.4.5, Box 4.8}

D.5.4 Policy tools can help mobilize incremental resources, including through shifting global investments and savings and through market and non-market based instruments as well as accompanying measures to secure the equity of the transition, acknowledging the challenges related with implementation, including those of energy costs, depreciation of assets and impacts on international competition, and utilizing the opportunities to maximize co-benefits (*high confidence*). {1.3.3, 2.3.4, 2.3.5, 2.5.1, 2.5.2, Cross-Chapter Box 8 in Chapter 3, Cross-Chapter Box 11 in Chapter 4, 4.4.5, 5.5.2}

D.5.5 The systems transitions consistent with adapting to and limiting global warming to 1.5°C include the widespread adoption of new and possibly disruptive technologies and practices and enhanced climate-driven innovation. These imply enhanced technological innovation capabilities, including in industry and finance. Both national innovation policies and international cooperation can contribute to the development, commercialization and widespread adoption of mitigation and adaptation technologies. Innovation policies may be more effective when they combine public support for research and development with policy mixes that provide incentives for technology diffusion. (*high confidence*) {4.4.4, 4.4.5}.

D.5.6 Education, information, and community approaches, including those that are informed by indigenous knowledge and local knowledge, can accelerate the wide-scale behaviour changes consistent with adapting to and limiting global warming to 1.5°C. These approaches are more effective when combined with other policies and tailored to the motivations, capabilities and resources of specific actors and contexts (*high confidence*). Public acceptability can enable or inhibit the implementation of policies and measures to limit global warming to 1.5°C and to adapt to the consequences. Public acceptability depends on the individual's evaluation of expected policy consequences, the perceived fairness of the distribution of these consequences, and perceived fairness of decision procedures (*high confidence*). {1.1, 1.5, 4.3.5, 4.4.1, 4.4.3, Box 4.3, 5.5.3, 5.6.5}

D.6 Sustainable development supports, and often enables, the fundamental societal and systems transitions and transformations that help limit global warming to 1.5°C. Such changes facilitate the pursuit of climate-resilient development pathways that achieve ambitious mitigation and adaptation in conjunction with poverty eradication and efforts to reduce inequalities (*high confidence*). {Box 1.1, 1.4.3, Figure 5.1, 5.5.3, Box 5.3}

D.6.1 Social justice and equity are core aspects of climate-resilient development pathways that aim to limit global warming to 1.5°C as they address challenges and inevitable trade-offs, widen opportunities, and ensure that options, visions, and values are deliberated, between and within countries and communities, without making the poor and disadvantaged worse off (*high confidence*). {5.5.2, 5.5.3, Box 5.3, Figure 5.1, Figure 5.6, Cross-Chapter Boxes 12 and 13 in Chapter 5}

D.6.2 The potential for climate-resilient development pathways differs between and within regions and nations, due to different development contexts and systemic vulnerabilities (*very high confidence*). Efforts along such pathways to date have been limited (*medium confidence*) and enhanced efforts would involve strengthened and timely action from all countries and non-state actors (*high confidence*). {5.5.1, 5.5.3, Figure 5.1}

D.6.3 Pathways that are consistent with sustainable development show fewer mitigation and adaptation challenges and are associated with lower mitigation costs. The large majority of modelling studies could not construct pathways characterized by lack of international cooperation, inequality and poverty that were able to limit global warming to 1.5°C. (*high confidence*) {2.3.1, 2.5.1, 2.5.3, 5.5.2}

D.7 Strengthening the capacities for climate action of national and sub-national authorities, civil society, the private sector, indigenous peoples and local communities can support the implementation of ambitious actions implied by limiting global warming to 1.5°C (*high confidence*). International cooperation can provide an enabling environment for this to be achieved in all countries and for all people, in the context of sustainable development. International cooperation is a critical enabler for developing countries and vulnerable regions (*high confidence*). {1.4, 2.3, 2.5, 4.2, 4.4, 4.5, 5.3, 5.4, 5.5, 5.6, 5, Box 4.1, Box 4.2, Box 4.7, Box 5.3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 13 in Chapter 5}

D.7.1 Partnerships involving non-state public and private actors, institutional investors, the banking system, civil society and scientific institutions would facilitate actions and responses consistent with limiting global warming to 1.5°C (*very high confidence*). {1.4, 4.4.1, 4.2.2, 4.4.3, 4.4.5, 4.5.3, 5.4.1, 5.6.2, Box 5.3}.

D.7.2 Cooperation on strengthened accountable multilevel governance that includes non-state actors such as industry, civil society and scientific institutions, coordinated sectoral and cross-sectoral policies at various governance levels, gender-sensitive policies, finance including innovative financing, and cooperation on technology development and transfer can ensure participation, transparency, capacity building and learning among different players (*high confidence*). {2.5.1, 2.5.2, 4.2.2, 4.4.1, 4.4.2, 4.4.3, 4.4.4, 4.4.5, 4.5.3, Cross-Chapter Box 9 in Chapter 4, 5.3.1, 5.5.3, Cross-Chapter Box 13 in Chapter 5, 5.6.1, 5.6.3}

D.7.3 International cooperation is a critical enabler for developing countries and vulnerable regions to strengthen their action for the implementation of 1.5°C-consistent climate responses, including through enhancing access to finance and technology and enhancing domestic capacities, taking into account national and local circumstances and needs (*high confidence*). {2.3.1, 2.5.1, 4.4.1, 4.4.2, 4.4.4, 4.4.5, 5.4.1 5.5.3, 5.6.1, Box 4.1, Box 4.2, Box 4.7}.

D.7.4 Collective efforts at all levels, in ways that reflect different circumstances and capabilities, in the pursuit of limiting global warming to 1.5°C, taking into account equity as well as effectiveness, can facilitate strengthening the global response to climate change, achieving sustainable development and eradicating poverty (*high confidence*). {1.4.2, 2.3.1, 2.5.1, 2.5.2, 2.5.3, 4.2.2, 4.4.1, 4.4.2, 4.4.3, 4.4.4, 4.4.5, 4.5.3, 5.3.1, 5.4.1, 5.5.3, 5.6.1, 5.6.2, 5.6.3}

Box SPM.1: Core Concepts Central to this Special Report

Global mean surface temperature (GMST): Estimated global average of near-surface air temperatures over land and sea ice, and sea surface temperatures over ice-free ocean regions, with changes normally expressed as departures from a value over a specified reference period. When estimating changes in GMST, near-surface air temperature over both land and oceans are also used.[19] {1.2.1.1}

Pre-industrial: The multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial GMST. {1.2.1.2}

Global warming: The estimated increase in GMST averaged over a 30-year period, or the 30-year period centred on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified. For 30-year periods that span past and future years, the current multi-decadal warming trend is assumed to continue. {1.2.1}

Net zero CO_2 emissions: Net zero carbon dioxide (CO_2) emissions are achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period.

Carbon dioxide removal (CDR): Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities.

Total carbon budget: Estimated cumulative net global anthropogenic CO_2 emissions from the pre-industrial period to the time that anthropogenic CO_2 emissions reach net zero that would result, at some probability, in limiting global warming to a given level, accounting for the impact of other anthropogenic emissions. {2.2.2}

Remaining carbon budget: Estimated cumulative net global anthropogenic CO_2 emissions from a given start date to the time that anthropogenic CO_2 emissions reach net zero that would result, at some probability, in limiting global warming to a given level, accounting for the impact of other anthropogenic emissions. {2.2.2}

Temperature overshoot: The temporary exceedance of a specified level of global warming.

Emission pathways: In this Summary for Policymakers, the modelled trajectories of global anthropogenic emissions over the 21st century are termed emission pathways. Emission pathways are classified by their temperature trajectory over the 21st century: pathways giving at least 50% probability based on current knowledge of limiting global warming to below 1.5°C are classified as 'no overshoot'; those limiting warming to below 1.6°C and returning to 1.5°C by 2100 are classified as '1.5°C limited-overshoot'; while those exceeding 1.6°C but still returning to 1.5°C by 2100 are classified as 'higher-overshoot'.

Impacts: Effects of climate change on human and natural systems. Impacts can have beneficial or adverse outcomes for livelihoods, health and well-being, ecosystems and species, services, infrastructure, and economic, social and cultural assets.

Risk: The potential for adverse consequences from a climate-related hazard for human and natural systems, resulting from the interactions between the hazard and the vulnerability and exposure of the affected system. Risk integrates the likelihood of exposure to a hazard and the magnitude of its impact. Risk also can describe the potential for adverse consequences of adaptation or mitigation responses to climate change.

Climate-resilient development pathways (CRDPs): Trajectories that strengthen sustainable development at multiple scales and efforts to eradicate poverty through equitable societal and systems transitions and transformations while reducing the threat of climate change through ambitious mitigation, adaptation and climate resilience.

19 Past IPCC reports, reflecting the literature, have used a variety of approximately equivalent metrics of GMST change.

Summary for Policymakers

SPM

Summary for Policymakers

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Introduction

This Special Report on Climate Change and Land[1] responds to the Panel decision in 2016 to prepare three Special Reports[2] during the Sixth Assessment cycle, taking account of proposals from governments and observer organisations.[3] This report addresses greenhouse gas (GHG) fluxes in land-based ecosystems, land use and sustainable land management[4] in relation to climate change adaptation and mitigation, desertification[5], land degradation[6] and food security[7]. This report follows the publication of other recent reports, including the IPCC *Special Report on Global Warming of 1.5°C* (SR15), the thematic assessment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) on *Land Degradation and Restoration*, the IPBES *Global Assessment Report on Biodiversity and Ecosystem Services*, and the *Global Land Outlook* of the UN Convention to Combat Desertification (UNCCD). This report provides an updated assessment of the current state of knowledge[8] while striving for coherence and complementarity with other recent reports.

This Summary for Policymakers (SPM) is structured in four parts: *A) People, land and climate in a warming world; B) Adaptation and mitigation response options; C) Enabling response options; and, D) Action in the near-term.*

Confidence in key findings is indicated using the IPCC calibrated language; the underlying scientific basis of each key finding is indicated by references to the main report.[9]

---

1 The terrestrial portion of the biosphere that comprises the natural resources (soil, near-surface air, vegetation and other biota, and water), the ecological processes, topography, and human settlements and infrastructure that operate within that system.

2 The three Special reports are: *Global Warming of 1.5°C: an IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty; Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems; The Ocean and Cryosphere in a Changing Climate.*

3 Related proposals were: climate change and desertification; desertification with regional aspects; land degradation – an assessment of the interlinkages and integrated strategies for mitigation and adaptation; agriculture, forestry and other land use; food and agriculture; and food security and climate change.

4 Sustainable land management is defined in this report as 'the stewardship and use of land resources, including soils, water, animals and plants, to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions'.

5 Desertification is defined in this report as 'land degradation in arid, semi-arid, and dry sub-humid areas resulting from many factors, including climatic variations and human activities'.

6 Land degradation is defined in this report as 'a negative trend in land condition, caused by direct or indirect human induced processes, including anthropogenic climate change, expressed as long-term reduction and as loss of at least one of the following: biological productivity; ecological integrity; or value to humans'.

7 Food security is defined in this report as 'a situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life'.

8 The assessment covers literature accepted for publication by 7th April 2019.

9 Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not >50–100%, more unlikely than likely 0–<50%, extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, for example, very likely. This is consistent with IPCC AR5.

A. People, land and climate in a warming world

A.1 Land provides the principal basis for human livelihoods and well-being including the supply of food, freshwater and multiple other ecosystem services, as well as biodiversity. Human use directly affects more than 70% (*likely* 69–76%) of the global, ice-free land surface (*high confidence*). Land also plays an important role in the climate system. (Figure SPM.1) {1.1, 1.2, 2.3, 2.4}

A.1.1 People currently use one quarter to one third of land's potential net primary production[10] for food, feed, fibre, timber and energy. Land provides the basis for many other ecosystem functions and services,[11] including cultural and regulating services, that are essential for humanity (*high confidence*). In one economic approach, the world's terrestrial ecosystem services have been valued on an annual basis to be approximately equivalent to the annual global Gross Domestic Product[12] *(medium confidence*). (Figure SPM.1) {1.1, 1.2, 3.2, 4.1, 5.1, 5.5}

A.1.2 Land is both a source and a sink of GHGs and plays a key role in the exchange of energy, water and aerosols between the land surface and atmosphere. Land ecosystems and biodiversity are vulnerable to ongoing climate change, and weather and climate extremes, to different extents. Sustainable land management can contribute to reducing the negative impacts of multiple stressors, including climate change, on ecosystems and societies (*high confidence*). (Figure SPM.1) {1.1, 1.2, 3.2, 4.1, 5.1, 5.5}

A.1.3 Data available since 1961[13] show that global population growth and changes in per capita consumption of food, feed, fibre, timber and energy have caused unprecedented rates of land and freshwater use (*very high confidence*) with agriculture currently accounting for ca. 70% of global fresh-water use (*medium confidence*). Expansion of areas under agriculture and forestry, including commercial production, and enhanced agriculture and forestry productivity have supported consumption and food availability for a growing population (*high confidence*). With large regional variation, these changes have contributed to increasing net GHG emissions (*very high confidence*), loss of natural ecosystems (e.g., forests, savannahs, natural grasslands and wetlands) and declining biodiversity (*high confidence*). (Figure SPM.1) {1.1, 1.3, 5.1, 5.5}

A.1.4 Data available since 1961 shows the per capita supply of vegetable oils and meat has more than doubled and the supply of food calories per capita has increased by about one third (*high confidence*). Currently, 25–30% of total food produced is lost or wasted (*medium confidence*). These factors are associated with additional GHG emissions (*high confidence*). Changes in consumption patterns have contributed to about two billion adults now being overweight or obese (*high confidence*). An estimated 821 million people are still undernourished (*high confidence*). (Figure SPM.1) {1.1, 1.3, 5.1, 5.5}

A.1.5 About a quarter of the Earth's ice-free land area is subject to human-induced degradation (*medium confidence*). Soil erosion from agricultural fields is estimated to be currently 10 to 20 times (no tillage) to more than 100 times (conventional tillage) higher than the soil formation rate (*medium confidence*). Climate change exacerbates land degradation, particularly in low-lying coastal areas, river deltas, drylands and in permafrost areas (*high confidence*). Over the period 1961–2013, the annual area of drylands in drought has increased, on average by slightly more than 1% per year, with large inter-annual variability. In 2015, about 500 (380-620) million people lived within areas which experienced desertification between the 1980s and 2000s. The highest numbers of people affected are in South and East Asia, the circum Sahara region including North Africa, and the Middle East including the Arabian Peninsula (*low confidence*). Other dryland regions have also experienced desertification. People living in already degraded or desertified areas are increasingly negatively affected by climate change (*high confidence*). (Figure SPM.1) {1.1, 1.2, 3.1, 3.2, 4.1, 4.2, 4.3}

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[10] Land's potential net primary production (NPP) is defined in this report as 'the amount of carbon accumulated through photosynthesis minus the amount lost by plant respiration over a specified time period that would prevail in the absence of land use'.

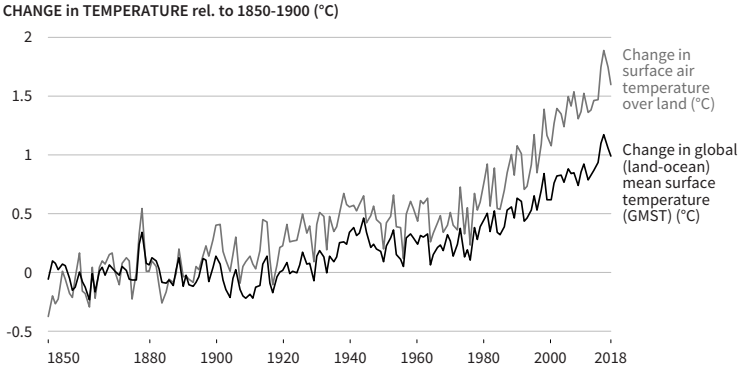
[11] In its conceptual framework, IPBES uses 'nature's contribution to people' in which it includes ecosystem goods and services.

[12] I.e., estimated at $75 trillion for 2011, based on US dollars for 2007.

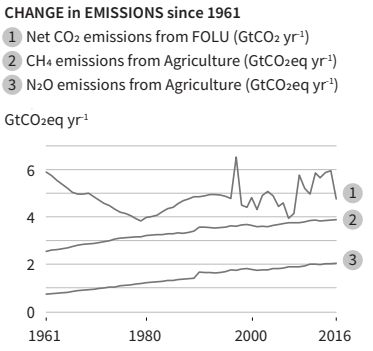
[13] This statement is based on the most comprehensive data from national statistics available within FAOSTAT, which starts in 1961. This does not imply that the changes started in 1961. Land use changes have been taking place from well before the pre-industrial period to the present.

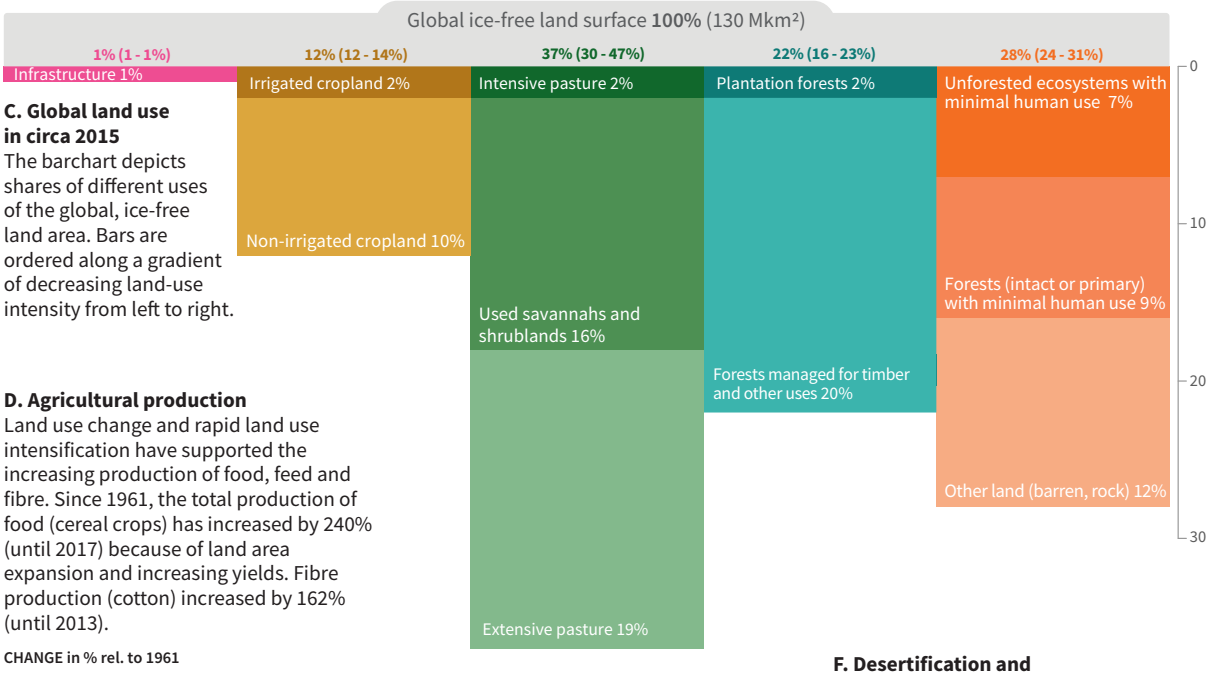
Land use and observed climate change

A. Observed temperature change relative to 1850-1900
Since the pre-industrial period (1850-1900) the observed mean land surface air temperature has risen considerably more than the global mean surface (land and ocean) temperature (GMST).



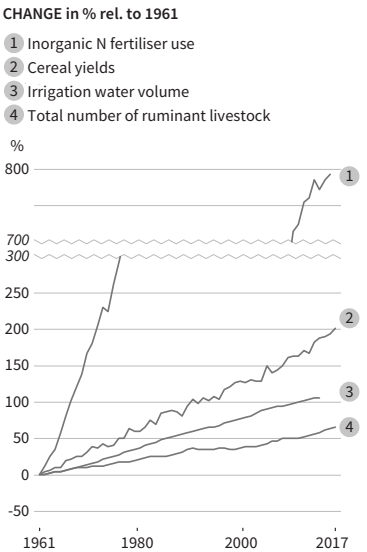
B. GHG emissions
An estimated 23% of total anthropogenic greenhouse gas emissions (2007-2016) derive from Agriculture, Forestry and Other Land Use (AFOLU).



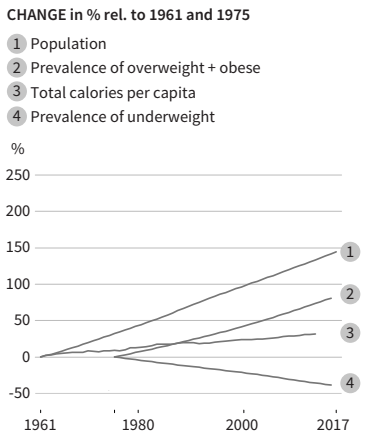


C. Global land use in circa 2015
The barchart depicts shares of different uses of the global, ice-free land area. Bars are ordered along a gradient of decreasing land-use intensity from left to right.

D. Agricultural production
Land use change and rapid land use intensification have supported the increasing production of food, feed and fibre. Since 1961, the total production of food (cereal crops) has increased by 240% (until 2017) because of land area expansion and increasing yields. Fibre production (cotton) increased by 162% (until 2013).



E. Food demand
Increases in production are linked to consumption changes.



F. Desertification and land degradation
Land-use change, land-use intensification and climate change have contributed to desertification and land degradation.

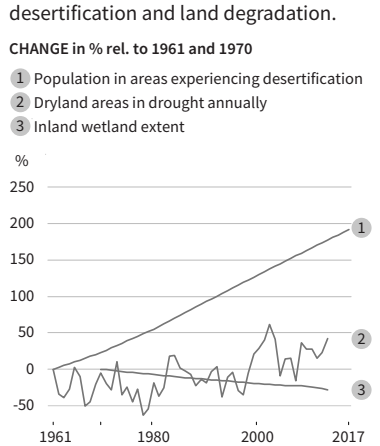


Figure SPM.1: Land use and observed climate change | A representation of the land use and observed climate change covered in this assessment report. Panels A-F show the status and trends in selected land use and climate variables that represent many of the core topics covered in this report. The annual time series in B and D-F are based on the most comprehensive, available data from national statistics, in most cases from FAOSTAT which starts in 1961. Y-axes in panels D-F are expressed relative to the starting year of the time series (rebased to zero). Data sources and notes: **A:** The warming curves are averages of four datasets {2.1, Figure 2.2, Table 2.1} **B:** N_2O and CH_4 from agriculture are from FAOSTAT; Net CO_2 emissions from FOLU using the mean of two bookkeeping models (including emissions from peatland fires since 1997). All values expressed in units of CO_2-eq are based on AR5 100-year Global Warming Potential values without climate-carbon feedbacks (N_2O=265; CH_4=28). (Table SPM.1) {1.1, 2.3} **C:** Depicts shares of different uses of the global, ice-free land area for approximately the year 2015, ordered along a gradient of decreasing land-use intensity from left to right. Each bar represents a broad land cover category; the numbers on top are the total percentage of the ice-free area covered, with uncertainty ranges in brackets. Intensive pasture is defined as having a livestock density greater than 100 animals/km^2. The area of 'forest managed for timber and other uses' was calculated as total forest area minus 'primary/intact' forest area. {1.2, Table 1.1, Figure 1.3} **D:** Note that fertiliser use is shown on a split axis. The large percentage change in fertiliser use reflects the low level of use in 1961 and relates to both increasing fertiliser input per area as well as the expansion of fertilised cropland and grassland to increase food production. {1.1, Figure 1.3} **E:** Overweight population is defined as having a body mass index (BMI) > 25 kg m^{-2}; underweight is defined as BMI < 18.5 kg m^{-2}. {5.1, 5.2} **F:** Dryland areas were estimated using TerraClimate precipitation and potential evapotranspiration (1980-2015) to identify areas where the Aridity Index is below 0.65. Population data are from the HYDE3.2 database. Areas in drought are based on the 12-month accumulation Global Precipitation Climatology Centre Drought Index. The inland wetland extent (including peatlands) is based on aggregated data from more than 2000 time series that report changes in local wetland area over time. {3.1, 4.2, 4.6}

A.2 Since the pre-industrial period, the land surface air temperature has risen nearly twice as much as the global average temperature (*high confidence*). Climate change, including increases in frequency and intensity of extremes, has adversely impacted food security and terrestrial ecosystems as well as contributed to desertification and land degradation in many regions (*high confidence*). {2.2, 3.2, 4.2, 4.3, 4.4, 5.1, 5.2, Executive Summary Chapter 7, 7.2}

A.2.1 Since the pre-industrial period (1850-1900) the observed mean land surface air temperature has risen considerably more than the global mean surface (land and ocean) temperature (GMST) (*high confidence*). From 1850-1900 to 2006-2015 mean land surface air temperature has increased by 1.53°C (*very likely* range from 1.38°C to 1.68°C) while GMST increased by 0.87°C (*likely* range from 0.75°C to 0.99°C). (Figure SPM.1) {2.2.1}

A.2.2 Warming has resulted in an increased frequency, intensity and duration of heat-related events, including heatwaves[14] in most land regions (*high confidence*). Frequency and intensity of droughts has increased in some regions (including the Mediterranean, west Asia, many parts of South America, much of Africa, and north-eastern Asia) (*medium confidence*) and there has been an increase in the intensity of heavy precipitation events at a global scale (*medium confidence*). {2.2.5, 4.2.3, 5.2}

A.2.3 Satellite observations[15] have shown vegetation greening[16] over the last three decades in parts of Asia, Europe, South America, central North America, and southeast Australia. Causes of greening include combinations of an extended growing season, nitrogen deposition, Carbon Dioxide (CO_2) fertilisation[17], and land management (*high confidence*). Vegetation browning[18] has been observed in some regions including northern Eurasia, parts of North America, Central Asia and the Congo Basin, largely as a result of water stress (*medium confidence*). Globally, vegetation greening has occurred over a larger area than vegetation browning (*high confidence*). {2.2.3, Box 2.3, 2.2.4, 3.2.1, 3.2.2, 4.3.1, 4.3.2, 4.6.2, 5.2.2}

A.2.4 The frequency and intensity of dust storms have increased over the last few decades due to land use and land cover changes and climate-related factors in many dryland areas resulting in increasing negative impacts on human health, in regions such as the Arabian Peninsula and broader Middle East, Central Asia (*high confidence*).[19] {2.4.1, 3.4.2}

A.2.5 In some dryland areas, increased land surface air temperature and evapotranspiration and decreased precipitation amount, in interaction with climate variability and human activities, have contributed to desertification. These areas include Sub-Saharan Africa, parts of East and Central Asia, and Australia. (*medium confidence*) {2.2, 3.2.2, 4.4.1}

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[14] A heatwave is defined in this report as 'a period of abnormally hot weather'. Heatwaves and warm spells have various and, in some cases, overlapping definitions.

[15] The interpretation of satellite observations can be affected by insufficient ground validation and sensor calibration. In addition their spatial resolution can make it difficult to resolve small-scale changes.

[16] Vegetation greening is defined in this report as 'an increase in photosynthetically active plant biomass which is inferred from satellite observations'.

[17] CO_2 fertilisation is defined in this report as 'the enhancement of plant growth as a result of increased atmospheric carbon dioxide (CO_2) concentration'. The magnitude of CO_2 fertilisation depends on nutrients and water availability.

[18] Vegetation browning is defined in this report as 'a decrease in photosynthetically active plant biomass which is inferred from satellite observations'.

[19] Evidence relative to such trends in dust storms and health impacts in other regions is limited in the literature assessed in this report.

A.2.6 Global warming has led to shifts of climate zones in many world regions, including expansion of arid climate zones and contraction of polar climate zones (*high confidence*). As a consequence, many plant and animal species have experienced changes in their ranges, abundances, and shifts in their seasonal activities (*high confidence*). {2.2, 3.2.2, 4.4.1}

A.2.7 Climate change can exacerbate land degradation processes (*high confidence*) including through increases in rainfall intensity, flooding, drought frequency and severity, heat stress, dry spells, wind, sea-level rise and wave action, and permafrost thaw with outcomes being modulated by land management. Ongoing coastal erosion is intensifying and impinging on more regions with sea-level rise adding to land use pressure in some regions (*medium confidence*). {4.2.1, 4.2.2, 4.2.3, 4.4.1, 4.4.2, 4.9.6, Table 4.1, 7.2.1, 7.2.2}

A.2.8 Climate change has already affected food security due to warming, changing precipitation patterns, and greater frequency of some extreme events (*high confidence*). Studies that separate out climate change from other factors affecting crop yields have shown that yields of some crops (e.g., maize and wheat) in many lower-latitude regions have been affected negatively by observed climate changes, while in many higher-latitude regions, yields of some crops (e.g., maize, wheat, and sugar beets) have been affected positively over recent decades (*high confidence*). Climate change has resulted in lower animal growth rates and productivity in pastoral systems in Africa (*high confidence*). There is robust evidence that agricultural pests and diseases have already responded to climate change resulting in both increases and decreases of infestations (*high confidence*). Based on indigenous and local knowledge, climate change is affecting food security in drylands, particularly those in Africa, and high mountain regions of Asia and South America.[20] {5.2.1, 5.2.2, 7.2.2}

A.3 Agriculture, Forestry and Other Land Use (AFOLU) activities accounted for around 13% of CO_2, 44% of methane (CH_4), and 81% of nitrous oxide (N_2O) emissions from human activities globally during 2007-2016, representing 23% (12.0 ± 2.9 $GtCO_2eq\ yr^{-1}$) of total net anthropogenic emissions of GHGs (*medium confidence*).[21] The natural response of land to human-induced environmental change caused a net sink of around 11.2 $GtCO_2\ yr^{-1}$ during 2007–2016 (equivalent to 29% of total CO2 emissions) (*medium confidence*); the persistence of the sink is uncertain due to climate change (*high confidence*). If emissions associated with pre- and post-production activities in the global food system[22] are included, the emissions are estimated to be 21–37% of total net anthropogenic GHG emissions (*medium confidence*). {2.3, Table 2.2, 5.4}

A.3.1 Land is simultaneously a source and a sink of CO_2 due to both anthropogenic and natural drivers, making it hard to separate anthropogenic from natural fluxes (*very high confidence*). Global models estimate net CO_2 emissions of 5.2 ± 2.6 $GtCO_2\ yr^{-1}$ (*likely* range) from land use and land-use change during 2007–2016. These net emissions are mostly due to deforestation, partly offset by afforestation/reforestation, and emissions and removals by other land use activities (*very high confidence*).[23] There is no clear trend in annual emissions since 1990 (*medium confidence*). (Figure SPM.1, Table SPM.1) {1.1, 2.3, Table 2.2, Table 2.3}

A.3.2 The natural response of land to human-induced environmental changes such as increasing atmospheric CO_2 concentration, nitrogen deposition, and climate change, resulted in global net removals of 11.2 ± 2.6 $GtCO_2\ yr^{-1}$ (*likely* range) during 2007–2016. The sum of the net removals due to this response and the AFOLU net emissions gives a total net land-atmosphere flux that removed 6.0 ± 3.7 $GtCO_2\ yr^{-1}$ during 2007–2016 (*likely* range). Future net increases in CO_2 emissions from vegetation and soils due to climate change are projected to counteract increased removals due to CO_2 fertilisation and longer growing seasons (*high confidence*). The balance between these processes is a key source of uncertainty for determining the future of the land carbon sink. Projected thawing of permafrost is expected to increase the loss of soil carbon (*high confidence*). During the 21st century, vegetation growth in those areas may compensate in part for this loss (*low confidence*). (Table SPM.1) {Box 2.3, 2.3.1, 2.5.3, 2.7, Table 2.3}

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[20] The assessment covered literature whose methodologies included interviews and surveys with indigenous peoples and local communities.

[21] This assessment only includes CO_2, CH_4 and N_2O.

[22] Global food system in this report is defined as 'all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities, including socioeconomic and environmental outcomes at the global level'. These emissions data are not directly comparable to the national inventories prepared according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

[23] The net anthropogenic flux of CO_2 from 'bookkeeping' or 'carbon accounting' models is composed of two opposing gross fluxes: gross emissions (about 20 $GtCO_2\ yr^{-1}$) are from deforestation, cultivation of soils, and oxidation of wood products; gross removals (about 14 $GtCO_2\ yr^{-1}$) are largely from forest growth following wood harvest and agricultural abandonment (*medium confidence*).

A.3.3 Global models and national GHG inventories use different methods to estimate anthropogenic CO_2 emissions and removals for the land sector. Both produce estimates that are in close agreement for land-use change involving forest (e.g., deforestation, afforestation), and differ for managed forest. Global models consider as managed forest those lands that were subject to harvest whereas, consistent with IPCC guidelines, national GHG inventories define managed forest more broadly. On this larger area, inventories can also consider the natural response of land to human-induced environmental changes as anthropogenic, while the global model approach (Table SPM.1) treats this response as part of the non-anthropogenic sink. For illustration, from 2005 to 2014, the sum of the national GHG inventories net emission estimates is 0.1 ± 1.0 $GtCO_2$ yr^{-1}, while the mean of two global bookkeeping models is 5.2 ± 2.6 $GtCO_2$ yr^{-1} (*likely* range). Consideration of differences in methods can enhance understanding of land sector net emission estimates and their applications. {2.4.1, 2.7.3, Fig 2.5, Box 2.2}

Net anthropogenic emissions due to Agriculture, Forestry, and other Land Use (AFOLU) and non-AFOLU (Panel 1) and global food systems (average for 2007–2016)[1] (Panel 2). Positive values represent emissions; negative values represent removals.

		Direct Anthropogenic							
Gas	Units	Net anthropogenic emissions due to Agriculture, Forestry, and Other Land Use (AFOLU)			Non-AFOLU anthropogenic GHG emissions[6]	Total net anthropogenic emissions (AFOLU + non-AFOLU) by gas	AFOLU as a % of total net anthropogenic emissions, by gas	Natural response of land to human-induced environmental change[7]	Net land – atmosphere flux from all lands
Panel 1: Contribution of AFOLU									
		FOLU	Agriculture	Total					
		A	B	C = A + B	D	**E = C + D**	F = (C/E) ×100	G	A + G
CO_2[2]									
	$GtCO_2\ yr^{-1}$	5.2 ± 2.6	No data[11]	5.2 ± 2.6	33.9 ± 1.8	**39.1 ± 3.2**	13%	-11.2 ± 2.6	-6.0 ± 3.7
CH_4[3,8]	$MtCH_4\ yr^{-1}$	19.2 ± 5.8	142 ± 42	161 ± 43	201 ± 101	**362 ± 109**			
	$GtCO_2eq\ yr^{-1}$	0.5 ± 0.2	4.0 ± 1.2	4.5 ± 1.2	5.6 ± 2.8	**10.1 ± 3.1**	44%		
N_2O[3,8]	$MtN_2O\ yr^{-1}$	0.3 ± 0.1	8.3 ± 2.5	8.7 ± 2.5	2.0 ± 1.0	**10.6 ± 2.7**			
	$GtCO_2eq\ yr^{-1}$	0.09 ± 0.03	2.2 ± 0.7	2.3 ± 0.7	0.5 ± 0.3	**2.8 ± 0.7**	81%		
Total (GHG)	**$GtCO_2eq\ yr^{-1}$**	**5.8 ± 2.6**	**6.2 ± 1.4**	**12.0 ± 2.9**	**40.0 ± 3.4**	**52.0 ± 4.5**	**23%**		
Panel 2: Contribution of global food system									
		Land-use change	Agriculture		Non-AFOLU[5] other sectors pre- to post-production	Total global food system emissions			
CO_2 Land-use change[4]	$GtCO_2\ yr^{-1}$	4.9 ± 2.5							
CH_4 Agriculture[3,8,9]	$GtCO_2eq\ yr^{-1}$		4.0 ± 1.2						
N_2O Agriculture[3,8,9]	$GtCO_2eq\ yr^{-1}$		2.2 ± 0.7						
CO_2 other sectors[5]	$GtCO_2yr^{-1}$				2.6 – 5.2				
Total[10]	**$GtCO_2eq\ yr^{-1}$**	**4.9 ± 2.5**	**6.2 ± 1.4**		**2.6 – 5.2**	**10.8 – 19.1**			

Table SPM.1 | Data sources and notes:

[1] Estimates are only given until 2016 as this is the latest date when data are available for all gases.

[2] Net anthropogenic flux of CO_2 due to land cover change such as deforestation and afforestation, and land management including wood harvest and regrowth, as well as peatland burning, based on two bookkeeping models as used in the Global Carbon Budget and for AR5. Agricultural soil carbon stock change under the same land use is not considered in these models. {2.3.1.2.1, Table 2.2, Box 2.2}

[3] Estimates show the mean and assessed uncertainty of two databases, FAOSTAT and USEPA. 2012 {2.3, Table 2.2}

[4] Based on FAOSTAT. Categories included in this value are 'net forest conversion' (net deforestation), drainage of organic soils (cropland and grassland), biomass burning (humid tropical forests, other forests, organic soils). It excludes 'forest land' (forest management plus net forest expansion), which is primarily a sink due to afforestation. Note: Total FOLU emissions from FAOSTAT are 2.8 (±1.4) $GtCO_2\ yr^{-1}$ for the period 2007–2016. {Table 2.2, Table 5.4}

[5] CO_2 emissions induced by activities not included in the AFOLU sector, mainly from energy (e.g., grain drying), transport (e.g., international trade), and industry (e.g., synthesis of inorganic fertilisers) part of food systems, including agricultural production activities (e.g., heating in greenhouses), pre-production (e.g., manufacturing of farm inputs) and post-production (e.g., agri-food processing) activities. This estimate is land based and hence excludes emissions from fisheries. It includes emissions from fibre and other non-food agricultural products since these are not separated from food use in databases. The CO_2 emissions related to the food system in sectors other than AFOLU are 6–-13% of total anthropogenic CO_2 emissions. These emissions are typically low in smallholder subsistence farming. When added to AFOLU emissions, the estimated share of food systems in global anthropogenic emissions is 21–-37%. {5.4.5, Table 5.4}

[6] Total non-AFOLU emissions were calculated as the sum of total CO_2eq emissions values for energy, industrial sources, waste and other emissions with data from the Global Carbon Project for CO_2, including international aviation and shipping and from the PRIMAP database for CH_4 and N_2O averaged over 2007–2014 only as that was the period for which data were available. {2.3, Table 2.2}.

[7] The natural response of land to human-induced environmental changes is the response of vegetation and soils to environmental changes such as increasing atmospheric CO_2 concentration, nitrogen deposition, and climate change. The estimate shown represents the average from Dynamic Global Vegetation Models {2.3.1.2, Box 2.2, Table 2.3}

[8] All values expressed in units of CO_2eq are based on AR5 100-year Global Warming Potential (GWP) values without climate-carbon feedbacks (N_2O = 265; CH_4 = 28). Note that the GWP has been used across fossil fuel and biogenic sources of methane. If a higher GWP for fossil fuel CH_4 (30 per AR5) were used, then total anthropogenic CH_4 emissions expressed in CO_2eq would be 2% greater.

[9] This estimate is land based and hence excludes emissions from fisheries and emissions from aquaculture (except emissions from feed produced on land and used in aquaculture), and also includes non-food use (e.g. fibre and bioenergy) since these are not separated from food use in databases. It excludes non-CO_2 emissions associated with land use change (FOLU category) since these are from fires in forests and peatlands.

[10] Emissions associated with food loss and waste are included implicitly, since emissions from the food system are related to food produced, including food consumed for nutrition and to food loss and waste. The latter is estimated at 8–10% of total anthropogenic emissions in CO_2eq. {5.5.2.5}

[11] No global data are available for agricultural CO_2 emissions.

A.3.4 Global AFOLU emissions of methane in the period 2007–2016 were 161 ± 43 $MtCH_4\ yr^{-1}$ (4.5 ± 1.2 $GtCO_2eq\ yr^{-1}$) (*medium confidence*). The globally averaged atmospheric concentration of CH_4 shows a steady increase between the mid-1980s and early 1990s, slower growth thereafter until 1999, a period of no growth between 1999–2006, followed by a resumption of growth in 2007 (*high confidence*). Biogenic sources make up a larger proportion of emissions than they did before 2000 (*high confidence*). Ruminants and the expansion of rice cultivation are important contributors to the rising concentration (*high confidence*). (Figure SPM.1) {Table 2.2, 2.3.2, 5.4.2, 5.4.3}

A.3.5 Anthropogenic AFOLU N_2O emissions are rising, and were 8.7 ± 2.5 $MtN_2O\ yr^{-1}$ (2.3 ± 0.7 $GtCO_2eq\ yr^{-1}$) during the period 2007-2016. Anthropogenic N_2O emissions {Figure SPM.1, Table SPM.1} from soils are primarily due to nitrogen application including inefficiencies (over-application or poorly synchronised with crop demand timings) (*high confidence*). Cropland soils emitted around 3 $MtN_2O\ yr^{-1}$ (around 795 $MtCO_2$ eq yr^{-1}) during the period 2007–2016 (*medium confidence*). There has been a major growth in emissions from managed pastures due to increased manure deposition (*medium confidence*). Livestock on managed pastures and rangelands accounted for more than one half of total anthropogenic N_2O emissions from agriculture in 2014 (*medium confidence*). {Table 2.1, 2.3.3, 5.4.2, 5.4.3}

A.3.6 Total net GHG emissions from AFOLU emissions represent 12.0 ± 2.9 $GtCO_2eq\ yr^{-1}$ during 2007–2016. This represents 23% of total net anthropogenic emissions {Table SPM.1}.[24] Other approaches, such as global food system, include agricultural emissions and land use change (i.e., deforestation and peatland degradation), as well as outside farm gate emissions from energy, transport and industry sectors for food production. Emissions within farm gate and from agricultural land expansion contributing to the global food system represent 16–27% of total anthropogenic emissions (*medium confidence*). Emissions outside the farm gate represent 5–10% of total anthropogenic emissions (*medium confidence*). Given the diversity of food systems, there are large regional differences in the contributions from different components of the food system (*very high confidence*). Emissions from agricultural production are projected to increase (*high confidence*), driven by population and income growth and changes in consumption patterns (*medium confidence*). {5.5, Table 5.4}

[24] This assessment only includes CO_2, CH_4 and N_2O.

A.4 Changes in land conditions,[25] either from land-use or climate change, affect global and regional climate (*high confidence*). At the regional scale, changing land conditions can reduce or accentuate warming and affect the intensity, frequency and duration of extreme events. The magnitude and direction of these changes vary with location and season (*high confidence*). {Executive Summary Chapter 2, 2.3, 2.4, 2.5, 3.3}

A.4.1 Since the pre-industrial period, changes in land cover due to human activities have led to both a net release of CO_2 contributing to global warming (*high confidence*), and an increase in global land albedo[26] causing surface cooling (*medium confidence*). Over the historical period, the resulting net effect on globally averaged surface temperature is estimated to be small (*medium confidence*). {2.4, 2.6.1, 2.6.2}

A.4.2 The likelihood, intensity and duration of many extreme events can be significantly modified by changes in land conditions, including heat related events such as heatwaves (*high confidence*) and heavy precipitation events (*medium confidence*). Changes in land conditions can affect temperature and rainfall in regions as far as hundreds of kilometres away (*high confidence*). {2.5.1, 2.5.2, 2.5.4, 3.3, Cross-Chapter Box 4 in Chapter 2}

A.4.3 Climate change is projected to alter land conditions with feedbacks on regional climate. In those boreal regions where the treeline migrates northward and/or the growing season lengthens, winter warming will be enhanced due to decreased snow cover and albedo while warming will be reduced during the growing season because of increased evapotranspiration (*high confidence*). In those tropical areas where increased rainfall is projected, increased vegetation growth will reduce regional warming (*medium confidence*). Drier soil conditions resulting from climate change can increase the severity of heat waves, while wetter soil conditions have the opposite effect (*high confidence*). {2.5.2, 2.5.3}

A.4.4 Desertification amplifies global warming through the release of CO_2 linked with the decrease in vegetation cover (*high confidence*). This decrease in vegetation cover tends to increase local albedo, leading to surface cooling (*high confidence*). {3.3}

A.4.5 Changes in forest cover, for example from afforestation, reforestation and deforestation, directly affect regional surface temperature through exchanges of water and energy (*high confidence*).[27] Where forest cover increases in tropical regions cooling results from enhanced evapotranspiration (*high confidence*). Increased evapotranspiration can result in cooler days during the growing season (*high confidence*) and can reduce the amplitude of heat related events (*medium confidence*). In regions with seasonal snow cover, such as boreal and some temperate regions, increased tree and shrub cover also has a wintertime warming influence due to reduced surface albedo (*high confidence*).[28] {2.3, 2.4.3, 2.5.1, 2.5.2, 2.5.4}

A.4.6 Both global warming and urbanisation can enhance warming in cities and their surroundings (heat island effect), especially during heat related events, including heat waves (*high confidence*). Night-time temperatures are more affected by this effect than daytime temperatures (*high confidence*). Increased urbanisation can also intensify extreme rainfall events over the city or downwind of urban areas (*medium confidence*). {2.5.1, 2.5.2, 2.5.3, 4.9.1, Cross-Chapter Box 4 in Chapter 2}

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[25] Land conditions encompass changes in land cover (e.g., deforestation, afforestation, urbanisation), in land use (e.g., irrigation), and in land state (e.g., degree of wetness, degree of greening, amount of snow, amount of permafrost).

[26] Land with high albedo reflects more incoming solar radiation than land with low albedo.

[27] The literature indicates that forest cover changes can also affect climate through changes in emissions of reactive gases and aerosols. {2.4, 2.5}

[28] Emerging literature shows that boreal forest-related aerosols may counteract at least partly the warming effect of surface albedo. {2.4.3}

Box SPM. 1 | Shared Socio-economic Pathways (SSPs)

In this report the implications of future socio-economic development on climate change mitigation, adaptation and land-use are explored using shared socio-economic pathways (SSPs). The SSPs span a range of challenges to climate change mitigation and adaptation.

- SSP1 includes a peak and decline in population (~7 billion in 2100), high income and reduced inequalities, effective land-use regulation, less resource intensive consumption, including food produced in low-GHG emission systems and lower food waste, free trade and environmentally-friendly technologies and lifestyles. Relative to other pathways, SSP1 has low challenges to mitigation and low challenges to adaptation (i.e., high adaptive capacity)

- SSP2 includes medium population growth (~9 billion in 2100), medium income, technological progress, production and consumption patterns are a continuation of past trends, and only a gradual reduction in inequality occurs. Relative to other pathways, SSP2 has medium challenges to mitigation and medium challenges to adaptation (i.e., medium adaptive capacity).

- SSP3 includes high population growth (~13 billion in 2100), low income and continued inequalities, material-intensive consumption and production, barriers to trade, and slow rates of technological change. Relative to other pathways, SSP3 has high challenges to mitigation and high challenges to adaptation (i.e., low adaptive capacity).

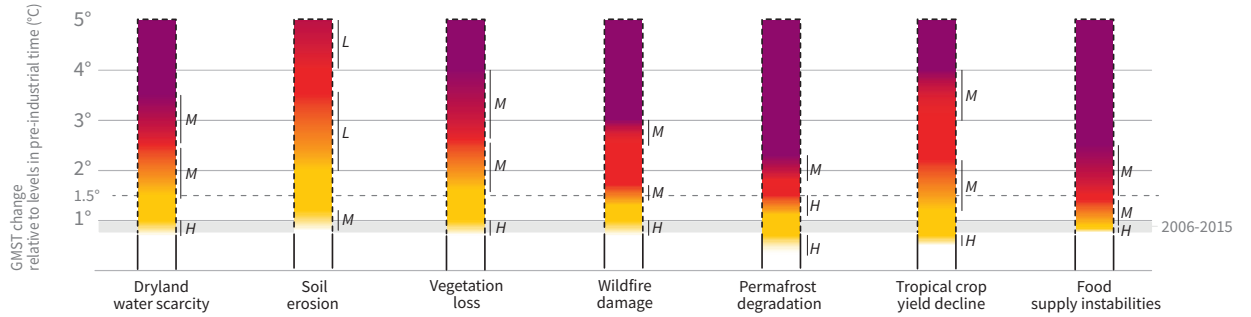
- SSP4 includes medium population growth (~9 billion in 2100), medium income, but significant inequality within and across regions. Relative to other pathways, SSP4 has low challenges to mitigation, but high challenges to adaptation (i.e., low adaptive capacity).

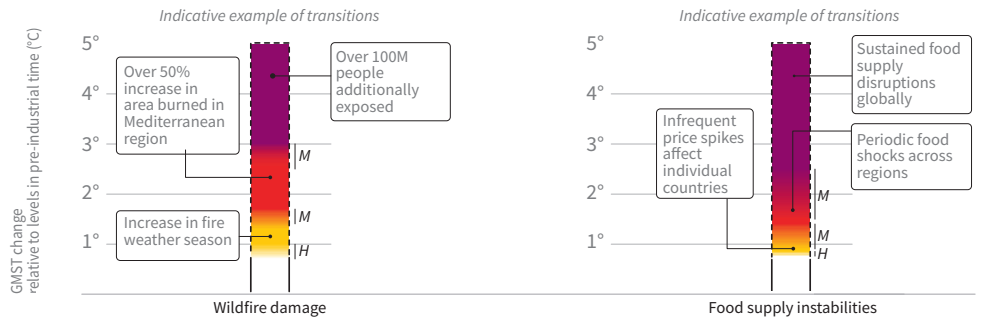
- SSP5 includes a peak and decline in population (~7 billion in 2100), high income, reduced inequalities, and free trade. This pathway includes resource-intensive production, consumption and lifestyles. Relative to other pathways, SSP5 has high challenges to mitigation, but low challenges to adaptation (i.e., high adaptive capacity).

- The SSPs can be combined with Representative Concentration Pathways (RCPs) which imply different levels of mitigation, with implications for adaptation. Therefore, SSPs can be consistent with different levels of global mean surface temperature rise as projected by different SSP-RCP combinations. However, some SSP-RCP combinations are not possible; for instance RCP2.6 and lower levels of future global mean surface temperature rise (e.g., 1.5°C) are not possible in SSP3 in modelled pathways. {1.2.2, 6.1.4, Cross-Chapter Box 1 in Chapter 1, Cross-Chapter Box 9 in Chapter 6}

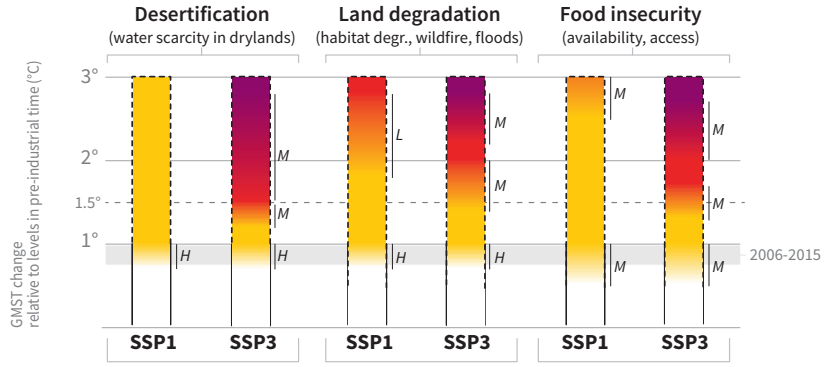
A. Risks to humans and ecosystems from changes in land-based processes as a result of climate change

Increases in global mean surface temperature (GMST), relative to pre-industrial levels, affect processes involved in **desertification** (water scarcity), **land degradation** (soil erosion, vegetation loss, wildfire, permafrost thaw) and **food security** (crop yield and food supply instabilities). Changes in these processes drive risks to food systems, livelihoods, infrastructure, the value of land, and human and ecosystem health. Changes in one process (e.g. wildfire or water scarcity) may result in compound risks. Risks are location-specific and differ by region.

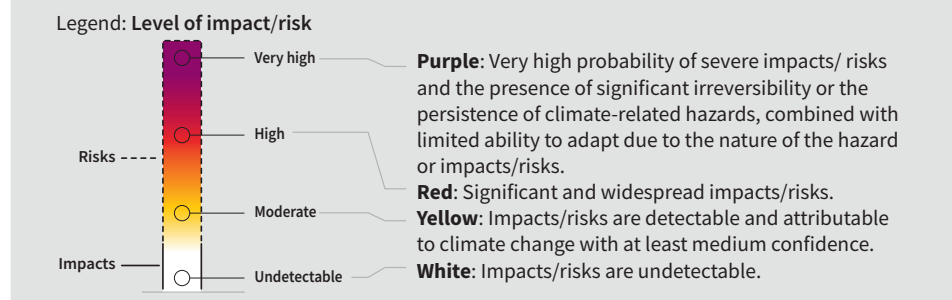




B. Different socioeconomic pathways affect levels of climate related risks



Socio-economic choices can reduce or exacerbate climate related risks as well as influence the rate of temperature increase. The **SSP1** pathway illustrates a world with low population growth, high income and reduced inequalities, food produced in low GHG emission systems, effective land use regulation and high adaptive capacity. The **SSP3** pathway has the opposite trends. Risks are lower in SSP1 compared with SSP3 given the same level of GMST increase.



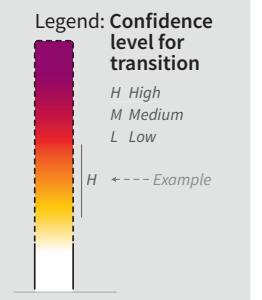


Figure SPM.2: Risks to land-related human systems and ecosystems from global climate change, socio-economic development and mitigation choices in terrestrial ecosystems. | As in previous IPCC reports the literature was used to make expert judgements to assess the levels of global warming at which levels of risk are undetectable, moderate, high or very high, as described further in Chapter 7 and other parts of the underlying report. The Figure indicates assessed risks at approximate warming levels which may be influenced by a variety of factors, including adaptation responses. The assessment considers adaptive capacity consistent with the SSP pathways as described below. **Panel A**: Risks to selected elements of the land system as a function of global mean surface temperature {2.1, Box 2.1, 3.5, 3.7.1.1, 4.4.1.1, 4.4.1.2, 4.4.1.3, 5.2.2, 5.2.3, 5.2.4, 5.2.5, 7.2, 7.3, Table SM7.1}. Links to broader systems are illustrative and not intended to be comprehensive. Risk levels are estimated assuming medium exposure and vulnerability driven by moderate trends in socioeconomic conditions broadly consistent with an SSP2 pathway. {Table SM7.4} **Panel B**: Risks associated with desertification, land degradation and food security due to climate change and patterns of socio-economic development. Increasing risks associated with desertification include population exposed and vulnerable to water scarcity in drylands. Risks related to land degradation include increased habitat degradation, population exposed to wildfire and floods and costs of floods. Risks to food security include availability and access to food, including population at risk of hunger, food price increases and increases in disability adjusted life years attributable due to childhood underweight. Risks are assessed for two contrasted socio-economic pathways (SSP1 and SSP3 {Box SPM.1}) excluding the effects of targeted mitigation policies. {3.5, 4.2.1.2, 5.2.2, 5.2.3, 5.2.4, 5.2.5, 6.1.4, 7.2, Table SM7.5} Risks are not indicated beyond 3°C because SSP1 does not exceed this level of temperature change. **All panels:** As part of the assessment, literature was compiled and data extracted into a summary table. A formal expert elicitation protocol (based on modified-Delphi technique and the Sheffield Elicitation Framework), was followed to identify risk transition thresholds. This included a multi-round elicitation process with two rounds of independent anonymous threshold judgement, and a final consensus discussion. Further information on methods and underlying literature can be found in Chapter 7 Supplementary Material.

A.5 Climate change creates additional stresses on land, exacerbating existing risks to livelihoods, biodiversity, human and ecosystem health, infrastructure, and food systems (*high confidence*). Increasing impacts on land are projected under all future GHG emission scenarios (*high confidence*). Some regions will face higher risks, while some regions will face risks previously not anticipated (*high confidence*). Cascading risks with impacts on multiple systems and sectors also vary across regions (*high confidence*). (Figure SPM.2) {2.2, 3.5, 4.2, 4.4, 4.7, 5.1, 5.2, 5.8, 6.1, 7.2, 7.3, Cross-Chapter Box 9 in Chapter 6}

A.5.1 With increasing warming, the frequency, intensity and duration of heat related events including heatwaves are projected to continue to increase through the 21st century (*high confidence*). The frequency and intensity of droughts are projected to increase particularly in the Mediterranean region and southern Africa (*medium confidence*). The frequency and intensity of extreme rainfall events are projected to increase in many regions (*high confidence*). {2.2.5, 3.5.1, 4.2.3, 5.2}

A.5.2 With increasing warming, climate zones are projected to further shift poleward in the middle and high latitudes (*high confidence*). In high-latitude regions, warming is projected to increase disturbance in boreal forests, including drought, wildfire, and pest outbreaks (*high confidence*). In tropical regions, under medium and high GHG emissions scenarios, warming is projected to result in the emergence of unprecedented[29] climatic conditions by the mid to late 21st century (*medium confidence*). {2.2.4, 2.2.5, 2.5.3, 4.3.2}

A.5.3 Current levels of global warming are associated with moderate risks from increased dryland water scarcity, soil erosion, vegetation loss, wildfire damage, permafrost thawing, coastal degradation and tropical crop yield decline (*high confidence*). Risks, including cascading risks, are projected to become increasingly severe with increasing temperatures. At around 1.5°C of global warming the risks from dryland water scarcity, wildfire damage, permafrost degradation and food supply instabilities are projected to be high (*medium confidence*). At around 2°C of global warming the risk from permafrost degradation and food supply instabilities are projected to be very high (*medium confidence*). Additionally, at around 3°C of global warming risk from vegetation loss, wildfire damage, and dryland water scarcity are also projected to be very high (*medium confidence*). Risks from droughts, water stress, heat related events such as heatwaves and habitat degradation simultaneously increase between 1.5°C and 3°C warming (*low confidence*). (Figure SPM.2) {7.2.2, Cross-Chapter Box 9 in Chapter 6, Chapter 7 Supplementary Material}

A.5.4 The stability of food supply[30] is projected to decrease as the magnitude and frequency of extreme weather events that disrupt food chains increases (*high confidence*). Increased atmospheric CO_2 levels can also lower the nutritional quality of crops (*high confidence*). In SSP2, global crop and economic models project a median increase of 7.6% (range of 1–23%) in cereal prices in 2050 due to climate change (RCP6.0), leading to higher food prices and increased risk of food insecurity and hunger (*medium*

[29] Unprecedented climatic conditions are defined in this report as 'not having occurred anywhere during the 20th century'. They are characterised by high temperature with strong seasonality and shifts in precipitation. In the literature assessed, the effect of climatic variables other than temperature and precipitation were not considered.

[30] The supply of food is defined in this report as 'encompassing availability and access (including price)'. Food supply instability refers to variability that influences food security through reducing access.

Summary for Policymakers

SPM

confidence). The most vulnerable people will be more severely affected (*high confidence*). {5.2.3, 5.2.4, 5.2.5, 5.8.1, 7.2.2.2, 7.3.1}

A.5.5 In drylands, climate change and desertification are projected to cause reductions in crop and livestock productivity (*high confidence*), modify the plant species mix and reduce biodiversity (*medium confidence*). Under SSP2, the dryland population vulnerable to water stress, drought intensity and habitat degradation is projected to reach 178 million people by 2050 at 1.5°C warming, increasing to 220 million people at 2°C warming, and 277 million people at 3°C warming (*low confidence*). {3.5.1, 3.5.2, 3.7.3}

A.5.6 Asia and Africa[31] are projected to have the highest number of people vulnerable to increased desertification. North America, South America, Mediterranean, southern Africa and central Asia may be increasingly affected by wildfire. The tropics and subtropics are projected to be most vulnerable to crop yield decline. Land degradation resulting from the combination of sea-level rise and more intense cyclones is projected to jeopardise lives and livelihoods in cyclone prone areas (*very high confidence*). Within populations, women, the young, elderly and poor are most at risk (*high confidence*). {3.5.1, 3.5.2, 4.4, Table 4.1, 5.2.2, 7.2.2, Cross-Chapter Box 3 in Chapter 2}

A.5.7 Changes in climate can amplify environmentally induced migration both within countries and across borders (*medium confidence*), reflecting multiple drivers of mobility and available adaptation measures (*high confidence*). Extreme weather and climate or slow-onset events may lead to increased displacement, disrupted food chains, threatened livelihoods (*high confidence*), and contribute to exacerbated stresses for conflict (*medium confidence*). {3.4.2, 4.7.3, 5.2.3, 5.2.4, 5.2.5, 5.8.2, 7.2.2, 7.3.1}

A.5.8 Unsustainable land management has led to negative economic impacts (*high confidence*). Climate change is projected to exacerbate these negative economic impacts (*high confidence*). {4.3.1, 4.4.1, 4.7, 4.8.5, 4.8.6, 4.9.6, 4.9.7, 4.9.8, 5.2, 5.8.1, 7.3.4, 7.6.1, Cross-Chapter Box 10 in Chapter 7}

A.6 The level of risk posed by climate change depends both on the level of warming and on how population, consumption, production, technological development, and land management patterns evolve (*high confidence*). Pathways with higher demand for food, feed, and water, more resource-intensive consumption and production, and more limited technological improvements in agriculture yields result in higher risks from water scarcity in drylands, land degradation, and food insecurity (*high confidence*). (Figure SPM.2b) {5.1.4, 5.2.3, 6.1.4, 7.2, Cross-Chapter Box 9 in Chapter 6}

A.6.1 Projected increases in population and income, combined with changes in consumption patterns, result in increased demand for food, feed, and water in 2050 in all SSPs (*high confidence*). These changes, combined with land management practices, have implications for land-use change, food insecurity, water scarcity, terrestrial GHG emissions, carbon sequestration potential, and biodiversity (*high confidence*). Development pathways in which incomes increase and the demand for land conversion is reduced, either through reduced agricultural demand or improved productivity, can lead to reductions in food insecurity (*high confidence*). All assessed future socio-economic pathways result in increases in water demand and water scarcity (*high confidence*). SSPs with greater cropland expansion result in larger declines in biodiversity (*high confidence*). {6.1.4}

A.6.2 Risks related to water scarcity in drylands are lower in pathways with low population growth, less increase in water demand, and high adaptive capacity, as in SSP1. In these scenarios the risk from water scarcity in drylands is moderate even at global warming of 3°C (*low confidence*). By contrast, risks related to water scarcity in drylands are greater for pathways with high population growth, high vulnerability, higher water demand, and low adaptive capacity, such as SSP3. In SSP3 the transition from moderate to high risk occurs between 1.2°C and 1.5°C (*medium confidence*). (Figure SPM.2b, Box SPM.1) {7.2}

A.6.3 Risks related to climate change driven land degradation are higher in pathways with a higher population, increased land-use change, low adaptive capacity and other barriers to adaptation (e.g., SSP3). These scenarios result in more people exposed to ecosystem degradation, fire, and coastal flooding (*medium confidence*). For land degradation, the projected transition from moderate to high risk occurs for global warming between 1.8°C and 2.8°C in SSP1 (*low confidence*) and between 1.4°C and 2°C in SSP3 (*medium confidence*). The projected transition from high to very high risk occurs between 2.2°C and 2.8°C for SSP3 (*medium confidence*). (Figure SPM.2b) {4.4, 7.2}

[31] West Africa has a high number of people vulnerable to increased desertification and yield decline. North Africa is vulnerable to water scarcity.

A.6.4 Risks related to food security are greater in pathways with lower income, increased food demand, increased food prices resulting from competition for land, more limited trade, and other challenges to adaptation (e.g., SSP3) (*high confidence*). For food security, the transition from moderate to high risk occurs for global warming between 2.5°C and 3.5°C in SSP1 (*medium confidence*) and between 1.3°C and 1.7°C in SSP3 (*medium confidence*). The transition from high to very high risk occurs between 2°C and 2.7°C for SSP3 (*medium confidence*). (Figure SPM.2b) {7.2}

A.6.5 Urban expansion is projected to lead to conversion of cropland leading to losses in food production (*high confidence*). This can result in additional risks to the food system. Strategies for reducing these impacts can include urban and peri-urban food production and management of urban expansion, as well as urban green infrastructure that can reduce climate risks in cities[32] (*high confidence*). (Figure SPM.3) {4.9.1, 5.5, 5.6, 6.3, 6.4, 7.5.6}

[32] The land systems considered in this report do not include urban ecosystem dynamics in detail. Urban areas, urban expansion, and other urban processes and their relation to land-related processes are extensive, dynamic, and complex. Several issues addressed in this report such as population, growth, incomes, food production and consumption, food security, and diets have close relationships with these urban processes. Urban areas are also the setting of many processes related to land-use change dynamics, including loss of ecosystem functions and services, that can lead to increased disaster risk. Some specific urban issues are assessed in this report.

B. Adaptation and mitigation response options

B.1 Many land-related responses that contribute to climate change adaptation and mitigation can also combat desertification and land degradation and enhance food security. The potential for land-related responses and the relative emphasis on adaptation and mitigation is context specific, including the adaptive capacities of communities and regions. While land-related response options can make important contributions to adaptation and mitigation, there are some barriers to adaptation and limits to their contribution to global mitigation. (*very high confidence*) (Figure SPM.3) {2.6, 4.8, 5.6, 6.1, 6.3, 6.4}

B.1.1 Some land-related actions are already being taken that contribute to climate change adaptation, mitigation and sustainable development. The response options were assessed across adaptation, mitigation, combating desertification and land degradation, food security and sustainable development, and a select set of options deliver across all of these challenges. These options include, but are not limited to, sustainable food production, improved and sustainable forest management, soil organic carbon management, ecosystem conservation and land restoration, reduced deforestation and degradation, and reduced food loss and waste (*high confidence*). These response options require integration of biophysical, socioeconomic and other enabling factors. {6.3, 6.4.5, 7.5.6, Cross-Chapter Box 10 in Chapter 7}

B.1.2 While some response options have immediate impacts, others take decades to deliver measurable results. Examples of response options with immediate impacts include the conservation of high-carbon ecosystems such as peatlands, wetlands, rangelands, mangroves and forests. Examples that provide multiple ecosystem services and functions, but take more time to deliver, include afforestation and reforestation as well as the restoration of high-carbon ecosystems, agroforestry, and the reclamation of degraded soils (*high confidence*). {6.4.5, 7.5.6, Cross-Chapter Box 10 in Chapter 7}

B.1.3 The successful implementation of response options depends on consideration of local environmental and socio-economic conditions. Some options such as soil carbon management are potentially applicable across a broad range of land use types, whereas the efficacy of land management practices relating to organic soils, peatlands and wetlands, and those linked to freshwater resources, depends on specific agro-ecological conditions (*high confidence*). Given the site-specific nature of climate change impacts on food system components and wide variations in agroecosystems, adaptation and mitigation options and their barriers are linked to environmental and cultural context at regional and local levels (*high confidence*). Achieving land degradation neutrality depends on the integration of multiple responses across local, regional and national scales and across multiple sectors including agriculture, pasture, forest and water (*high confidence*). {4.8, 6.2, 6.3, 6.4.4, 7.5.6}

B.1.4 Land-based options that deliver carbon sequestration in soil or vegetation, such as afforestation, reforestation, agroforestry, soil carbon management on mineral soils, or carbon storage in harvested wood products, do not continue to sequester carbon indefinitely (*high confidence*). Peatlands, however, can continue to sequester carbon for centuries (*high confidence*). When vegetation matures or when vegetation and soil carbon reservoirs reach saturation, the annual removal of CO_2 from the atmosphere declines towards zero, while carbon stocks can be maintained (*high confidence*). However, accumulated carbon in vegetation and soils is at risk from future loss (or sink reversal) triggered by disturbances such as flood, drought, fire, or pest outbreaks, or future poor management (*high confidence*). {6.4.1}

B.2 Most of the response options assessed contribute positively to sustainable development and other societal goals (*high confidence*). Many response options can be applied without competing for land and have the potential to provide multiple co-benefits (*high confidence*). A further set of response options has the potential to reduce demand for land, thereby enhancing the potential for other response options to deliver across each of climate change adaptation and mitigation, combating desertification and land degradation, and enhancing food security (*high confidence*). (Figure SPM.3) {4.8, 6.2, 6.3.6, 6.4.3}

B.2.1 A number of land management options, such as improved management of cropland and grazing lands, improved and sustainable forest management, and increased soil organic carbon content, do not require land use change and do not create demand for more land conversion (*high confidence*). Further, a number of response options such as increased food productivity, dietary choices and food losses, and waste reduction, can reduce demand for land conversion, thereby potentially freeing land and creating opportunities for enhanced implementation of other response options (*high confidence*). Response

options that reduce competition for land are possible and are applicable at different scales, from farm to regional (*high confidence*). (Figure SPM.3) {4.8, 6.3.6, 6.4}

B.2.2 A wide range of adaptation and mitigation responses, e.g., preserving and restoring natural ecosystems such as peatland, coastal lands and forests, biodiversity conservation, reducing competition for land, fire management, soil management, and most risk management options (e.g., use of local seeds, disaster risk management, risk sharing instruments) have the potential to make positive contributions to sustainable development, enhancement of ecosystem functions and services and other societal goals (*medium confidence*). Ecosystem-based adaptation can, in some contexts, promote nature conservation while alleviating poverty and can even provide co-benefits by removing GHGs and protecting livelihoods (e.g., mangroves) (*medium confidence*). {6.4.3, 7.4.6.2}

B.2.3 Most of the land management-based response options that do not increase competition for land, and almost all options based on value chain management (e.g., dietary choices, reduced post-harvest losses, reduced food waste) and risk management, can contribute to eradicating poverty and eliminating hunger while promoting good health and wellbeing, clean water and sanitation, climate action, and life on land (*medium confidence*). {6.4.3}

B.3 Although most response options can be applied without competing for available land, some can increase demand for land conversion (*high confidence*). At the deployment scale of several $GtCO_2$ yr^{-1}, this increased demand for land conversion could lead to adverse side effects for adaptation, desertification, land degradation and food security (*high confidence*). If applied on a limited share of total land and integrated into sustainably managed landscapes, there will be fewer adverse side-effects and some positive co-benefits can be realised (*high confidence*). (Figure SPM.3) {4.5, 6.2, 6.4, Cross-Chapter Box 7 in Chapter 6}

B.3.1 If applied at scales necessary to remove CO_2 from the atmosphere at the level of several $GtCO_2$ yr^{-1}, afforestation, reforestation and the use of land to provide feedstock for bioenergy with or without carbon capture and storage, or for biochar, could greatly increase demand for land conversion (*high confidence*). Integration into sustainably managed landscapes at appropriate scale can ameliorate adverse impacts (*medium confidence*). Reduced grassland conversion to croplands, restoration and reduced conversion of peatlands, and restoration and reduced conversion of coastal wetlands affect smaller land areas globally, and the impacts on land use change of these options are smaller or more variable (*high confidence*). (Figure SPM.3) {Cross-Chapter Box 7 in Chapter 6, 6.4}

B.3.2 While land can make a valuable contribution to climate change mitigation, there are limits to the deployment of land-based mitigation measures such as bioenergy crops or afforestation. Widespread use at the scale of several millions of km^2 globally could increase risks for desertification, land degradation, food security and sustainable development (*medium confidence*). Applied on a limited share of total land, land-based mitigation measures that displace other land uses have fewer adverse side-effects and can have positive co-benefits for adaptation, desertification, land degradation or food security. (*high confidence*) (Figure SPM.3) {4.2, 4.5, 6.4; Cross-Chapter Box 7 in Chapter 6}

B.3.3 The production and use of biomass for bioenergy can have co-benefits, adverse side-effects, and risks for land degradation, food insecurity, GHG emissions and other environmental and sustainable development goals (*high confidence*). These impacts are context specific and depend on the scale of deployment, initial land use, land type, bioenergy feedstock, initial carbon stocks, climatic region and management regime, and other land-demanding response options can have a similar range of consequences (*high confidence*). The use of residues and organic waste as bioenergy feedstock can mitigate land use change pressures associated with bioenergy deployment, but residues are limited and the removal of residues that would otherwise be left on the soil could lead to soil degradation (*high confidence*). (Figure SPM.3) {2.6.1.5, Cross-Chapter Box 7 in Chapter 6}

B.3.4 For projected socioeconomic pathways with low population, effective land-use regulation, food produced in low-GHG emission systems and lower food loss and waste (SSP1), the transition from low to moderate risk to food security, land degradation and water scarcity in dry lands occur between 1 and 4 million km^2 of bioenergy or bioenergy with carbon capture and storage (BECCS) (*medium confidence*). By contrast, in pathways with high population, low income and slow rates of technological change (SSP3), the transition from low to moderate risk occurs between 0.1 and 1 million km^2 (*medium confidence*). (Box SPM.1) {6.4, Table SM7.6, Cross-Chapter Box 7 in Chapter 6}

B.4 Many activities for combating desertification can contribute to climate change adaptation with mitigation co-benefits, as well as to halting biodiversity loss with sustainable development co-benefits to society (*high confidence*). Avoiding, reducing and reversing desertification would enhance soil fertility, increase carbon storage in soils and biomass, while benefitting agricultural productivity and food security (*high confidence*). Preventing desertification is preferable to attempting to restore degraded land due to the potential for residual risks and maladaptive outcomes (*high confidence*). {3.6.1, 3.6.2, 3.6.3, 3.6.4, 3.7.1, 3.7.2}

B.4.1 Solutions that help adapt to and mitigate climate change while contributing to combating desertification are site and regionally specific and include *inter alia*: water harvesting and micro-irrigation, restoring degraded lands using drought-resilient ecologically appropriate plants, agroforestry, and other agroecological and ecosystem-based adaptation practices (*high confidence*). {3.3, 3.6.1, 3.7.2, 3.7.5, 5.2, 5.6}

B.4.2 Reducing dust and sand storms and sand dune movement can lessen the negative effects of wind erosion and improve air quality and health (*high confidence*). Depending on water availability and soil conditions, afforestation, tree planting and ecosystem restoration programs, which aim for the creation of windbreaks in the form of 'green walls' and 'green dams' using native and other climate resilient tree species with low water needs, can reduce sand storms, avert wind erosion, and contribute to carbon sinks, while improving micro-climates, soil nutrients and water retention (*high confidence*). {3.3, 3.6.1, 3.7.2, 3.7.5}

B.4.3 Measures to combat desertification can promote soil carbon sequestration (*high confidence*). Natural vegetation restoration and tree planting on degraded land enriches, in the long term, carbon in the topsoil and subsoil (*medium confidence*). Modelled rates of carbon sequestration following the adoption of conservation agriculture practices in drylands depend on local conditions (*medium confidence*). If soil carbon is lost, it may take a prolonged period of time for carbon stocks to recover. {3.1.4, 3.3, 3.6.1, 3.6.3, 3.7.1, 3.7.2}

B.4.4 Eradicating poverty and ensuring food security can benefit from applying measures promoting land degradation neutrality (including avoiding, reducing and reversing land degradation) in rangelands, croplands and forests, which contribute to combating desertification, while mitigating and adapting to climate change within the framework of sustainable development. Such measures include avoiding deforestation and locally suitable practices including management of rangeland and forest fires (*high confidence*). {3.4.2, 3.6.1, 3.6.2, 3.6.3, 4.8.5}

B.4.5 Currently there is a lack of knowledge of adaptation limits and potential maladaptation to combined effects of climate change and desertification. In the absence of new or enhanced adaptation options, the potential for residual risks and maladaptive outcomes is high (*high confidence*). Even when solutions are available, social, economic and institutional constraints could pose barriers to their implementation (*medium confidence*). Some adaptation options can become maladaptive due to their environmental impacts, such as irrigation causing soil salinisation or over extraction leading to ground-water depletion (*medium confidence*). Extreme forms of desertification can lead to the complete loss of land productivity, limiting adaptation options or reaching the limits to adaptation (*high confidence*). {Executive Summary Chapter 3, 3.6.4, 3.7.5, 7.4.9}

B.4.6 Developing, enabling and promoting access to cleaner energy sources and technologies can contribute to adaptation and mitigating climate change and combating desertification and forest degradation through decreasing the use of traditional biomass for energy while increasing the diversity of energy supply (*medium confidence*). This can have socioeconomic and health benefits, especially for women and children. (*high confidence*). The efficiency of wind and solar energy infrastructures is recognised; the efficiency can be affected in some regions by dust and sand storms (*high confidence*). {3.5.3, 3.5.4, 4.4.4, 7.5.2, Cross-Chapter Box 12 in Chapter 7}

B.5 Sustainable land management,[33] including sustainable forest management,[34] can prevent and reduce land degradation, maintain land productivity, and sometimes reverse the adverse impacts of climate change on land degradation (*very high confidence*). It can also contribute to mitigation and adaptation (*high confidence*). Reducing and reversing land degradation, at scales from individual farms to entire watersheds, can provide cost effective, immediate, and long-term benefits to communities and support several Sustainable Development Goals (SDGs) with co-benefits for adaptation (*very high confidence*) and mitigation (*high confidence*). Even with implementation of sustainable land management, limits to adaptation can be exceeded in some situations (*medium confidence*). {1.3.2, 4.1.5, 4.8, 7.5.6, Table 4.2}

B.5.1 Land degradation in agriculture systems can be addressed through sustainable land management, with an ecological and socioeconomic focus, with co-benefits for climate change adaptation. Management options that reduce vulnerability to soil erosion and nutrient loss include growing green manure crops and cover crops, crop residue retention, reduced/zero tillage, and maintenance of ground cover through improved grazing management (*very high confidence*). {4.8}

B.5.2 The following options also have mitigation co-benefits. Farming systems such as agroforestry, perennial pasture phases and use of perennial grains, can substantially reduce erosion and nutrient leaching while building soil carbon (*high confidence*). The global sequestration potential of cover crops would be about 0.44 ± 0.11 $GtCO_2$ yr^{-1} if applied to 25% of global cropland (*high confidence*). The application of certain biochars can sequester carbon (*high confidence*), and improve soil conditions in some soil types/climates (*medium confidence*). {4.8.1.1, 4.8.1.3, 4.9.2, 4.9.5, 5.5.1, 5.5.4, Cross-Chapter Box 6 in Chapter 5}

B.5.3 Reducing deforestation and forest degradation lowers GHG emissions (*high confidence*), with an estimated technical mitigation potential of 0.4–5.8 $GtCO_2$ yr^{-1}. By providing long-term livelihoods for communities, sustainable forest management can reduce the extent of forest conversion to non-forest uses (e.g., cropland or settlements) (*high confidence*). Sustainable forest management aimed at providing timber, fibre, biomass, non-timber resources and other ecosystem functions and services, can lower GHG emissions and can contribute to adaptation (*high confidence*). {2.6.1.2, 4.1.5, 4.3.2, 4.5.3, 4.8.1.3, 4.8.3, 4.8.4}

B.5.4 Sustainable forest management can maintain or enhance forest carbon stocks, and can maintain forest carbon sinks, including by transferring carbon to wood products, thus addressing the issue of sink saturation (*high confidence*). Where wood carbon is transferred to harvested wood products, these can store carbon over the long-term and can substitute for emissions-intensive materials reducing emissions in other sectors (*high confidence*). Where biomass is used for energy, e.g., as a mitigation strategy, the carbon is released back into the atmosphere more quickly (*high confidence*). (Figure SPM.3) {2.6.1, 2.7, 4.1.5, 4.8.4, 6.4.1, Cross-Chapter Box 7 in Chapter 6}

B.5.5 Climate change can lead to land degradation, even with the implementation of measures intended to avoid, reduce or reverse land degradation (*high confidence*). Such limits to adaptation are dynamic, site-specific and are determined through the interaction of biophysical changes with social and institutional conditions (*very high confidence*). In some situations, exceeding the limits of adaptation can trigger escalating losses or result in undesirable transformational changes (*medium confidence*) such as forced migration (*low confidence*), conflicts (*low confidence*) or poverty (*medium confidence*). Examples of climate change induced land degradation that may exceed limits to adaptation include coastal erosion exacerbated by sea level rise where land disappears (*high confidence*), thawing of permafrost affecting infrastructure and livelihoods (*medium confidence*), and extreme soil erosion causing loss of productive capacity (*medium confidence*). {4.7, 4.8.5, 4.8.6, 4.9.6, 4.9.7, 4.9.8}

B.6 Response options throughout the food system, from production to consumption, including food loss and waste, can be deployed and scaled up to advance adaptation and mitigation (*high confidence*). The total technical mitigation potential from crop and livestock activities, and agroforestry is estimated as 2.3 – 9.6 $GtCO_2eq$ yr^{-1} by 2050 (*medium confidence*). The total technical mitigation potential of dietary changes is estimated as 0.7 – 8 $GtCO_2eq$ yr^{-1} by 2050 (*medium confidence*). {5.3, 5.5, 5.6}

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[33] Sustainable land management is defined in this report as 'the stewardship and use of land resources, including soils, water, animals and plants, to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions'. Examples of options include, *inter alia*, agroecology (including agroforestry), conservation agriculture and forestry practices, crop and forest species diversity, appropriate crop and forest rotations, organic farming, integrated pest management, the conservation of pollinators, rain water harvesting, range and pasture management, and precision agriculture systems.

[34] Sustainable forest management is defined in this report as 'the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality, and their potential to fulfil now and in the future, relevant ecological, economic and social functions at local, national and global levels and that does not cause damage to other ecosystems'.

B.6.1 Practices that contribute to climate change adaptation and mitigation in cropland include increasing soil organic matter, erosion control, improved fertiliser management, improved crop management, for example paddy rice management, and use of varieties and genetic improvements for heat and drought tolerance. For livestock, options include better grazing land management, improved manure management, higher-quality feed, and use of breeds and genetic improvement. Different farming and pastoral systems can achieve reductions in the emissions intensity of livestock products. Depending on the farming and pastoral systems and level of development, reductions in the emissions intensity of livestock products may lead to absolute reductions in GHG emissions (*medium confidence*). Many livestock related options can enhance the adaptive capacity of rural communities, in particular, of smallholders and pastoralists. Significant synergies exist between adaptation and mitigation, for example through sustainable land management approaches (*high confidence*). {4.8, 5.3.3, 5.5.1, 5.6}

B.6.2 Diversification in the food system (e.g., implementation of integrated production systems, broad-based genetic resources, and diets) can reduce risks from climate change (*medium confidence*). Balanced diets, featuring plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, and animal-sourced food produced in resilient, sustainable and low-GHG emission systems, present major opportunities for adaptation and mitigation while generating significant co-benefits in terms of human health (*high confidence*). By 2050, dietary changes could free several million km^2 (*medium confidence*) of land and provide a technical mitigation potential of 0.7 to 8.0 $GtCO_2eq\ yr^{-1}$, relative to business as usual projections (*high confidence*). Transitions towards low-GHG emission diets may be influenced by local production practices, technical and financial barriers and associated livelihoods and cultural habits (*high confidence*). {5.3, 5.5.2, 5.5, 5.6}

B.6.3 Reduction of food loss and waste can lower GHG emissions and contribute to adaptation through reduction in the land area needed for food production (*medium confidence*). During 2010-2016, global food loss and waste contributed 8 –10% of total anthropogenic GHG emissions (*medium confidence*). Currently, 25 –30% of total food produced is lost or wasted (*medium confidence*). Technical options such as improved harvesting techniques, on-farm storage, infrastructure, transport, packaging, retail and education can reduce food loss and waste across the supply chain. Causes of food loss and waste differ substantially between developed and developing countries, as well as between regions (*medium confidence*). By 2050, reduced food loss and waste can free several million km^2 of land (*low confidence*). {5.5.2, 6.3.6}

B.7 Future land use depends, in part, on the desired climate outcome and the portfolio of response options deployed (*high confidence*). All assessed modelled pathways that limit warming to 1.5°C or well below 2°C require land-based mitigation and land-use change, with most including different combinations of reforestation, afforestation, reduced deforestation, and bioenergy (*high confidence*). A small number of modelled pathways achieve 1.5°C with reduced land conversion (*high confidence*) and thus reduced consequences for desertification, land degradation, and food security (*medium confidence*). (Figure SPM.4) {2.6, 6.4, 7.4, 7.6, Cross-Chapter Box 9 in Chapter 6}

B.7.1 Modelled pathways limiting global warming to 1.5°C[35] include more land-based mitigation than higher warming level pathways (*high confidence*), but the impacts of climate change on land systems in these pathways are less severe (*medium confidence*). (Figure SPM.2, Figure SPM.4) {2.6, 6.4, 7.4, Cross-Chapter Box 9 in Chapter 6}

B.7.2 Modelled pathways limiting global warming to 1.5°C and 2°C project a 2 million km^2 reduction to a 12 million km^2 increase in forest area in 2050 relative to 2010 (*medium confidence*). 3°C pathways project lower forest areas, ranging from a 4 million km^2 reduction to a 6 million km^2 increase (*medium confidence*). (Figure SPM.3, Figure SPM.4) {2.5, 6.3, 7.3, 7.5, Cross-Chapter Box 9 in Chapter 6}

B.7.3 The land area needed for bioenergy in modelled pathways varies significantly depending on the socio-economic pathway, the warming level, and the feedstock and production system used (*high confidence*). Modelled pathways limiting global warming to 1.5°C use up to 7 million km^2 for bioenergy in 2050; bioenergy land area is smaller in 2°C (0.4 to 5 million km^2) and 3°C pathways (0.1 to 3 million km^2) (*medium confidence*). Pathways with large levels of land conversion may imply adverse side-effects impacting water scarcity, biodiversity, land degradation, desertification, and food security, if not adequately and carefully managed, whereas best practice implementation at appropriate scales can have co-benefits, such as management of dryland salinity, enhanced biocontrol and biodiversity and enhancing soil carbon sequestration (*high confidence*). (Figure SPM.3) {2.6, 6.1, 6.4, 7.2, Cross-Chapter Box 7 in Chapter 6}

[35] In this report references to pathways limiting global warming to a particular level are based on a 66% probability of staying below that temperature level in 2100 using the MAGICC model.

B.7.4 Most mitigation pathways include substantial deployment of bioenergy technologies. A small number of modelled pathways limit warming to 1.5ºC with reduced dependence on bioenergy and BECCS (land area below <1 million km^2 in 2050) and other carbon dioxide removal (CDR) options (*high confidence*). These pathways have even more reliance on rapid and far-reaching transitions in energy, land, urban systems and infrastructure, and on behavioural and lifestyle changes compared to other 1.5°C pathways. {2.6.2, 5.5.1, 6.4, Cross-Chapter Box 7 in Chapter 6}

B.7.5 These modelled pathways do not consider the effects of climate change on land or CO_2 fertilisation. In addition, these pathways include only a subset of the response options assessed in this report (*high confidence*); the inclusion of additional response options in models could reduce the projected need for bioenergy or CDR that increases the demand for land. {6.4.4, Cross-Chapter Box 9 in Chapter 6}

Potential global contribution of response options to mitigation, adaptation, combating desertification and land degradation, and enhancing food security

Panel A shows response options that can be implemented without or with limited competition for land, including some that have the potential to reduce the demand for land. Co-benefits and adverse side effects are shown quantitatively based on the high end of the range of potentials assessed. Magnitudes of contributions are categorised using thresholds for positive or negative impacts. Letters within the cells indicate confidence in the magnitude of the impact relative to the thresholds used (see legend). Confidence in the direction of change is generally higher.

	Response options based on land management	Mitigation	Adaptation	Desertification	Land Degradation	Food Security	Cost
Agriculture	Increased food productivity	L	M	L	M	H	—
	Agro-forestry	M	M	M	M	L	●
	Improved cropland management	M	L	L	L	L	●●
	Improved livestock management	M	L	L	L	L	●●●
	Agricultural diversification	L	L	L	M	L	●
	Improved grazing land management	M	L	L	L	L	—
	Integrated water management	L	L	L	L	L	●●
	Reduced grassland conversion to cropland	L	—	L	L	- L	●
Forests	Forest management	M	L	L	L	L	●●
	Reduced deforestation and forest degradation	H	L	L	L	L	●●
Soils	Increased soil organic carbon content	H	L	M	M	L	●●
	Reduced soil erosion	↔ L	L	M	M	L	●●
	Reduced soil salinization	—	L	L	L	L	●●
	Reduced soil compaction	—	L	—	L	L	●
Other ecosystems	Fire management	M	M	M	M	L	●
	Reduced landslides and natural hazards	L	L	L	L	L	—
	Reduced pollution including acidification	↔ M	M	L	L	L	—
	Restoration & reduced conversion of coastal wetlands	M	L	M	M	↔ L	—
	Restoration & reduced conversion of peatlands	M	—	na	M	- L	●
	Response options based on value chain management						
Demand	Reduced post-harvest losses	H	M	L	L	H	—
	Dietary change	H	—	L	H	H	—
	Reduced food waste (consumer or retailer)	H	—	L	M	M	—
Supply	Sustainable sourcing	—	L	—	L	L	—
	Improved food processing and retailing	L	L	—	—	L	—
	Improved energy use in food systems	L	L	—	—	L	—
	Response options based on risk management						
Risk	Livelihood diversification	—	L	—	L	L	—
	Management of urban sprawl	—	L	L	M	L	—
	Risk sharing instruments	↔ L	L	—	↔ L	L	●●

Options shown are those for which data are available to assess global potential for three or more land challenges.
The magnitudes are assessed independently for each option and are not additive.

Key for criteria used to define magnitude of impact of each integrated response option

		Mitigation *Gt CO_2-eq yr^{-1}*	Adaptation *Million people*	Desertification *Million km^2*	Land Degradation *Million km^2*	Food Security *Million people*
Positive	Large	More than 3	Positive for more than 25	Positive for more than 3	Positive for more than 3	Positive for more than 100
	Moderate	0.3 to 3	1 to 25	0.5 to 3	0.5 to 3	1 to 100
	Small	Less than 0.3	Less than 1	Less than 0.5	Less than 0.5	Less than 1
	Negligible	No effect	No effect	No effect	No effect	No effect
Negative	- Small	Less than -0.3	Less than 1	Less than 0.5	Less than 0.5	Less than 1
	- Moderate	-0.3 to -3	1 to 25	0.5 to 3	0.5 to 3	1 to 100
	- Large	More than -3	Negative for more than 25	Negative for more than 3	Negative for more than 3	Negative for more than 100

↔ **Variable**: Can be positive or negative — no data — na not applicable

Confidence level

Indicates confidence in the estimate of magnitude category.

H High confidence
M Medium confidence
L Low confidence

Cost range

See technical caption for cost ranges in US$ tCO_2e^{-1} or US$ ha^{-1}.

●●● High cost
●● Medium cost
● Low cost
— no data

Potential global contribution of response options to mitigation, adaptation, combating desertification and land degradation, and enhancing food security

Panel B shows response options that rely on additional land-use change and could have implications across three or more land challenges under different implementation contexts. For each option, the first row (high level implementation) shows a quantitative assessment (as in Panel A) of implications for global implementation at scales delivering CO_2 removals of more than 3 $GtCO_2\ yr^{-1}$ using the magnitude thresholds shown in Panel A. The red hatched cells indicate an increasing pressure but unquantified impact. For each option, the second row (best practice implementation) shows qualitative estimates of impact if implemented using best practices in appropriately managed landscape systems that allow for efficient and sustainable resource use and supported by appropriate governance mechanisms. In these qualitative assessments, green indicates a positive impact, grey indicates a neutral interaction.

Bioenergy and BECCS

High level: Impacts on adaptation, desertification, land degradation and food security are maximum potential impacts, assuming carbon dioxide removal by BECCS at a scale of 11.3 $GtCO_2\ yr^{-1}$ in 2050, and noting that bioenergy without CCS can also achieve emissions reductions of up to several $GtCO_2\ yr^{-1}$ when it is a low carbon energy source {2.6.1; 6.3.1}. Studies linking bioenergy to food security estimate an increase in the population at risk of hunger to up to 150 million people at this level of implementation {6.3.5}. The red hatched cells for desertification and land degradation indicate that while up to 15 million km_2 of additional land is required in 2100 in 2°C scenarios which will increase pressure for desertification and land degradation, the actual area affected by this additional pressure is not easily quantified {6.3.3; 6.3.4}.

Best practice: The sign and magnitude of the effects of bioenergy and BECCS depends on the scale of deployment, the type of bioenergy feedstock, which other response options are included, and where bioenergy is grown (including prior land use and indirect land use change emissions). For example, limiting bioenergy production to marginal lands or abandoned cropland would have negligible effects on biodiversity, food security, and potentially co-benefits for land degradation; however, the benefits for mitigation could also be smaller. {Table 6.58}

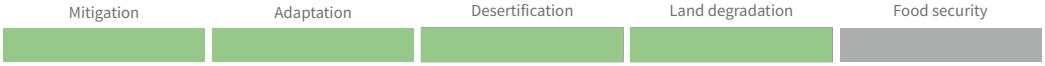
Reforestation and forest restoration

High level: Impacts on adaptation, desertification, land degradation and food security are maximum potential impacts assuming implementation of reforestation and forest restoration (partly overlapping with afforestation) at a scale of 10.1 $GtCO_2\ yr^{-1}$ removal {6.3.1}. Large-scale afforestation could cause increases in food prices of 80% by 2050, and more general mitigation measures in the AFOLU sector can translate into a rise in undernourishment of 80–300 million people; the impact of reforestation is lower {6.3.5}.

Best practice: There are co-benefits of reforestation and forest restoration in previously forested areas, assuming small scale deployment using native species and involving local stakeholders to provide a safety net for food security. Examples of sustainable implementation include, but are not limited to, reducing illegal logging and halting illegal forest loss in protected areas, reforesting and restoring forests in degraded and desertified lands {Box6.1C; Table 6.6}.

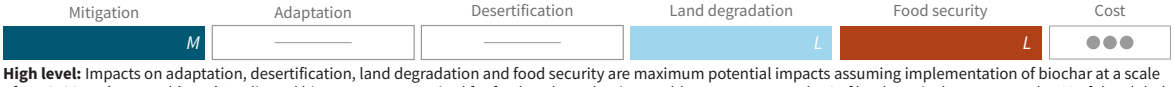
Afforestation

High level: Impacts on adaptation, desertification, land degradation and food security are maximum potential impacts assuming implementation of afforestation (partly overlapping with reforestation and forest restoration) at a scale of 8.9 $GtCO_2\ yr^{-1}$ removal {6.3.1}. Large-scale afforestation could cause increases in food prices of 80% by 2050, and more general mitigation measures in the AFOLU sector can translate into a rise in undernourishment of 80–300 million people {6.3.5}.

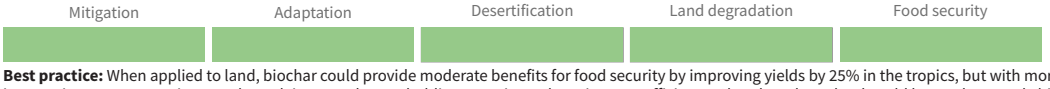


Best practice: Afforestation is used to prevent desertification and to tackle land degradation. Forested land also offers benefits in terms of food supply, especially when forest is established on degraded land, mangroves, and other land that cannot be used for agriculture. For example, food from forests represents a safety-net during times of food and income insecurity {6.3.5}.

Biochar addition to soil



High level: Impacts on adaptation, desertification, land degradation and food security are maximum potential impacts assuming implementation of biochar at a scale of 6.6 $GtCO_2\ yr^{-1}$ removal {6.3.1}. Dedicated biomass crops required for feedstock production could occupy 0.4–2.6 Mkm^2 of land, equivalent to around 20% of the global cropland area, which could potentially have a large effect on food security for up to 100 million people {6.3.5}.



Best practice: When applied to land, biochar could provide moderate benefits for food security by improving yields by 25% in the tropics, but with more limited impacts in temperate regions, or through improved water holding capacity and nutrient use efficiency. Abandoned cropland could be used to supply biomass for biochar, thus avoiding competition with food production; 5-9 Mkm^2 of land is estimated to be available for biomass production without compromising food security and biodiversity, considering marginal and degraded land and land released by pasture intensification {6.3.5}.

Figure SPM.3: Potential global contribution of response options to mitigation, adaptation, combating desertification and land degradation, and enhancing food security. | This Figure is based on an aggregation of information from studies with a wide variety of assumptions about how response options are implemented and the contexts in which they occur. Response options implemented differently at local to global scales could lead to different outcomes. **Magnitude of potential:** For panel A, magnitudes are for the technical potential of response options globally. For each land challenge, magnitudes are set relative to a marker level as follows. For mitigation, potentials are set relative to the approximate potentials for the response options with the largest individual impacts (~3 $GtCO_2$-eq yr^{-1}). The threshold for the 'large' magnitude category is set at this level. For adaptation, magnitudes are set relative to the 100 million lives estimated to be affected by climate change and a carbon-based economy between 2010 and 2030. The threshold for the 'large' magnitude category represents 25% of this total. For desertification and land degradation, magnitudes are set relative to the lower end of current estimates of degraded land, 10–60 million km^2. The threshold for the 'large' magnitude category represents 30% of the lower estimate. For food security, magnitudes are set relative to the approximately 800 million people who are currently undernourished. The threshold for the 'large' magnitude category represents 12.5% of this total. For panel B, for the first row (high level implementation) for each response option, the magnitude and thresholds are as defined for panel A. In the second row (best practice implementation) for each response option, the qualitative assessments that are green denote potential positive impacts, and those shown in grey indicate neutral interactions. Increased food production is assumed to be achieved through sustainable intensification rather than through injudicious application of additional external inputs such as agrochemicals. **Levels of confidence:** Confidence in the magnitude category (high, medium or low) into which each option falls for mitigation, adaptation, combating desertification and land degradation, and enhancing food security. *High confidence* means that there is a high level of agreement and evidence in the literature to support the categorisation as high, medium or low magnitude. *Low confidence* denotes that the categorisation of magnitude is based on few studies. *Medium confidence* reflects medium evidence and agreement in the magnitude of response. **Cost ranges:** Cost estimates are based on aggregation of often regional studies and vary in the components of costs that are included. In panel B, cost estimates are not provided for best practice implementation. One coin indicates low cost (<USD10 tCO_2-eq^{-1} or <USD20 ha^{-1}), two coins indicate medium cost (USD10-USD100 tCO_2-eq^{-1} or USD20 –USD200 ha^{-1}), and three coins indicate high cost (>USD100 tCO_2-eq^{-1} or USD200 ha^{-1}). Thresholds in USD ha^{-1} are chosen to be comparable, but precise conversions will depend on the response option. **Supporting evidence:** Supporting evidence for the magnitude of the quantitative potential for land management-based response options can be found as follows: for mitigation Table's 6.13 to 6.20, with further evidence in Section 2.7.1; for adaptation Table's 6.21 to 6.28; for combating desertification Table's 6.29 to 6.36, with further evidence in Chapter 3; for combating degradation tables 6.37 to 6.44, with further evidence in Chapter 4; for enhancing food security Table's 6.45 to 6.52, with further evidence in Chapter 5. Other synergies and trade-offs not shown here are discussed in Chapter 6. Additional supporting evidence for the qualitative assessments in the second row for each option in panel B can be found in the Table's 6.6, 6.55, 6.56 and 6.58, Section 6.3.5.1.3, and Box 6.1c.

C. Enabling response options

C.1 Appropriate design of policies, institutions and governance systems at all scales can contribute to land-related adaptation and mitigation while facilitating the pursuit of climate-adaptive development pathways (*high confidence*). Mutually supportive climate and land policies have the potential to save resources, amplify social resilience, support ecological restoration, and foster engagement and collaboration between multiple stakeholders (*high confidence*). (Figure SPM.1, Figure SPM.2, Figure SPM.3) {3.6.2, 3.6.3, 4.8, 4.9.4, 5.7, 6.3, 6.4, 7.2.2, 7.3, 7.4, 7.4.7, 7.4.8, 7.5, 7.5.5, 7.5.6, 7.6.6, Cross-Chapter Box 10 in Chapter 7}

C.1.1 Land-use zoning, spatial planning, integrated landscape planning, regulations, incentives (such as payment for ecosystem services), and voluntary or persuasive instruments (such as environmental farm planning, standards and certification for sustainable production, use of scientific, local and indigenous knowledge and collective action), can achieve positive adaptation and mitigation outcomes (*medium confidence*). They can also contribute revenue and provide incentive to rehabilitate degraded lands and adapt to and mitigate climate change in certain contexts (*medium confidence*). Policies promoting the target of land degradation neutrality can also support food security, human wellbeing and climate change adaptation and mitigation (*high confidence*). (Figure SPM.2) {3.4.2, 4.1.6, 4.7, 4.8.5, 5.1.2, 5.7.3, 7.3, 7.4.6, 7.4.7, 7.5}

C.1.2 Insecure land tenure affects the ability of people, communities and organisations to make changes to land that can advance adaptation and mitigation (*medium confidence*). Limited recognition of customary access to land and ownership of land can result in increased vulnerability and decreased adaptive capacity (*medium confidence*). Land policies (including recognition of customary tenure, community mapping, redistribution, decentralisation, co-management, regulation of rental markets) can provide both security and flexibility response to climate change (*medium confidence*). {3.6.1, 3.6.2, 5.3, 7.2.4, 7.6.4, Cross-Chapter Box 6 in Chapter 5}

C.1.3 Achieving land degradation neutrality will involve a balance of measures that avoid and reduce land degradation, through adoption of sustainable land management, and measures to reverse degradation through rehabilitation and restoration of degraded land. Many interventions to achieve land degradation neutrality commonly also deliver climate change adaptation and mitigation benefits. The pursuit of land degradation neutrality provides impetus to address land degradation and climate change simultaneously (*high confidence*). {4.5.3, 4.8.5, 4.8.7, 7.4.5}

C.1.4 Due to the complexity of challenges and the diversity of actors involved in addressing land challenges, a mix of policies, rather than single policy approaches, can deliver improved results in addressing the complex challenges of sustainable land management and climate change (*high confidence*). Policy mixes can strongly reduce the vulnerability and exposure of human and natural systems to climate change (*high confidence*). Elements of such policy mixes may include weather and health insurance, social protection and adaptive safety nets, contingent finance and reserve funds, universal access to early warning systems combined with effective contingency plans (*high confidence*). (Figure SPM.4) {1.2, 4.8, 4.9.2, 5.3.2, 5.6, 5.6.6, 5.7.2, 7.3.2, 7.4, 7.4.2, 7.4.6, 7.4.7, 7.4.8, 7.5.5, 7.5.6, 7.6.4}

C.2 Policies that operate across the food system, including those that reduce food loss and waste and influence dietary choices, enable more sustainable land-use management, enhanced food security and low emissions trajectories (*high confidence*). Such policies can contribute to climate change adaptation and mitigation, reduce land degradation, desertification and poverty as well as improve public health (*high confidence*). The adoption of sustainable land management and poverty eradication can be enabled by improving access to markets, securing land tenure, factoring environmental costs into food, making payments for ecosystem services, and enhancing local and community collective action (*high confidence*). {1.1.2, 1.2.1, 3.6.3, 4.7.1, 4.7.2, 4.8, 5.5, 6.4, 7.4.6, 7.6.5}

C.2.1 Policies that enable and incentivise sustainable land management for climate change adaptation and mitigation include improved access to markets for inputs, outputs and financial services, empowering women and indigenous peoples, enhancing local and community collective action, reforming subsidies and promoting an enabling trade system (*high confidence*). Land restoration and rehabilitation efforts can be more effective when policies support local management of natural resources, while strengthening cooperation between actors and institutions, including at the international level. {3.6.3, 4.1.6, 4.5.4, 4.8.2, 4.8.4, 5.7, 7.2, 7.3}

C.2.2 Reflecting the environmental costs of land-degrading agricultural practices can incentivise more sustainable land management (*high confidence*). Barriers to the reflection of environmental costs arise from technical difficulties in estimating these costs and those embodied in foods. {3.6.3, 5.5.1, 5.5.2, 5.6.6, 5.7, 7.4.4, Cross-Chapter Box 10 in Chapter 7}

C.2.3 Adaptation and enhanced resilience to extreme events impacting food systems can be facilitated by comprehensive risk management, including risk sharing and transfer mechanisms (*high confidence*). Agricultural diversification, expansion of market access, and preparation for increasing supply chain disruption can support the scaling up of adaptation in food systems (*high confidence*). {5.3.2, 5.3.3, 5.3.5}

C.2.4 Public health policies to improve nutrition, such as increasing the diversity of food sources in public procurement, health insurance, financial incentives, and awareness-raising campaigns, can potentially influence food demand, reduce healthcare costs, contribute to lower GHG emissions and enhance adaptive capacity (*high confidence*). Influencing demand for food, through promoting diets based on public health guidelines, can enable more sustainable land management and contribute to achieving multiple SDGs (*high confidence*). {3.4.2, 4.7.2, 5.1, 5.7, 6.3, 6.4}

C.3 Acknowledging co-benefits and trade-offs when designing land and food policies can overcome barriers to implementation (*medium confidence*). Strengthened multi-level, hybrid and cross-sectoral governance, as well as policies developed and adopted in an iterative, coherent, adaptive and flexible manner can maximise co-benefits and minimise trade-offs, given that land management decisions are made from farm level to national scales, and both climate and land policies often range across multiple sectors, departments and agencies (*high confidence*). (Figure SPM.3) {4.8.5, 4.9, 5.6, 6.4, 7.3, 7.4.6, 7.4.8, 7.4.9, 7.5.6, 7.6.2}

C.3.1 Addressing desertification, land degradation, and food security in an integrated, coordinated and coherent manner can assist climate resilient development and provides numerous potential co-benefits (*high confidence*). {3.7.5, 4.8, 5.6, 5.7, 6.4, 7.2.2, 7.3.1, 7.3.4, 7.4.7, 7.4.8, 7.5.6, 7.5.5}

C.3.2 Technological, biophysical, socio-economic, financial and cultural barriers can limit the adoption of many land-based response options, as can uncertainty about benefits (*high confidence*). Many sustainable land management practices are not widely adopted due to insecure land tenure, lack of access to resources and agricultural advisory services, insufficient and unequal private and public incentives, and lack of knowledge and practical experience (*high confidence*). Public discourse, carefully designed policy interventions, incorporating social learning and market changes can together help reduce barriers to implementation (*medium confidence*). {3.6.1, 3.6.2, 5.3.5, 5.5.2, 5.6, 6.2, 6.4, 7.4, 7.5, 7.6}

C.3.3 The land and food sectors face particular challenges of institutional fragmentation and often suffer from a lack of engagement between stakeholders at different scales and narrowly focused policy objectives (*medium confidence*). Coordination with other sectors, such as public health, transportation, environment, water, energy and infrastructure, can increase co-benefits, such as risk reduction and improved health (*medium confidence*). {5.6.3, 5.7, 6.2, 6.4.4, 7.1, 7.3, 7.4.8, 7.6.2, 7.6.3}

C.3.4 Some response options and policies may result in trade-offs, including social impacts, ecosystem functions and services damage, water depletion, or high costs, that cannot be well-managed, even with institutional best practices (*medium confidence*). Addressing such trade-offs helps avoid maladaptation (*medium confidence*). Anticipation and evaluation of potential trade-offs and knowledge gaps supports evidence-based policymaking to weigh the costs and benefits of specific responses for different stakeholders (*medium confidence*). Successful management of trade-offs often includes maximising stakeholder input with structured feedback processes, particularly in community-based models, use of innovative fora like facilitated dialogues or spatially explicit mapping, and iterative adaptive management that allows for continuous readjustments in policy as new evidence comes to light (*medium confidence*). {5.3.5, 6.4.2, 6.4.4, 6.4.5, 7.5.6, Cross-Chapter Box 9 in Chapter 7}

C.4 The effectiveness of decision-making and governance is enhanced by the involvement of local stakeholders (particularly those most vulnerable to climate change including indigenous peoples and local communities, women, and the poor and marginalised) in the selection, evaluation, implementation and monitoring of policy instruments for land-based climate change adaptation and mitigation (*high confidence*). Integration across sectors and scales increases the chance of maximising co-benefits and minimising trade-offs (*medium confidence*). {1.4, 3.1, 3.6, 3.7, 4.8, 4.9, 5.1.3, Box 5.1, 7.4, 7.6}

C.4.1 Successful implementation of sustainable land management practices requires accounting for local environmental and socio-economic conditions (*very high confidence*). Sustainable land management in the context of climate change is typically advanced by involving all relevant stakeholders in identifying land-use pressures and impacts (such as biodiversity decline, soil loss, over-extraction of groundwater, habitat loss, land-use change in agriculture, food production and forestry) as well as preventing, reducing and restoring degraded land (*medium confidence*). {1.4.1, 4.1.6, 4.8.7, 5.2.5, 7.2.4, 7.6.2, 7.6.4}

C.4.2 Inclusiveness in the measurement, reporting and verification of the performance of policy instruments can support sustainable land management (*medium confidence*). Involving stakeholders in the selection of indicators, collection of climate data, land modelling and land-use planning, mediates and facilitates integrated landscape planning and choice of policy (*medium confidence*). {3.7.5, 5.7.4, 7.4.1, 7.4.4, 7.5.3, 7.5.4, 7.5.5, 7.6.4, 7.6.6}

C.4.3 Agricultural practices that include indigenous and local knowledge can contribute to overcoming the combined challenges of climate change, food security, biodiversity conservation, and combating desertification and land degradation (*high confidence*). Coordinated action across a range of actors including businesses, producers, consumers, land managers and policymakers in partnership with indigenous peoples and local communities enable conditions for the adoption of response options (*high confidence*) {3.1.3, 3.6.1, 3.6.2, 4.8.2, 5.5.1, 5.6.4, 5.7.1, 5.7.4, 6.2, 7.3, 7.4.6, 7.6.4}

C.4.4 Empowering women can bring synergies and co-benefits to household food security and sustainable land management (*high confidence*). Due to women's disproportionate vulnerability to climate change impacts, their inclusion in land management and tenure is constrained. Policies that can address land rights and barriers to women's participation in sustainable land management include financial transfers to women under the auspices of anti-poverty programmes, spending on health, education, training and capacity building for women, subsidised credit and program dissemination through existing women's community-based organisations (*medium confidence*). {1.4.1, 4.8.2, 5.1.3, Cross-Chapter Box 11 in Chapter 7}

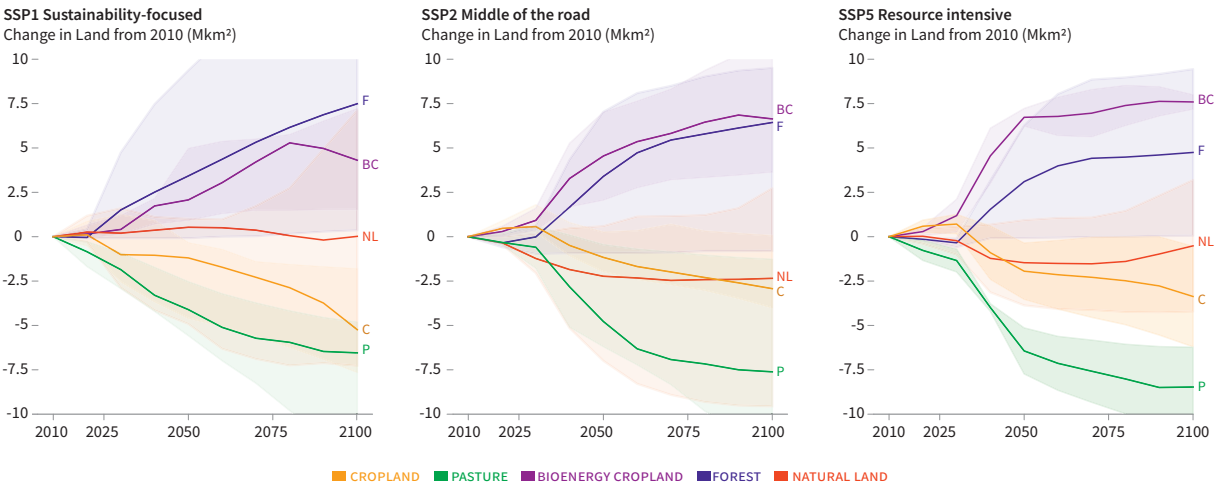
A. Pathways linking socioeconomic development, mitigation responses and land

Socioeconomic development and land management influence the evolution of the land system including the relative amount of land allocated to **CROPLAND**, **PASTURE**, **BIOENERGY CROPLAND**, **FOREST**, and **NATURAL LAND**. The lines show the median across Integrated Assessment Models (IAMs) for three alternative shared socioeconomic pathways (**SSP1**, **SSP2** and **SSP5** at **RCP1.9**); shaded areas show the range across models. Note that pathways illustrate the effects of climate change mitigation but not those of climate change impacts or adaptation.

A. Sustainability-focused (SSP1)
Sustainability in land management, agricultural intensification, production and consumption patterns result in reduced need for agricultural land, despite increases in per capita food consumption. This land can instead be used for reforestation, afforestation, and bioenergy.

B. Middle of the road (SSP2)
Societal as well as technological development follows historical patterns. Increased demand for land mitigation options such as bioenergy, reduced deforestation or afforestation decreases availability of agricultural land for food, feed and fibre.

C. Resource intensive (SSP5)
Resource-intensive production and consumption patterns, results in high baseline emissions. Mitigation focuses on technological solutions including substantial bioenergy and BECCS . Intensification and competing land uses contribute to declines in agricultural land.



B. Land use and land cover change in the SSPs

	Quantitative indicators for the SSPs	Count of models included*	Change in Natural Land from 2010 Mkm²	Change in Bioenergy Cropland from 2010 Mkm²	Change in Cropland from 2010 Mkm²	Change in Forest from 2010 Mkm²	Change in Pasture from 2010 Mkm²
SSP1	**RCP1.9** in 2050	5/5	0.5 (-4.9, 1)	2.1 (0.9, 5)	-1.2 (-4.6, -0.3)	3.4 (-0.1, 9.4)	-4.1 (-5.6, -2.5)
	└ 2100		0 (-7.3, 7.1)	4.3 (1.5, 7.2)	-5.2 (-7.6, -1.8)	7.5 (0.4, 15.8)	-6.5 (-12.2, -4.8)
	RCP2.6 in 2050	5/5	-0.9 (-2.2, 1.5)	1.3 (0.4, 1.9)	-1 (-4.7, 1)	2.6 (-0.1, 8.4)	-3 (-4, -2.4)
	└ 2100		0.2 (-3.5, 1.1)	5.1 (1.6, 6.3)	-3.2 (-7.7, -1.8)	6.6 (-0.1, 10.5)	-5.5 (-9.9, -4.2)
	RCP4.5 in 2050	5/5	0.5 (-1, 1.7)	0.8 (0.5, 1.3)	0.1 (-3.2, 1.5)	0.6 (-0.7, 4.2)	-2.4 (-3.3, -0.9)
	└ 2100		1.8 (-1.7, 6)	1.9 (1.4, 3.7)	-2.3 (-6.4, -1.6)	3.9 (0.2, 8.8)	-4.6 (-7.3, -2.7)
	Baseline in 2050	5/5	0.3 (-1.1, 1.8)	0.5 (0.2, 1.4)	0.2 (-1.6, 1.9)	-0.1 (-0.8, 1.1)	-1.5 (-2.9, -0.2)
	└ 2100		3.3 (-0.3, 5.9)	1.8 (1.4, 2.4)	-1.5 (-5.7, -0.9)	0.9 (0.3, 3)	-2.1 (-7, 0)
SSP2	**RCP1.9** in 2050	4/5	-2.2 (-7, 0.6)	4.5 (2.1, 7)	-1.2 (-2, 0.3)	3.4 (-0.9, 7)	-4.8 (-6.2, -0.4)
	└ 2100		-2.3 (-9.6, 2.7)	6.6 (3.6, 11)	-2.9 (-4, 0.1)	6.4 (-0.8, 9.5)	-7.6 (-11.7, -1.3)
	RCP2.6 in 2050	5/5	-3.2 (-4.2, 0.1)	2.2 (1.7, 4.7)	0.6 (-1.9, 1.9)	1.6 (-0.9, 4.2)	-1.4 (-3.7, 0.4)
	└ 2100		-5.2 (-7.2, 0.5)	6.9 (2.3, 10.8)	-1.4 (-4, 0.8)	5.6 (-0.9, 5.9)	-7.2 (-8, 0.5)
	RCP4.5 in 2050	5/5	-2.2 (-2.2, 0.7)	1.5 (0.1, 2.1)	1.2 (-0.9, 2.7)	-0.9 (-2.5, 2.9)	-0.1 (-2.5, 1.6)
	└ 2100		-3.4 (-4.7, 1.5)	4.1 (0.4, 6.3)	0.7 (-2.6, 3.1)	-0.5 (-3.1, 5.9)	-2.8 (-5.3, 1.9)
	Baseline in 2050	5/5	-1.5 (-2.6, -0.2)	0.7 (0, 1.5)	1.3 (1, 2.7)	-1.3 (-2.5, -0.4)	-0.1 (-1.2, 1.6)
	└ 2100		-2.1 (-5.9, 0.3)	1.2 (0.1, 2.4)	1.9 (0.8, 2.8)	-1.3 (-2.7, -0.2)	-0.2 (-1.9, 2.1)
SSP3	**RCP1.9** in 2050	Infeasible in all assessed models		-	-	-	-
	└ 2100			-	-	-	-
	RCP2.6 in 2050	Infeasible in all assessed models		-	-	-	-
	└ 2100			-	-	-	-
	RCP4.5 in 2050	3/3	-3.4 (-4.4, -2)	1.3 (1.3, 2)	2.3 (1.2, 3)	-2.4 (-4, -1)	2.1 (-0.1, 3.8)
	└ 2100		-6.2 (-6.8, -5.4)	4.6 (1.5, 7.1)	3.4 (1.9, 4.5)	-3.1 (-5.5, -0.3)	2 (-2.5, 4.4)
	Baseline in 2050	4/4	-3 (-4.6, -1.7)	1 (0.2, 1.5)	2.5 (1.5, 3)	-2.5 (-4, -1.5)	2.4 (0.6, 3.8)
	└ 2100		-5 (-7.1, -4.2)	1.1 (0.9, 2.5)	5.1 (3.8, 6.1)	-5.3 (-6, -2.6)	3.4 (0.9, 6.4)
SSP4	**RCP1.9** in 2050	Infeasible in all assessed models**		-	-	-	-
	└ 2100			-	-	-	-
	RCP2.6 in 2050	3/3	-4.5 (-6, -2.1)	3.3 (1.5, 4.5)	0.5 (-0.1, 0.9)	0.7 (-0.3, 2.2)	-0.6 (-0.7, 0.1)
	└ 2100		-5.8 (-10.2, -4.7)	2.5 (2.3, 15.2)	-0.8 (-0.8, 1.8)	1.4 (-1.7, 4.1)	-1.2 (-2.5, -0.2)
	RCP4.5 in 2050	3/3	-2.7 (-4.4, -0.4)	1.7 (1, 1.9)	1.1 (-0.1, 1.7)	-1.8 (-2.3, 2.1)	0.8 (-0.5, 1.5)
	└ 2100		-2.8 (-7.8, -2)	2.7 (2.3, 4.7)	1.1 (0.2, 1.2)	-0.7 (-2.6, 1)	1.4 (-1, 1.8)
	Baseline in 2050	3/3	-2.8 (-2.9, -0.2)	1.1 (0.7, 2)	1.1 (0.7, 1.8)	-1.8 (-2.3, -1)	1.5 (-0.5, 2.1)
	└ 2100		-2.4 (-5, -1)	1.7 (1.4, 2.6)	1.2 (1.2, 1.9)	-2.4 (-2.5, -2)	1.3 (-1, 4.4)
SSP5	**RCP1.9** in 2050	2/4	-1.5 (-3.9, 0.9)	6.7 (6.2, 7.2)	-1.9 (-3.5, -0.4)	3.1 (-0.1, 6.3)	-6.4 (-7.7, -5.1)
	└ 2100		-0.5 (-4.2, 3.2)	7.6 (7.2, 8)	-3.4 (-6.2, -0.5)	4.7 (0.1, 9.4)	-8.5 (-10.7, -6.2)
	RCP2.6 in 2050	4/4	-3.4 (-6.9, 0.3)	4.8 (3.8, 5.1)	-2.1 (-4, 1)	3.9 (-0.1, 6.7)	-4.4 (-5, 0.2)
	└ 2100		-4.3 (-8.4, 0.5)	9.1 (7.7, 9.2)	-3.3 (-6.5, -0.5)	3.9 (-0.1, 9.3)	-6.3 (-9.1, -1.4)
	RCP4.5 in 2050	4/4	-2.5 (-3.7, 0.2)	1.7 (0.6, 2.9)	0.6 (-3.3, 1.9)	-0.1 (-1.7, 6)	-1.2 (-2.6, 2.3)
	└ 2100		-4.1 (-4.6, 0.7)	4.8 (2, 8)	-1 (-5.5, 1)	-0.2 (-1.4, 9.1)	-3 (-5.2, 2.1)
	Baseline in 2050	4/4	-0.6 (-3.8, 0.4)	0.8 (0, 2.1)	1.5 (-0.7, 3.3)	-1.9 (-3.4, 0.5)	-0.1 (-1.5, 2.9)
	└ 2100		-0.2 (-2.4, 1.8)	1 (0.2, 2.3)	1 (-2, 2.5)	-2.1 (-3.4, 1.1)	-0.4 (-2.4, 2.8)

** Count of models included / Count of models attempted. One model did not provide land data and is excluded from all entries.*

*** One model could reach RCP1.9 with SSP4, but did not provide land data*

Figure SPM.4: Pathways linking socioeconomic development, mitigation responses and land | Future scenarios provide a framework for understanding the implications of mitigation and socioeconomics on land. The Shared Socioeconomic Pathways (SSPs) span a range of different socioeconomic assumptions (Box SPM.1). They are combined with Representative Concentration Pathways (RCPs)[36] which imply different levels of mitigation. The changes in cropland, pasture, bioenergy cropland, forest, and natural land from 2010 are shown. For this Figure, Cropland includes all land in food, feed, and fodder crops, as well as other arable land (cultivated area). This category includes first generation non-forest bioenergy crops (e.g., corn for ethanol, sugar cane for ethanol, soybeans for biodiesel), but excludes second generation bioenergy crops. Pasture includes categories of pasture land, not only high-quality rangeland, and is based on FAO definition of 'permanent meadows and pastures'. Bioenergy cropland includes land dedicated to second generation energy crops (e.g., switchgrass, miscanthus, fast-growing wood species). Forest includes managed and unmanaged forest. Natural land includes other grassland, savannah, and shrubland. **Panel A:** This panel shows integrated assessment model (IAM)[37] results for SSP1, SSP2 and SSP5 at RCP1.9.[38] For each pathway, the shaded areas show the range across all IAMs; the line indicates the median across models. For RCP1.9, SSP1, SSP2 and SSP5 results are from five, four and two IAMs respectively. **Panel B:** Land use and land cover change are indicated for various SSP-RCP combinations, showing multi-model median and range (min, max). (Box SPM.1) {1.3.2, 2.7.2, 6.1, 6.4.4, 7.4.2, 7.4.4, 7.4.5, 7.4.6, 7.4.7, 7.4.8, 7.5.3, 7.5.6, Cross-Chapter Box 1 in Chapter 1, Cross-Chapter Box 9 in Chapter 6}

[36] Representative Concentration Pathways (RCPs) are scenarios that include timeseries of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover.

[37] Integrated Assessment Models (IAMs) integrate knowledge from two or more domains into a single framework. In this figure, IAMs are used to assess linkages between economic, social and technological development and the evolution of the climate system.

[38] The RCP1.9 pathways assessed in this report have a 66% chance of limiting warming to 1.5°C in 2100, but some of these pathways overshoot 1.5°C of warming during the 21st century by >0.1°C.

D. Action in the near-term

D.1 Actions can be taken in the near-term, based on existing knowledge, to address desertification, land degradation and food security while supporting longer-term responses that enable adaptation and mitigation to climate change. These include actions to build individual and institutional capacity, accelerate knowledge transfer, enhance technology transfer and deployment, enable financial mechanisms, implement early warning systems, undertake risk management and address gaps in implementation and upscaling (*high confidence*). {3.6.1, 3.6.2, 3.7.2, 4.8, 5.3.3, 5.5, 5.6.4, 5.7, 6.2, 6.4, 7.3, 7.4, 7.6, Cross-Chapter Box 10 in Chapter 7}

D.1.1 Near-term capacity-building, technology transfer and deployment, and enabling financial mechanisms can strengthen adaptation and mitigation in the land sector. Knowledge and technology transfer can help enhance the sustainable use of natural resources for food security under a changing climate (*medium confidence*). Raising awareness, capacity building and education about sustainable land management practices, agricultural extension and advisory services, and expansion of access to agricultural services to producers and land users can effectively address land degradation (*medium confidence*). {3.1, 5.7.4, 7.2, 7.3.4, 7.5.4}

D.1.2 Measuring and monitoring land use change including land degradation and desertification is supported by the expanded use of new information and communication technologies (cell phone based applications, cloud-based services, ground sensors, drone imagery), use of climate services, and remotely sensed land and climate information on land resources (*medium confidence*). Early warning systems for extreme weather and climate events are critical for protecting lives and property and enhancing disaster risk reduction and management (*high confidence*). Seasonal forecasts and early warning systems are critical for food security (famine) and biodiversity monitoring including pests and diseases and adaptive climate risk management (*high confidence*). There are high returns on investments in human and institutional capacities. These investments include access to observation and early warning systems, and other services derived from in-situ hydro-meteorological and remote sensing-based monitoring systems and data, field observation, inventory and survey, and expanded use of digital technologies (*high confidence*). {1.2, 3.6.2, 4.2.2, 4.2.4, 5.3.1, 5.3.6, 6.4, 7.3.4, 7.4.3, 7.5.4, 7.5.5, 7.6.4, Cross-Chapter Box 5 in Chapter 3}

D.1.3 Framing land management in terms of risk management, specific to land, can play an important role in adaptation through landscape approaches, biological control of outbreaks of pests and diseases, and improving risk sharing and transfer mechanisms (*high confidence*). Providing information on climate-related risk can improve the capacity of land managers and enable timely decision making (*high confidence*). {5.3.2, 5.3.5, 5.6.2, 5.6.3 5.6.5, 5.7.1, 5.7.2, 7.2.4, Cross-Chapter Box 6 in Chapter 5}

D.1.4 Sustainable land management can be improved by increasing the availability and accessibility of data and information relating to the effectiveness, co-benefits and risks of emerging response options and increasing the efficiency of land use (*high confidence*). Some response options (e.g., improved soil carbon management) have been implemented only at small-scale demonstration facilities and knowledge, financial, and institutional gaps and challenges exist with upscaling and the widespread deployment of these options (*medium confidence*). {4.8, 5.5.1, 5.5.2, 5.6.1, 5.6.5, 5.7.5, 6.2, 6.4}

D.2 Near-term action to address climate change adaptation and mitigation, desertification, land degradation and food security can bring social, ecological, economic and development co-benefits (*high confidence*). Co-benefits can contribute to poverty eradication and more resilient livelihoods for those who are vulnerable (*high confidence*). {3.4.2, 5.7, 7.5}

D.2.1 Near-term actions to promote sustainable land management will help reduce land and food-related vulnerabilities, and can create more resilient livelihoods, reduce land degradation and desertification, and loss of biodiversity (*high confidence*). There are synergies between sustainable land management, poverty eradication efforts, access to market, non-market mechanisms and the elimination of low-productivity practices. Maximising these synergies can lead to adaptation, mitigation, and development co-benefits through preserving ecosystem functions and services (*medium confidence*). {3.4.2, 3.6.3, Table 4.2, 4.7, 4.9, 4.10, 5.6, 5.7, 7.3, 7.4, 7.5, 7.6, Cross-Chapter Box 12 in Chapter 7}

D.2.2 Investments in land restoration can result in global benefits and in drylands can have benefit-cost ratios of between three and six in terms of the estimated economic value of restored ecosystem services (*medium confidence*). Many sustainable land management technologies and practices are profitable within three to ten years (*medium confidence*). While they can

require upfront investment, actions to ensure sustainable land management can improve crop yields and the economic value of pasture. Land restoration and rehabilitation measures improve livelihood systems and provide both short-term positive economic returns and longer-term benefits in terms of climate change adaptation and mitigation, biodiversity and enhanced ecosystem functions and services (*high confidence*). {3.6.1, 3.6.3, 4.8.1, 7.2.4, 7.2.3, 7.3.1, 7.4.6, Cross-Chapter Box 10 in Chapter 7}

D.2.3 Upfront investments in sustainable land management practices and technologies can range from about USD20 ha^{-1} to USD5000 ha^{-1}, with a median estimated to be around USD500 ha^{-1}. Government support and improved access to credit can help overcome barriers to adoption, especially those faced by poor smallholder farmers (*high confidence*). Near-term change to balanced diets (SPM B6.2.) can reduce the pressure on land and provide significant health co-benefits through improving nutrition (*medium confidence*). {3.6.3, 4.8, 5.3, 5.5, 5.6, 5.7, 6.4, 7.4.7, 7.5.5, Cross-Chapter Box 9 in Chapter 6}

D.3 Rapid reductions in anthropogenic GHG emissions across all sectors following ambitious mitigation pathways reduce negative impacts of climate change on land ecosystems and food systems (*medium confidence*). Delaying climate mitigation and adaptation responses across sectors would lead to increasingly negative impacts on land and reduce the prospect of sustainable development (*medium confidence*). (Box SPM.1, Figure SPM.2) {2.5, 2.7, 5.2, 6.2, 6.4, 7.2, 7.3.1, 7.4.7, 7.4.8, 7.5.6, Cross-Chapter Box 9 in Chapter 6, Cross-Chapter Box 10 in Chapter 7}

D.3.1 Delayed action across sectors leads to an increasing need for widespread deployment of land-based adaptation and mitigation options and can result in a decreasing potential for the array of these options in most regions of the world and limit their current and future effectiveness (*high confidence*). Acting now may avert or reduce risks and losses, and generate benefits to society (*medium confidence*). Prompt action on climate mitigation and adaptation aligned with sustainable land management and sustainable development depending on the region could reduce the risk to millions of people from climate extremes, desertification, land degradation and food and livelihood insecurity (*high confidence*). {1.3.5, 3.4.2, 3.5.2, 4.1.6, 4.7.1, 4.7.2, 5.2.3, 5.3.1, 6.3, 6.5, 7.3.1}

D.3.2 In future scenarios, deferral of GHG emissions reductions implies trade-offs leading to significantly higher costs and risks associated with rising temperatures (*medium confidence*). The potential for some response options, such as increasing soil organic carbon, decreases as climate change intensifies, as soils have reduced capacity to act as sinks for carbon sequestration at higher temperatures (*high confidence*). Delays in avoiding or reducing land degradation and promoting positive ecosystem restoration risk long-term impacts including rapid declines in productivity of agriculture and rangelands, permafrost degradation and difficulties in peatland rewetting (*medium confidence*). {1.3.1, 3.6.2, 4.8, 4.9, 4.9.1, 5.5.2, 6.3, 6.4, 7.2, 7.3; Cross-Chapter Box 10 in Chapter 7}

D.3.3 Deferral of GHG emissions reductions from all sectors implies trade-offs including irreversible loss in land ecosystem functions and services required for food, health, habitable settlements and production, leading to increasingly significant economic impacts on many countries in many regions of the world (*high confidence*). Delaying action as is assumed in high emissions scenarios could result in some irreversible impacts on some ecosystems, which in the longer-term has the potential to lead to substantial additional GHG emissions from ecosystems that would accelerate global warming (*medium confidence*). {1.3.1, 2.5.3, 2.7, 3.6.2, 4.9, 4.10.1, 5.4.2.4, 6.3, 6.4, 7.2, 7.3, Cross-Chapter Box 9 in Chapter 6, Cross-Chapter Box 10 in Chapter 7}

Summary for Policymakers

SPM

Summary for Policymakers

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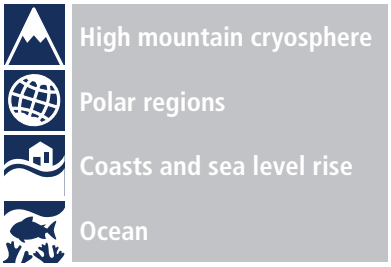
Introduction

This Special Report on the Ocean and Cryosphere[1] in a Changing Climate (SROCC) was prepared following an IPCC Panel decision in 2016 to prepare three Special Reports during the Sixth Assessment Cycle[2]. By assessing new scientific literature[3], the SROCC[4] responds to government and observer organization proposals. The SROCC follows the other two Special Reports on Global Warming of 1.5ºC (SR1.5) and on Climate Change and Land (SRCCL)[5] and the Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES) Global Assessment Report on Biodiversity and Ecosystem Services.

This Summary for Policymakers (SPM) compiles key findings of the report and is structured in three parts: SPM.A: Observed Changes and Impacts, SPM.B: Projected Changes and Risks, and SPM.C: Implementing Responses to Ocean and Cryosphere Change. To assist navigation of the SPM, icons indicate where content can be found. Confidence in key findings is reported using IPCC calibrated language[6] and the underlying scientific basis for each key finding is indicated by references to sections of the underlying report.

Key of icons to indicate content



1 The cryosphere is defined in this report (Annex I: Glossary) as the components of the Earth System at and below the land and ocean surface that are frozen, including snow cover, glaciers, ice sheets, ice shelves, icebergs, sea ice, lake ice, river ice, permafrost, and seasonally frozen ground.

2 The decision to prepare a Special Report on Climate Change and Oceans and the Cryosphere was made at the Forty-Third Session of the IPCC in Nairobi, Kenya, 11–13 April 2016.

3 Cut-off dates: 15 October 2018 for manuscript submission, 15 May 2019 for acceptance for publication.

4 The SROCC is produced under the scientific leadership of Working Group I and Working Group II. In line with the approved outline, mitigation options (Working Group III) are not assessed with the exception of the mitigation potential of blue carbon (coastal ecosystems).

5 The full titles of these two Special Reports are: "Global Warming of 1.5ºC. An IPCC special report on the impacts of global warming of 1.5ºC above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty"; "Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems".

6 Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, e.g., *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Assessed likelihood is typeset in italics, e.g., *very likely*. This is consistent with AR5 and the other AR6 Special Reports. Additional terms (extremely likely 95–100%, more likely than not >50–100%, more unlikely than likely 0–<50%, extremely unlikely 0–5%) are used when appropriate. This Report also uses the term '*likely* range' or '*very likely* range' to indicate that the assessed likelihood of an outcome lies within the 17–83% or 5–95% probability range. {1.9.2, Figure 1.4}

Startup Box | The Importance of the Ocean and Cryosphere for People

All people on Earth depend directly or indirectly on the ocean and cryosphere. The global ocean covers 71% of the Earth surface and contains about 97% of the Earth's water. The cryosphere refers to frozen components of the Earth system[1]. Around 10% of Earth's land area is covered by glaciers or ice sheets. The ocean and cryosphere support unique habitats, and are interconnected with other components of the climate system through global exchange of water, energy and carbon. The projected responses of the ocean and cryosphere to past and current human-induced greenhouse gas emissions and ongoing global warming include climate feedbacks, changes over decades to millennia that cannot be avoided, thresholds of abrupt change, and irreversibility. {Box 1.1, 1.2}

Human communities in close connection with coastal environments, small islands (including Small Island Developing States, SIDS), polar areas and high mountains[7] are particularly exposed to ocean and cryosphere change, such as sea level rise, extreme sea level and shrinking cryosphere. Other communities further from the coast are also exposed to changes in the ocean, such as through extreme weather events. Today, around 4 million people live permanently in the Arctic region, of whom 10% are Indigenous. The low-lying coastal zone[8] is currently home to around 680 million people (nearly 10% of the 2010 global population), projected to reach more than one billion by 2050. SIDS are home to 65 million people. Around 670 million people (nearly 10% of the 2010 global population), including Indigenous peoples, live in high mountain regions in all continents except Antarctica. In high mountain regions, population is projected to reach between 740 and 840 million by 2050 (about 8.4–8.7% of the projected global population). {1.1, 2.1, 3.1, Cross-Chapter Box 9, Figure 2.1}

In addition to their role within the climate system, such as the uptake and redistribution of natural and anthropogenic carbon dioxide (CO_2) and heat, as well as ecosystem support, services provided to people by the ocean and/or cryosphere include food and water supply, renewable energy, and benefits for health and well-being, cultural values, tourism, trade, and transport. The state of the ocean and cryosphere interacts with each aspect of sustainability reflected in the United Nations Sustainable Development Goals (SDGs). {1.1, 1.2, 1.5}

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7 High mountain areas include all mountain regions where glaciers, snow or permafrost are prominent features of the landscape. For a list of high mountain regions covered in this report, see Chapter 2. Population in high mountain regions is calculated for areas less than 100 kilometres from glaciers or permafrost in high mountain areas assessed in this report. {2.1} Projections for 2050 give the range of population in these regions across all five of the Shared Socioeconomic Pathways. {Cross-Chapter Box 1 in Chapter 1}

8 Population in the low elevation coastal zone is calculated for land areas connected to the coast, including small island states, that are less than 10 metres above sea level. {Cross-Chapter Box 9} Projections for 2050 give the range of population in these regions across all five of the Shared Socioeconomic Pathways. {Cross-Chapter Box 1 in Chapter 1}

A. Observed Changes and Impacts

Observed Physical Changes

A.1 Over the last decades, global warming has led to widespread shrinking of the cryosphere, with mass loss from ice sheets and glaciers (*very high confidence*), reductions in snow cover (*high confidence*) and Arctic sea ice extent and thickness (*very high confidence*), and increased permafrost temperature (*very high confidence*). {2.2, 3.2, 3.3, 3.4, Figures SPM.1, SPM.2}

A.1.1 Ice sheets and glaciers worldwide have lost mass (*very high confidence*). Between 2006 and 2015, the Greenland Ice Sheet[9] lost ice mass at an average rate of 278 ± 11 Gt yr^{-1} (equivalent to 0.77 ± 0.03 mm yr^{-1} of global sea level rise)[10], mostly due to surface melting (*high confidence*). In 2006–2015, the Antarctic Ice Sheet lost mass at an average rate of 155 ± 19 Gt yr^{-1} (0.43 ± 0.05 mm yr^{-1}), mostly due to rapid thinning and retreat of major outlet glaciers draining the West Antarctic Ice Sheet (*very high confidence*). Glaciers worldwide outside Greenland and Antarctica lost mass at an average rate of 220 ± 30 Gt yr^{-1} (equivalent to 0.61 ± 0.08 mm yr^{-1} sea level rise) in 2006–2015. {3.3.1, 4.2.3, Appendix 2.A, Figure SPM.1}

A.1.2 Arctic June snow cover extent on land declined by 13.4 ± 5.4% per decade from 1967 to 2018, a total loss of approximately 2.5 million km^2, predominantly due to surface air temperature increase (*high confidence*). In nearly all high mountain areas, the depth, extent and duration of snow cover have declined over recent decades, especially at lower elevation (*high confidence*). {2.2.2, 3.4.1, Figure SPM.1}

A.1.3 Permafrost temperatures have increased to record high levels (1980s–present) (*very high confidence*) including the recent increase by 0.29ºC ± 0.12ºC from 2007 to 2016 averaged across polar and high mountain regions globally. Arctic and boreal permafrost contain 1460–1600 Gt organic carbon, almost twice the carbon in the atmosphere (*medium confidence*). There is *medium evidence* with *low agreement* whether northern permafrost regions are currently releasing additional net methane and CO_2 due to thaw. Permafrost thaw and glacier retreat have decreased the stability of high mountain slopes (*high confidence*). {2.2.4, 2.3.2, 3.4.1, 3.4.3, Figure SPM.1}

A.1.4 Between 1979 and 2018, Arctic sea ice extent has *very likely* decreased for all months of the year. September sea ice reductions are *very likely* 12.8 ± 2.3% per decade. These sea ice changes in September are *likely* unprecedented for at least 1000 years. Arctic sea ice has thinned, concurrent with a transition to younger ice: between 1979 and 2018, the areal proportion of multi-year ice at least five years old has declined by approximately 90% (*very high confidence*). Feedbacks from the loss of summer sea ice and spring snow cover on land have contributed to amplified warming in the Arctic (*high confidence*) where surface air temperature *likely* increased by more than double the global average over the last two decades. Changes in Arctic sea ice have the potential to influence mid-latitude weather (*medium confidence*), but there is *low confidence* in the detection of this influence for specific weather types. Antarctic sea ice extent overall has had no statistically significant trend (1979–2018) due to contrasting regional signals and large interannual variability (*high confidence*). {3.2.1, 6.3.1, Box 3.1, Box 3.2, SPM A.1.2, Figures SPM.1, SPM.2}

[9] Including peripheral glaciers.

[10] 360 Gt ice corresponds to 1 mm of global mean sea level.

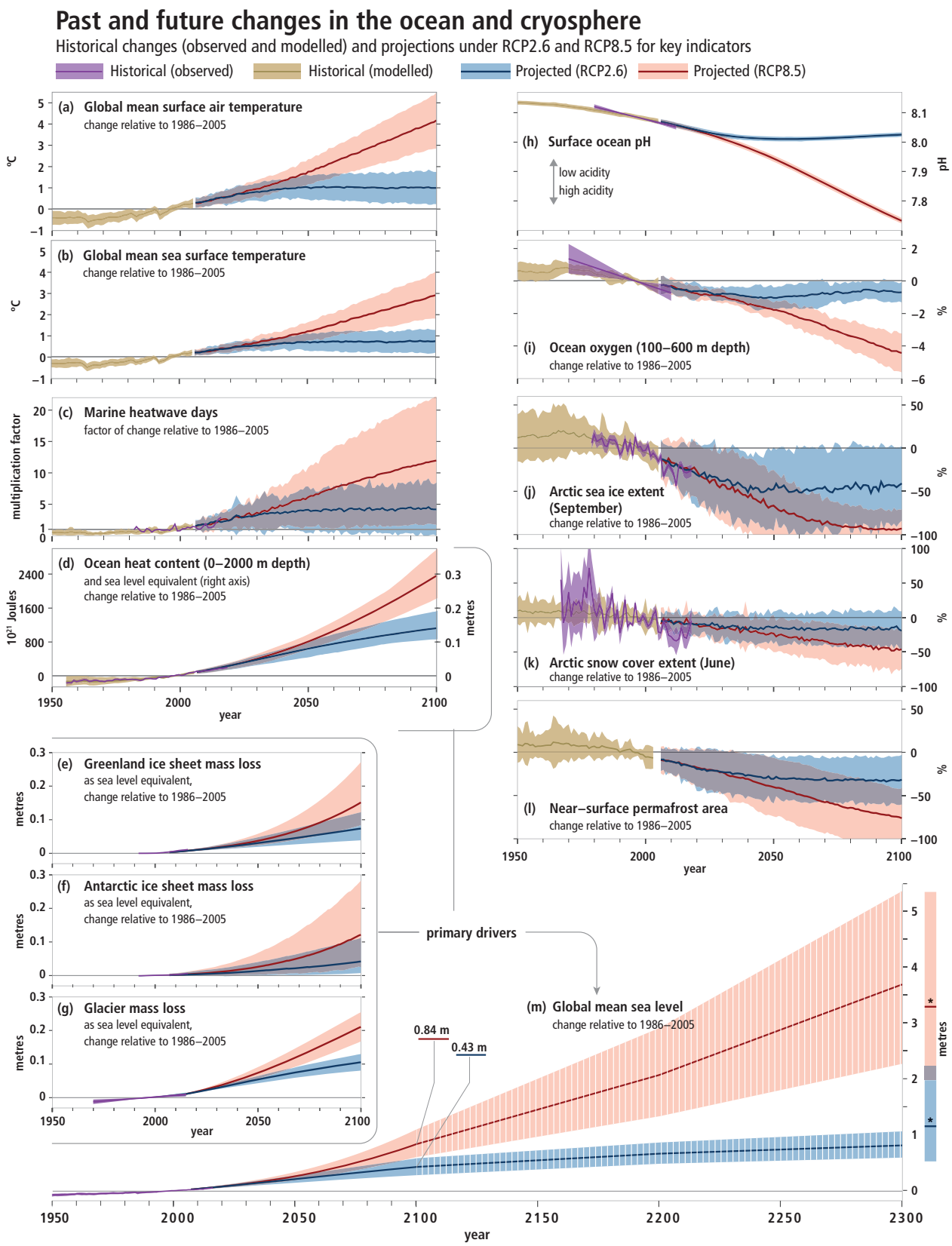

Figure SPM.1 | Observed and modelled historical changes in the ocean and cryosphere since 1950[11], and projected future changes under low (RCP2.6) and high (RCP8.5) greenhouse gas emissions scenarios. {Box SPM.1}

[11] This does not imply that the changes started in 1950. Changes in some variables have occurred since the pre-industrial period.

Figure SPM.1 (continued): Changes are shown for: **(a)** Global mean surface air temperature change with *likely* range. {Box SPM.1, Cross-Chapter Box 1 in Chapter 1} **Ocean-related changes** with *very likely* ranges for **(b)** Global mean sea surface temperature change {Box 5.1, 5.2.2}; **(c)** Change factor in surface ocean marine heatwave days {6.4.1}; **(d)** Global ocean heat content change (0–2000 m depth). An approximate steric sea level equivalent is shown with the right axis by multiplying the ocean heat content by the global-mean thermal expansion coefficient ($\varepsilon \approx 0.125$ m per 10^{24} Joules)[12] for observed warming since 1970 {Figure 5.1}; **(h)** Global mean surface pH (on the total scale). Assessed observational trends are compiled from open ocean time series sites longer than 15 years {Box 5.1, Figure 5.6, 5.2.2}; and **(i)** Global mean ocean oxygen change (100–600 m depth). Assessed observational trends span 1970–2010 centered on 1996 {Figure 5.8, 5.2.2}. **Sea level changes** with *likely* ranges for **(m)** Global mean sea level change. Hashed shading reflects *low confidence* in sea level projections beyond 2100 and bars at 2300 reflect expert elicitation on the range of possible sea level change {4.2.3, Figure 4.2}; and components from **(e,f)** Greenland and Antarctic ice sheet mass loss {3.3.1}; and **(g)** Glacier mass loss {Cross-Chapter Box 6 in Chapter 2, Table 4.1}. Further **cryosphere-related changes** with *very likely* ranges for **(j)** Arctic sea ice extent change for September[13] {3.2.1, 3.2.2 Figure 3.3}; **(k)** Arctic snow cover change for June (land areas north of 60ºN) {3.4.1, 3.4.2, Figure 3.10}; and **(l)** Change in near-surface (within 3–4 m) permafrost area in the Northern Hemisphere {3.4.1, 3.4.2, Figure 3.10}. Assessments of projected changes under the intermediate RCP4.5 and RCP6.0 scenarios are not available for all variables considered here, but where available can be found in the underlying report. {For RCP4.5 see: 2.2.2, Cross-Chapter Box 6 in Chapter 2, 3.2.2, 3.4.2, 4.2.3, for RCP6.0 see Cross-Chapter Box 1 in Chapter 1}

Box SPM.1 | Use of Climate Change Scenarios in SROCC

Assessments of projected future changes in this report are based largely on CMIP5[14] climate model projections using Representative Concentration Pathways (RCPs). RCPs are scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use / land cover. RCPs provide only one set of many possible scenarios that would lead to different levels of global warming. {Annex I: Glossary}

This report uses mainly RCP2.6 and RCP8.5 in its assessment, reflecting the available literature. RCP2.6 represents a low greenhouse gas emissions, high mitigation future, that in CMIP5 simulations gives a two in three chance of limiting global warming to below 2ºC by 2100[15]. By contrast, RCP8.5 is a high greenhouse gas emissions scenario in the absence of policies to combat climate change, leading to continued and sustained growth in atmospheric greenhouse gas concentrations. Compared to the total set of RCPs, RCP8.5 corresponds to the pathway with the highest greenhouse gas emissions. The underlying chapters also reference other scenarios, including RCP4.5 and RCP6.0 that have intermediate levels of greenhouse gas emissions and result in intermediate levels of warming. {Annex I: Glossary, Cross-Chapter Box 1 in Chapter 1}

Table SPM.1 provides estimates of total warming since the pre-industrial period under four different RCPs for key assessment intervals used in SROCC. The warming from the 1850–1900 period until 1986–2005 has been assessed as 0.63ºC (0.57ºC to 0.69ºC *likely* range) using observations of near-surface air temperature over the ocean and over land.[16] Consistent with the approach in AR5, modelled future changes in global mean surface air temperature relative to 1986–2005 are added to this observed warming. {Cross-Chapter Box 1 in Chapter 1}

Table SPM.1 | Projected global mean surface temperature change relative to 1850–1900 for two time periods under four RCPs[15] {Cross-Chapter Box 1 in Chapter 1}

	Near-term: 2031–2050		End-of-century: 2081–2100	
Scenario	Mean (ºC)	*Likely* range (ºC)	Mean (ºC)	*Likely* range (ºC)
RCP2.6	1.6	1.1 to 2.0	1.6	0.9 to 2.4
RCP4.5	1.7	1.3 to 2.2	2.5	1.7 to 3.3
RCP6.0	1.6	1.2 to 2.0	2.9	2.0 to 3.8
RCP8.5	2.0	1.5 to 2.4	4.3	3.2 to 5.4

[12] This scaling factor (global-mean ocean expansion as sea level rise in metres per unit heat) varies by about 10% between different models, and it will systematically increase by about 10% by 2100 under RCP8.5 forcing due to ocean warming increasing the average thermal expansion coefficient. {4.2.1, 4.2.2, 5.2.2}

[13] Antarctic sea ice is not shown here due to *low confidence* in future projections. {3.2.2}

[14] CMIP5 is Phase 5 of the Coupled Model Intercomparison Project (Annex I: Glossary).

[15] A pathway with lower emissions (RCP1.9), which would correspond to a lower level of projected warming than RCP2.6, was not part of CMIP5.

[16] In some instances this report assesses changes relative to 2006–2015. The warming from the 1850–1900 period until 2006–2015 has been assessed as 0.87ºC (0.75 to 0.99ºC *likely* range). {Cross-Chapter Box 1 in Chapter 1}

A.2 It is *virtually certain* that the global ocean has warmed unabated since 1970 and has taken up more than 90% of the excess heat in the climate system (*high confidence*). Since 1993, the rate of ocean warming has more than doubled (*likely*). Marine heatwaves have *very likely* doubled in frequency since 1982 and are increasing in intensity (*very high confidence*). By absorbing more CO_2, the ocean has undergone increasing surface acidification (*virtually certain*). A loss of oxygen has occurred from the surface to 1000 m (*medium confidence*). {1.4, 3.2, 5.2, 6.4, 6.7, Figures SPM.1, SPM.2}

A.2.1. The ocean warming trend documented in the IPCC Fifth Assessment Report (AR5) has continued. Since 1993 the rate of ocean warming and thus heat uptake has more than doubled (*likely*) from 3.22 ± 1.61 ZJ yr^{-1} (0–700 m depth) and 0.97 ± 0.64 ZJ yr^{-1} (700–2000 m) between 1969 and 1993, to 6.28 ± 0.48 ZJ yr^{-1} (0–700 m) and 3.86 ± 2.09 ZJ yr^{-1} (700–2000 m) between 1993 and 2017[17], and is attributed to anthropogenic forcing (*very likely*). {1.4.1, 5.2.2, Table 5.1, Figure SPM.1}

A.2.2 The Southern Ocean accounted for 35–43% of the total heat gain in the upper 2000 m global ocean between 1970 and 2017 (*high confidence*). Its share increased to 45–62% between 2005 and 2017 (*high confidence*). The deep ocean below 2000 m has warmed since 1992 (*likely*), especially in the Southern Ocean. {1.4, 3.2.1, 5.2.2, Table 5.1, Figure SPM.2}

A.2.3 Globally, marine heat-related events have increased; marine heatwaves[18], defined when the daily sea surface temperature exceeds the local 99th percentile over the period 1982 to 2016, have doubled in frequency and have become longer-lasting, more intense and more extensive (*very likely*). It is *very likely* that between 84–90% of marine heatwaves that occurred between 2006 and 2015 are attributable to the anthropogenic temperature increase. {Table 6.2, 6.4, Figures SPM.1, SPM.2}

A.2.4 Density stratification[19] has increased in the upper 200 m of the ocean since 1970 (*very likely*). Observed surface ocean warming and high latitude addition of freshwater are making the surface ocean less dense relative to deeper parts of the ocean (*high confidence*) and inhibiting mixing between surface and deeper waters (*high confidence*). The mean stratification of the upper 200 m has increased by 2.3 ± 0.1% (*very likely* range) from the 1971–1990 average to the 1998–2017 average. {5.2.2}

A.2.5 The ocean has taken up between 20–30% (*very likely*) of total anthropogenic CO_2 emissions since the 1980s causing further ocean acidification. Open ocean surface pH has declined by a *very likely* range of 0.017–0.027 pH units per decade since the late 1980s[20], with the decline in surface ocean pH *very likely* to have already emerged from background natural variability for more than 95% of the ocean surface area. {3.2.1, 5.2.2, Box 5.1, Figures SPM.1, SPM.2}

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17 ZJ is Zettajoule and is equal to 10^{21} Joules. Warming the entire ocean by 1°C requires about 5500 ZJ; 144 ZJ would warm the top 100 m by about 1°C.

18 A marine heatwave is a period of extreme warm near-sea surface temperature that persists for days to months and can extend up to thousands of kilometres (Annex I: Glossary).

19 In this report density stratification is defined as the density contrast between shallower and deeper layers. Increased stratification reduces the vertical exchange of heat, salinity, oxygen, carbon, and nutrients.

20 Based on in-situ records longer than fifteen years.

A.2.6 Datasets spanning 1970–2010 show that the open ocean has lost oxygen by a *very likely* range of 0.5–3.3% over the upper 1000 m, alongside a *likely* expansion of the volume of oxygen minimum zones by 3–8% (*medium confidence*). Oxygen loss is primarily due to increasing ocean stratification, changing ventilation and biogeochemistry (*high confidence*). {5.2.2, Figures SPM.1, SPM.2}

A.2.7 Observations, both in situ (2004–2017) and based on sea surface temperature reconstructions, indicate that the Atlantic Meridional Overturning Circulation (AMOC)[21] has weakened relative to 1850–1900 (*medium confidence*). There is insufficient data to quantify the magnitude of the weakening, or to properly attribute it to anthropogenic forcing due to the limited length of the observational record. Although attribution is currently not possible, CMIP5 model simulations of the period 1850–2015, on average, exhibit a weakening AMOC when driven by anthropogenic forcing. {6.7}

A.3 Global mean sea level (GMSL) is rising, with acceleration in recent decades due to increasing rates of ice loss from the Greenland and Antarctic ice sheets (*very high confidence*), as well as continued glacier mass loss and ocean thermal expansion. Increases in tropical cyclone winds and rainfall, and increases in extreme waves, combined with relative sea level rise, exacerbate extreme sea level events and coastal hazards (*high confidence*). {3.3, 4.2, 6.2, 6.3, 6.8, Figures SPM.1, SPM.2, SPM.4, SPM.5}

A.3.1 Total GMSL rise for 1902–2015 is 0.16 m (*likely* range 0.12–0.21 m). The rate of GMSL rise for 2006–2015 of 3.6 mm yr^{-1} (3.1–4.1 mm yr^{-1}, *very likely* range), is unprecedented over the last century (*high confidence*), and about 2.5 times the rate for 1901–1990 of 1.4 mm yr^{-1} (0.8– 2.0 mm yr^{-1}, *very likely* range). The sum of ice sheet and glacier contributions over the period 2006–2015 is the dominant source of sea level rise (1.8 mm yr^{-1}, *very likely* range 1.7–1.9 mm yr^{-1}), exceeding the effect of thermal expansion of ocean water (1.4 mm yr^{-1}, *very likely* range 1.1–1.7 mm yr^{-1})[22] (*very high confidence*). The dominant cause of global mean sea level rise since 1970 is anthropogenic forcing (*high confidence*). {4.2.1, 4.2.2, Figure SPM.1}

A.3.2 Sea level rise has accelerated (*extremely likely*) due to the combined increased ice loss from the Greenland and Antarctic ice sheets (*very high confidence*). Mass loss from the Antarctic ice sheet over the period 2007–2016 tripled relative to 1997–2006. For Greenland, mass loss doubled over the same period (*likely, medium confidence*). {3.3.1, Figures SPM.1, SPM.2, SPM A.1.1}

A.3.3 Acceleration of ice flow and retreat in Antarctica, which has the potential to lead to sea level rise of several metres within a few centuries, is observed in the Amundsen Sea Embayment of West Antarctica and in Wilkes Land, East Antarctica (*very high confidence*). These changes may be the onset of an irreversible[23] ice sheet instability. Uncertainty related to the onset of ice sheet instability arises from limited observations, inadequate model representation of ice sheet processes, and limited understanding of the complex interactions between the atmosphere, ocean and the ice sheet. {3.3.1, Cross-Chapter Box 8 in Chapter 3, 4.2.3}

A.3.4 Sea level rise is not globally uniform and varies regionally. Regional differences, within ±30% of the global mean sea level rise, result from land ice loss and variations in ocean warming and circulation. Differences from the global mean can be greater in areas of rapid vertical land movement including from local human activities (e.g. extraction of groundwater). (*high confidence*) {4.2.2, 5.2.2, 6.2.2, 6.3.1, 6.8.2, Figure SPM.2}

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21 The Atlantic Meridional Overturning Circulation (AMOC) is the main current system in the South and North Atlantic Oceans (Annex I: Glossary).

22 The total rate of sea level rise is greater than the sum of cryosphere and ocean contributions due to uncertainties in the estimate of landwater storage change.

23 The recovery time scale is hundreds to thousands of years (Annex I: Glossary).

A.3.5 Extreme wave heights, which contribute to extreme sea level events, coastal erosion and flooding, have increased in the Southern and North Atlantic Oceans by around 1.0 cm yr^{-1} and 0.8 cm yr^{-1} over the period 1985–2018 (*medium confidence*). Sea ice loss in the Arctic has also increased wave heights over the period 1992–2014 (*medium confidence*). {4.2.2, 6.2, 6.3, 6.8, Box 6.1}

A.3.6 Anthropogenic climate change has increased observed precipitation (*medium confidence*), winds (*low confidence*), and extreme sea level events (*high confidence*) associated with some tropical cyclones, which has increased intensity of multiple extreme events and associated cascading impacts (*high confidence*). Anthropogenic climate change may have contributed to a poleward migration of maximum tropical cyclone intensity in the western North Pacific in recent decades related to anthropogenically-forced tropical expansion (*low confidence*). There is emerging evidence for an increase in annual global proportion of Category 4 or 5 tropical cyclones in recent decades (*low confidence*). {6.2, Table 6.2, 6.3, 6.8, Box 6.1}

Observed Impacts on Ecosystems

A.4 Cryospheric and associated hydrological changes have impacted terrestrial and freshwater species and ecosystems in high mountain and polar regions through the appearance of land previously covered by ice, changes in snow cover, and thawing permafrost. These changes have contributed to changing the seasonal activities, abundance and distribution of ecologically, culturally, and economically important plant and animal species, ecological disturbances, and ecosystem functioning. (*high confidence*) {2.3.2, 2.3.3, 3.4.1, 3.4.3, Box 3.4, Figure SPM.2}

A.4.1 Over the last century some species of plants and animals have increased in abundance, shifted their range, and established in new areas as glaciers receded and the snow-free season lengthened (*high confidence*). Together with warming, these changes have increased locally the number of species in high mountains, as lower-elevation species migrate upslope (*very high confidence*). Some cold-adapted or snow-dependent species have declined in abundance, increasing their risk of extinction, notably on mountain summits (*high confidence*). In polar and mountain regions, many species have altered seasonal activities especially in late winter and spring (*high confidence*). {2.3.3, Box 3.4}

A.4.2 Increased wildfire and abrupt permafrost thaw, as well as changes in Arctic and mountain hydrology have altered frequency and intensity of ecosystem disturbances (*high confidence*). This has included positive and negative impacts on vegetation and wildlife such as reindeer and salmon (*high confidence*). {2.3.3, 3.4.1, 3.4.3}

A.4.3 Across tundra, satellite observations show an overall greening, often indicative of increased plant productivity (*high confidence*). Some browning areas in tundra and boreal forest are indicative that productivity has decreased (*high confidence*). These changes have negatively affected provisioning, regulating and cultural ecosystem services, with also some transient positive impacts for provisioning services, in both high mountains (*medium confidence*) and polar regions (*high confidence*). {2.3.1, 2.3.3, 3.4.1, 3.4.3, Annex I: Glossary}

A.5 Since about 1950 many marine species across various groups have undergone shifts in geographical range and seasonal activities in response to ocean warming, sea ice change and biogeochemical changes, such as oxygen loss, to their habitats (*high confidence*). This has resulted in shifts in species composition, abundance and biomass production of ecosystems, from the equator to the poles. Altered interactions between species have caused cascading impacts on ecosystem structure and functioning (*medium confidence*). In some marine ecosystems species are impacted by both the effects of fishing and climate changes (*medium confidence*). {3.2.3, 3.2.4, Box 3.4, 5.2.3, 5.3, 5.4.1, Figure SPM.2}

A.5.1 Rates of poleward shifts in distributions across different marine species since the 1950s are 52 ± 33 km per decade and 29 ± 16 km per decade (*very likely* ranges) for organisms in the epipelagic (upper 200 m from sea surface) and seafloor ecosystems, respectively. The rate and direction of observed shifts in distributions are shaped by local temperature, oxygen, and ocean currents across depth, latitudinal and longitudinal gradients (*high confidence*). Warming-induced species range expansions have led to altered ecosystem structure and functioning such as in the North Atlantic, Northeast Pacific and Arctic (*medium confidence*). {5.2.3, 5.3.2, 5.3.6, Box 3.4, Figure SPM.2}

A.5.2 In recent decades, Arctic net primary production has increased in ice-free waters (*high confidence*) and spring phytoplankton blooms are occurring earlier in the year in response to sea ice change and nutrient availability with spatially variable positive and negative consequences for marine ecosystems (*medium confidence*). In the Antarctic, such changes are spatially heterogeneous and have been associated with rapid local environmental change, including retreating glaciers and sea ice change (*medium confidence*). Changes in the seasonal activities, production and distribution of some Arctic zooplankton and a southward shift in the distribution of the Antarctic krill population in the South Atlantic are associated with climate-linked environmental changes (*medium confidence*). In polar regions, ice associated marine mammals and seabirds have experienced habitat contraction linked to sea ice changes (*high confidence*) and impacts on foraging success due to climate impacts on prey distributions (*medium confidence*). Cascading effects of multiple climate-related drivers on polar zooplankton have affected food web structure and function, biodiversity as well as fisheries (*high confidence*). {3.2.3, 3.2.4, Box 3.4, 5.2.3, Figure SPM.2}

A.5.3 Eastern Boundary Upwelling Systems (EBUS) are amongst the most productive ocean ecosystems. Increasing ocean acidification and oxygen loss are negatively impacting two of the four major upwelling systems: the California Current and Humboldt Current (*high confidence*). Ocean acidification and decrease in oxygen level in the California Current upwelling system have altered ecosystem structure, with direct negative impacts on biomass production and species composition (*medium confidence*). {Box 5.3, Figure SPM.2}

A.5.4 Ocean warming in the 20th century and beyond has contributed to an overall decrease in maximum catch potential (*medium confidence*), compounding the impacts from overfishing for some fish stocks (*high confidence*). In many regions, declines in the abundance of fish and shellfish stocks due to direct and indirect effects of global warming and biogeochemical changes have already contributed to reduced fisheries catches (*high confidence*). In some areas, changing ocean conditions have contributed to the expansion of suitable habitat and/or increases in the abundance of some species (*high confidence*). These changes have been accompanied by changes in species composition of fisheries catches since the 1970s in many ecosystems (*medium confidence*). {3.2.3, 5.4.1, Figure SPM.2}

A.6 Coastal ecosystems are affected by ocean warming, including intensified marine heatwaves, acidification, loss of oxygen, salinity intrusion and sea level rise, in combination with adverse effects from human activities on ocean and land (*high confidence*). Impacts are already observed on habitat area and biodiversity, as well as ecosystem functioning and services (*high confidence*). {4.3.2, 4.3.3, 5.3, 5.4.1, 6.4.2, Figure SPM.2}

A.6.1 Vegetated coastal ecosystems protect the coastline from storms and erosion and help buffer the impacts of sea level rise. Nearly 50% of coastal wetlands have been lost over the last 100 years, as a result of the combined effects of localised human pressures, sea level rise, warming and extreme climate events (*high confidence*). Vegetated coastal ecosystems are important carbon stores; their loss is responsible for the current release of 0.04–1.46 GtC yr^{-1} (*medium confidence*). In response to warming, distribution ranges of seagrass meadows and kelp forests are expanding at high latitudes and contracting at low latitudes since the late 1970s (*high confidence*), and in some areas episodic losses occur following heatwaves (*medium confidence*). Large-scale mangrove mortality that is related to warming since the 1960s has been partially offset by their encroachment into subtropical saltmarshes as a result of increase in temperature, causing the loss of open areas with herbaceous plants that provide food and habitat for dependent fauna (*high confidence*). {4.3.3, 5.3.2, 5.3.6, 5.4.1, 5.5.1, Figure SPM.2}

A.6.2 Increased sea water intrusion in estuaries due to sea level rise has driven upstream redistribution of marine species (*medium confidence*) and caused a reduction of suitable habitats for estuarine communities (*medium confidence*). Increased nutrient and organic matter loads in estuaries since the 1970s from intensive human development and riverine loads have exacerbated the stimulating effects of ocean warming on bacterial respiration, leading to expansion of low oxygen areas (*high confidence*). {5.3.1}

A.6.3 The impacts of sea level rise on coastal ecosystems include habitat contraction, geographical shift of associated species, and loss of biodiversity and ecosystem functionality. Impacts are exacerbated by direct human disturbances, and where anthropogenic barriers prevent landward shift of marshes and mangroves (termed coastal squeeze) (*high confidence*). Depending on local geomorphology and sediment supply, marshes and mangroves can grow vertically at rates equal to or greater than current mean sea level rise (*high confidence*). {4.3.2, 4.3.3, 5.3.2, 5.3.7, 5.4.1}

A.6.4 Warm-water coral reefs and rocky shores dominated by immobile, calcifying (e.g., shell and skeleton producing) organisms such as corals, barnacles and mussels, are currently impacted by extreme temperatures and ocean acidification (*high confidence*). Marine heatwaves have already resulted in large-scale coral bleaching events at increasing frequency (*very high confidence*) causing worldwide reef degradation since 1997, and recovery is slow (more than 15 years) if it occurs (*high confidence*). Prolonged periods of high environmental temperature and dehydration of the organisms pose high risk to rocky shore ecosystems (*high confidence*). {SR.1.5; 5.3.4, 5.3.5, 6.4.2, Figure SPM.2}

Observed regional impacts from changes in the ocean and the cryosphere

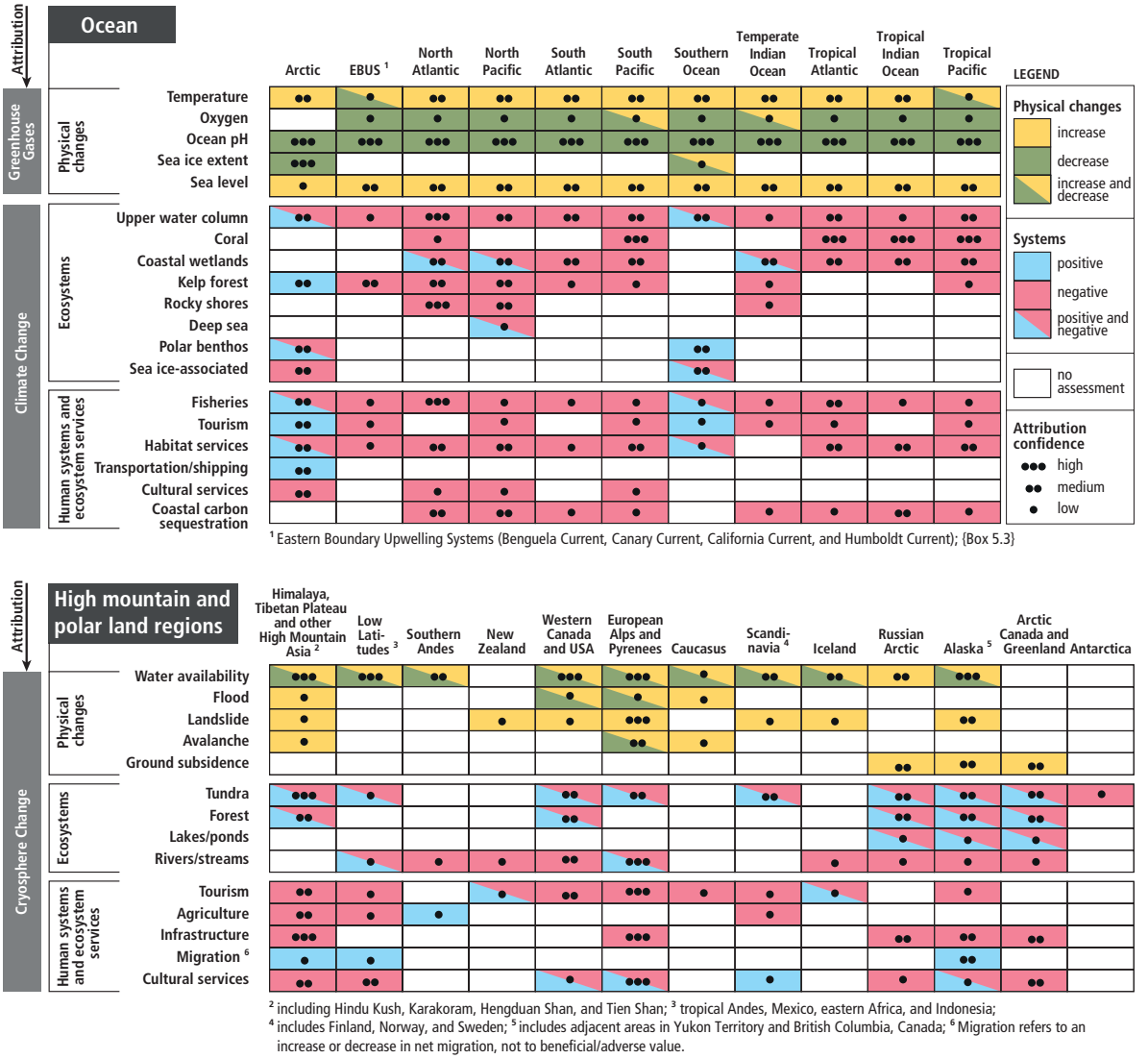


Figure SPM.2 | Synthesis of observed regional hazards and impacts in ocean[24] (top) and high mountain and polar land regions (bottom) assessed in SROCC. For each region, physical changes, impacts on key ecosystems, and impacts on human systems and ecosystem function and services are shown. For physical changes, yellow/green refers to an increase/decrease, respectively, in amount or frequency of the measured variable. For impacts on ecosystems, human systems and ecosystems services blue or red depicts whether an observed impact is positive (beneficial) or negative (adverse), respectively, to the given system or service. Cells assigned 'increase and decrease' indicate that within that region, both increase and decrease of physical changes are found, but are not necessarily equal; the same holds for cells showing 'positive and negative' attributable impacts. For ocean regions, the confidence level refers to the confidence in attributing observed changes to changes in greenhouse gas forcing for physical changes and to climate change for ecosystem, human systems, and ecosystem services. For high mountain and polar land regions, the level of confidence in attributing physical changes and impacts at least partly to a change in the cryosphere is shown. No assessment means: not applicable, not assessed at regional scale, or the evidence is insufficient for assessment. The physical changes in the ocean are defined as: Temperature change in 0–700 m layer of the ocean except for Southern Ocean (0–2000 m) and Arctic Ocean (upper mixed layer and major inflowing branches); Oxygen in the 0–1200 m layer or oxygen minimum layer; Ocean pH as surface pH (decreasing pH corresponds to increasing ocean acidification). Ecosystems in the ocean: Coral refers to warm-water coral reefs and cold-water corals. The 'upper water column' category refers to epipelagic zone for all ocean regions except Polar Regions, where the impacts on some pelagic organisms in open water deeper than the upper 200 m were included. Coastal wetland includes salt marshes, mangroves and seagrasses. Kelp forests are habitats of a specific group of macroalgae. Rocky shores are coastal habitats dominated by immobile calcified organisms such as mussels and barnacles. Deep sea is seafloor ecosystems that are 3000–6000 m deep. Sea-ice associated includes ecosystems in, on and below sea ice. Habitat services refer to supporting structures and services (e.g., habitat, biodiversity, primary production). Coastal Carbon Sequestration refers to the uptake and storage of carbon by coastal blue carbon ecosystems. Ecosystems on Land: Tundra refers to tundra and alpine meadows, and includes terrestrial Antarctic ecosystems.

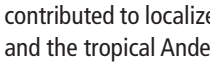
[24] Marginal seas are not assessed individually as ocean regions in this report.

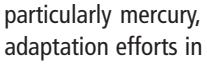
Figure SPM.2 (continued): Migration refers to an increase or decrease in net migration, not to beneficial/adverse value. Impacts on tourism refer to the operating conditions for the tourism sector. Cultural services include cultural identity, sense of home, and spiritual, intrinsic and aesthetic values, as well as contributions from glacier archaeology. The underlying information is given for land regions in tables SM2.6, SM2.7, SM2.8, SM3.8, SM3.9, and SM3.10, and for ocean regions in tables SM5.10, SM5.11, SM3.8, SM3.9, and SM3.10. {2.3.1, 2.3.2, 2.3.3, 2.3.4, 2.3.5, 2.3.6, 2.3.7, Figure 2.1, 3.2.1, 3.2.3, 3.2.4, 3.3.3, 3.4.1, 3.4.3, 3.5.2, Box 3.4, 4.2.2, 5.2.2, 5.2.3, 5.3.3, 5.4, 5.6, Figure 5.24, Box 5.3}

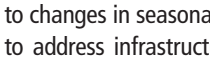
Observed Impacts on People and Ecosystem Services

A.7 Since the mid-20th century, the shrinking cryosphere in the Arctic and high mountain areas has led to predominantly negative impacts on food security, water resources, water quality, livelihoods, health and well-being, infrastructure, transportation, tourism and recreation, as well as culture of human societies, particularly for Indigenous peoples (*high confidence*). Costs and benefits have been unequally distributed across populations and regions. Adaptation efforts have benefited from the inclusion of Indigenous knowledge and local knowledge (*high confidence*). {1.1, 1.5, 1.6.2, 2.3, 2.4, 3.4, 3.5, Figure SPM.2}

A.7.1 Food and water security have been negatively impacted by changes in snow cover, lake and river ice, and permafrost in many Arctic regions (*high confidence*). These changes have disrupted access to, and food availability within, herding, hunting, fishing, and gathering areas, harming the livelihoods and cultural identity of Arctic residents including Indigenous populations (*high confidence*). Glacier retreat and snow cover changes have contributed to localized declines in agricultural yields in some high mountain regions, including Hindu Kush Himalaya and the tropical Andes (*medium confidence*). {2.3.1, 2.3.7, Box 2.4, 3.4.1, 3.4.2, 3.4.3, 3.5.2, Figure SPM.2}

A.7.2  In the Arctic, negative impacts of cryosphere change on human health have included increased risk of food- and waterborne diseases, malnutrition, injury, and mental health challenges especially among Indigenous peoples (*high confidence*). In some high mountain areas, water quality has been affected by contaminants, particularly mercury, released from melting glaciers and thawing permafrost (*medium confidence*). Health-related adaptation efforts in the Arctic range from local to international in scale, and successes have been underpinned by Indigenous knowledge (*high confidence*). {1.8, Cross-Chapter Box 4 in Chapter 1, 2.3.1, 3.4.3}

A.7.3  Arctic residents, especially Indigenous peoples, have adjusted the timing of activities to respond to changes in seasonality and safety of land, ice, and snow travel conditions. Municipalities and industry are beginning to address infrastructure failures associated with flooding and thawing permafrost and some coastal communities have planned for relocation (*high confidence*). Limited funding, skills, capacity, and institutional support to engage meaningfully in planning processes have challenged adaptation (*high confidence*). {3.5.2, 3.5.4, Cross-Chapter Box 9}

A.7.4  Summertime Arctic ship-based transportation (including tourism) increased over the past two decades concurrent with sea ice reductions (*high confidence*). This has implications for global trade and economies linked to traditional shipping corridors, and poses risks to Arctic marine ecosystems and coastal communities (*high confidence*), such as from invasive species and local pollution. {3.2.1, 3.2.4, 3.5.4, 5.4.2, Figure SPM.2}

A.7.5 In past decades, exposure of people and infrastructure to natural hazards has increased due to growing population, tourism and socioeconomic development (*high confidence).* Some disasters have been linked to changes in the cryosphere, for example in the Andes, high mountain Asia, Caucasus and European Alps (*medium confidence*). {2.3.2, Figure SPM.2}

A.7.6 Changes in snow and glaciers have changed the amount and seasonality of runoff and water resources in snow dominated and glacier-fed river basins (*very high confidence*). Hydropower facilities have experienced changes in seasonality and both increases and decreases in water input from high mountain areas, for

example, in central Europe, Iceland, Western USA/Canada, and tropical Andes (*medium confidence*). However, there is only *limited evidence* of resulting impacts on operations and energy production. {SPM B.1.4, 2.3.1}

A.7.7 High mountain aesthetic and cultural aspects have been negatively impacted by glacier and snow cover decline (e.g. in the Himalaya, East Africa, the tropical Andes) (*medium confidence*). Tourism and recreation, including ski and glacier tourism, hiking, and mountaineering, have also been negatively impacted in many mountain regions (*medium confidence*). In some places, artificial snowmaking has reduced negative impacts on ski tourism (*medium confidence*). {2.3.5, 2.3.6, Figure SPM.2}

A.8 Changes in the ocean have impacted marine ecosystems and ecosystem services with regionally diverse outcomes, challenging their governance (*high confidence*). Both positive and negative impacts result for food security through fisheries (*medium confidence*), local cultures and livelihoods (*medium confidence*), and tourism and recreation (*medium confidence*). The impacts on ecosystem services have negative consequences for health and well-being (*medium confidence*), and for Indigenous peoples and local communities dependent on fisheries (*high confidence*). {1.1, 1.5, 3.2.1, 5.4.1, 5.4.2, Figure SPM.2}

A.8.1 Warming-induced changes in the spatial distribution and abundance of some fish and shellfish stocks have had positive and negative impacts on catches, economic benefits, livelihoods, and local culture (*high confidence*). There are negative consequences for Indigenous peoples and local communities that are dependent on fisheries (*high confidence*). Shifts in species distributions and abundance has challenged international and national ocean and fisheries governance, including in the Arctic, North Atlantic and Pacific, in terms of regulating fishing to secure ecosystem integrity and sharing of resources between fishing entities (*high confidence*). {3.2.4, 3.5.3, 5.4.2, 5.5.2, Figure SPM.2}

A.8.2 Harmful algal blooms display range expansion and increased frequency in coastal areas since the 1980s in response to both climatic and non-climatic drivers such as increased riverine nutrients run-off (*high confidence*). The observed trends in harmful algal blooms are attributed partly to the effects of ocean warming, marine heatwaves, oxygen loss, eutrophication and pollution (*high confidence*). Harmful algal blooms have had negative impacts on food security, tourism, local economy, and human health (*high confidence*). The human communities who are more vulnerable to these biological hazards are those in areas without sustained monitoring programs and dedicated early warning systems for harmful algal blooms (*medium confidence*). {Box 5.4, 5.4.2, 6.4.2}

A.9 Coastal communities are exposed to multiple climate-related hazards, including tropical cyclones, extreme sea levels and flooding, marine heatwaves, sea ice loss, and permafrost thaw (*high confidence*). A diversity of responses has been implemented worldwide, mostly after extreme events, but also some in anticipation of future sea level rise, e.g., in the case of large infrastructure. {3.2.4, 3.4.3, 4.3.2, 4.3.3, 4.3.4, 4.4.2, 5.4.2, 6.2, 6.4.2, 6.8, Box 6.1, Cross Chapter Box 9, Figure SPM.5}

A.9.1 Attribution of current coastal impacts on people to sea level rise remains difficult in most locations since impacts were exacerbated by human-induced non-climatic drivers, such as land subsidence (e.g., groundwater extraction), pollution, habitat degradation, reef and sand mining (*high confidence*). {4.3.2, 4.3.3}

A.9.2 Coastal protection through hard measures, such as dikes, seawalls, and surge barriers, is widespread in many coastal cities and deltas. Ecosystem-based and hybrid approaches combining ecosystems and built infrastructure are becoming more popular worldwide. Coastal advance, which refers to the creation of new land by building seawards (e.g., land reclamation), has a long history in most areas where there are dense coastal

populations and a shortage of land. Coastal retreat, which refers to the removal of human occupation of coastal areas, is also observed, but is generally restricted to small human communities or occurs to create coastal wetland habitat. The effectiveness of the responses to sea level rise are assessed in Figure SPM.5. {3.5.3, 4.3.3, 4.4.2, 6.3.3, 6.9.1, Cross-Chapter Box 9}

B. Projected Changes and Risks

Projected Physical Changes[25]

B.1 Global-scale glacier mass loss, permafrost thaw, and decline in snow cover and Arctic sea ice extent are projected to continue in the near-term (2031–2050) due to surface air temperature increases (*high confidence*), with unavoidable consequences for river runoff and local hazards (*high confidence*). The Greenland and Antarctic Ice Sheets are projected to lose mass at an increasing rate throughout the 21st century and beyond (*high confidence*). The rates and magnitudes of these cryospheric changes are projected to increase further in the second half of the 21st century in a high greenhouse gas emissions scenario (*high confidence*). Strong reductions in greenhouse gas emissions in the coming decades are projected to reduce further changes after 2050 (*high confidence*). {2.2, 2.3, Cross-Chapter Box 6 in Chapter 2, 3.3, 3.4, Figure SPM.1, SPM Box SPM.1}

B.1.1 Projected glacier mass reductions between 2015 and 2100 (excluding the ice sheets) range from 18 ± 7% (*likely* range) for RCP2.6 to 36 ± 11% (*likely* range) for RCP8.5, corresponding to a sea level contribution of 94 ± 25 mm (*likely* range) sea level equivalent for RCP2.6, and 200 ± 44 mm (*likely* range) for RCP8.5 (*medium confidence*). Regions with mostly smaller glaciers (e.g., Central Europe, Caucasus, North Asia, Scandinavia, tropical Andes, Mexico, eastern Africa and Indonesia), are projected to lose more than 80% of their current ice mass by 2100 under RCP8.5 (*medium confidence*), and many glaciers are projected to disappear regardless of future emissions (*very high confidence*). {Cross-Chapter Box 6 in Chapter 2, Figure SPM.1}

B.1.2 In 2100, the Greenland Ice Sheet's projected contribution to GMSL rise is 0.07 m (0.04–0.12 m, *likely* range) under RCP2.6, and 0.15 m (0.08–0.27 m, *likely* range) under RCP8.5. In 2100, the Antarctic Ice Sheet is projected to contribute 0.04 m (0.01–0.11 m, *likely* range) under RCP2.6, and 0.12 m (0.03–0.28 m, *likely* range) under RCP8.5. The Greenland Ice Sheet is currently contributing more to sea level rise than the Antarctic Ice Sheet (*high confidence*), but Antarctica could become a larger contributor by the end of the 21st century as a consequence of rapid retreat (*low confidence*). Beyond 2100, increasing divergence between Greenland and Antarctica's relative contributions to GMSL rise under RCP8.5 has important consequences for the pace of relative sea level rise in the Northern Hemisphere. {3.3.1, 4.2.3, 4.2.5, 4.3.3, Cross-Chapter Box 8 in Chapter 3, Figure SPM.1}

B.1.3 Arctic autumn and spring snow cover are projected to decrease by 5–10%, relative to 1986–2005, in the near-term (2031–2050), followed by no further losses under RCP2.6, but an additional 15–25% loss by the end of century under RCP8.5 (*high confidence*). In high mountain areas, projected decreases in low elevation mean winter snow depth, compared to 1986–2005, are *likely* 10–40% by 2031–2050, regardless of emissions scenario (*high confidence*). For 2081–2100, this projected decrease is *likely* 10–40% for RCP2.6 and 50–90% for RCP8.5. {2.2.2, 3.3.2, 3.4.2, Figure SPM.1}

[25] This report primarily uses RCP2.6 and RCP8.5 for the following reasons: These scenarios largely represent the assessed range for the topics covered in this report; they largely represent what is covered in the assessed literature, based on CMIP5; and they allow a consistent narrative about projected changes. RCP4.5 and RCP6.0 are not available for all topics addressed in the report. {Box SPM.1}

B.1.4 Widespread permafrost thaw is projected for this century (*very high confidence*) and beyond. By 2100, projected near-surface (within 3–4 m) permafrost area shows a decrease of 24 ± 16% (*likely* range) for RCP2.6 and 69 ± 20% (*likely* range) for RCP8.5. The RCP8.5 scenario leads to the cumulative release of tens to hundreds of billions of tons (GtC) of permafrost carbon as CO_2[26] and methane to the atmosphere by 2100 with the potential to exacerbate climate change (*medium confidence*). Lower emissions scenarios dampen the response of carbon emissions from the permafrost region (*high confidence*). Methane contributes a small fraction of the total additional carbon release but is significant because of its higher warming potential. Increased plant growth is projected to replenish soil carbon in part, but will not match carbon releases over the long term (*medium confidence*). {2.2.4, 3.4.2, 3.4.3, Figure SPM.1, Cross-Chapter Box 5 in Chapter 1}

B.1.5 In many high mountain areas, glacier retreat and permafrost thaw are projected to further decrease the stability of slopes, and the number and area of glacier lakes will continue to increase (*high confidence*). Floods due to glacier lake outburst or rain-on-snow, landslides and snow avalanches, are projected to occur also in new locations or different seasons (*high confidence*). {2.3.2}

B.1.6 River runoff in snow-dominated or glacier-fed high mountain basins is projected to change regardless of emissions scenario (*very high confidence*), with increases in average winter runoff (*high confidence)* and earlier spring peaks (*very high confidence*). In all emissions scenarios, average annual and summer runoff from glaciers are projected to peak at or before the end of the 21st century (*high confidence*), e.g., around mid-century in High Mountain Asia, followed by a decline in glacier runoff. In regions with little glacier cover (e.g., tropical Andes, European Alps) most glaciers have already passed this peak (*high confidence*). Projected declines in glacier runoff by 2100 (RCP8.5) can reduce basin runoff by 10% or more in at least one month of the melt season in several large river basins, especially in High Mountain Asia during the dry season (*low confidence*). {2.3.1}

B.1.7 Arctic sea ice loss is projected to continue through mid-century, with differences thereafter depending on the magnitude of global warming: for stabilised global warming of 1.5ºC the annual probability of a sea ice-free September by the end of century is approximately 1%, which rises to 10–35% for stabilised global warming of 2ºC (*high confidence*). There is *low confidence* in projections for Antarctic sea ice. {3.2.2, Figure SPM.1}

B.2 Over the 21st century, the ocean is projected to transition to unprecedented conditions with increased temperatures (*virtually certain*), greater upper ocean stratification (*very likely*), further acidification (*virtually certain*), oxygen decline (*medium confidence*), and altered net primary production (*low confidence*). Marine heatwaves (*very high confidence)* and extreme El Niño and La Niña events (*medium confidence)* are projected to become more frequent. The Atlantic Meridional Overturning Circulation (AMOC) is projected to weaken (*very likely*). The rates and magnitudes of these changes will be smaller under scenarios with low greenhouse gas emissions (*very likely*). {3.2, 5.2, 6.4, 6.5, 6.7, Box 5.1, Figures SPM.1, SPM.3}

B.2.1 The ocean will continue to warm throughout the 21st century (*virtually certain*). By 2100, the top 2000 m of the ocean are projected to take up 5–7 times more heat under RCP8.5 (or 2–4 times more under RCP2.6) than the observed accumulated ocean heat uptake since 1970 (*very likely*). The annual mean density stratification[19] of the top 200 m, averaged between 60ºS and 60ºN, is projected to increase by 12–30% for RCP8.5 and 1–9% for RCP2.6, for 2081–2100 relative to 1986–2005 (*very likely*), inhibiting vertical nutrient, carbon and oxygen fluxes. {5.2.2, Figure SPM.1}

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[26] For context, total annual anthropogenic CO_2 emissions were 10.8 ± 0.8 GtC yr^{-1} (39.6 ± 2.9 $GtCO_2$ yr^{-1}) on average over the period 2008–2017. Total annual anthropogenic methane emissions were 0.35 ± 0.01 $GtCH_4$ yr^{-1}, on average over the period 2003–2012. {5.5.1}

B.2.2 By 2081–2100 under RCP8.5, ocean oxygen content (*medium confidence*), upper ocean nitrate content (*medium confidence*), net primary production (*low confidence*) and carbon export (*medium confidence*) are projected to decline globally by *very likely* ranges of 3–4%, 9–14%, 4–11% and 9–16% respectively, relative to 2006–2015. Under RCP2.6, globally projected changes by 2081–2100 are smaller compared to RCP8.5 for oxygen loss (*very likely*), nutrient availability (*about as likely as not*) and net primary production (*high confidence*). {5.2.2, Box 5.1, Figures SPM.1, SPM.3}

B.2.3 Continued carbon uptake by the ocean by 2100 is *virtually certain* to exacerbate ocean acidification. Open ocean surface pH is projected to decrease by around 0.3 pH units by 2081–2100, relative to 2006–2015, under RCP8.5 (*virtually certain*). For RCP8.5, there are elevated risks for keystone aragonite shell-forming species due to crossing an aragonite stability threshold year-round in the Polar and sub-Polar Oceans by 2081–2100 (*very likely*). For RCP2.6, these conditions will be avoided this century (*very likely*), but some eastern boundary upwelling systems are projected to remain vulnerable (*high confidence*). {3.2.3, 5.2.2, Box 5.1, Box 5.3, Figure SPM.1}

B.2.4 Climate conditions, unprecedented since the preindustrial period, are developing in the ocean, elevating risks for open ocean ecosystems. Surface acidification and warming have already emerged in the historical period (*very likely*). Oxygen loss between 100 and 600 m depth is projected to emerge over 59–80% of the ocean area by 2031–2050 under RCP8.5 (*very likely*). The projected time of emergence for five primary drivers of marine ecosystem change (surface warming and acidification, oxygen loss, nitrate content and net primary production change) are all prior to 2100 for over 60% of the ocean area under RCP8.5 and over 30% under RCP2.6 (*very likely*). {Annex I: Glossary, Box 5.1, Box 5.1 Figure 1}

B.2.5 Marine heatwaves are projected to further increase in frequency, duration, spatial extent and intensity (maximum temperature) (*very high confidence*). Climate models project increases in the frequency of marine heatwaves by 2081–2100, relative to 1850–1900, by approximately 50 times under RCP8.5 and 20 times under RCP2.6 (*medium confidence*). The largest increases in frequency are projected for the Arctic and the tropical oceans (*medium confidence*). The intensity of marine heatwaves is projected to increase about 10-fold under RCP8.5 by 2081–2100, relative to 1850–1900 (*medium confidence*). {6.4, Figure SPM.1}

B.2.6 Extreme El Niño and La Niña events are projected to *likely* increase in frequency in the 21st century and to *likely* intensify existing hazards, with drier or wetter responses in several regions across the globe. Extreme El Niño events are projected to occur about as twice as often under both RCP2.6 and RCP8.5 in the 21st century when compared to the 20th century (*medium confidence*). Projections indicate that extreme Indian Ocean Dipole events also increase in frequency (*low confidence*). {6.5, Figures 6.5, 6.6}

B.2.7 The AMOC is projected to weaken in the 21st century under all RCPs (*very likely*), although a collapse is *very unlikely* (*medium confidence)*. Based on CMIP5 projections, by 2300, an AMOC collapse is *about as likely as not* for high emissions scenarios and *very unlikely* for lower ones (*medium confidence)*. Any substantial weakening of the AMOC is projected to cause a decrease in marine productivity in the North Atlantic (*medium confidence*), more storms in Northern Europe (*medium confidence*), less Sahelian summer rainfall (*high confidence*) and South Asian summer rainfall (*medium confidence*), a reduced number of tropical cyclones in the Atlantic (*medium confidence*), and an increase in regional sea level along the northeast coast of North America (*medium confidence*). Such changes would be in addition to the global warming signal. {6.7, Figures 6.8–6.10}

B.3 Sea level continues to rise at an increasing rate. Extreme sea level events that are historically rare (once per century in the recent past) are projected to occur frequently (at least once per year) at many locations by 2050 in all RCP scenarios, especially in tropical regions (*high confidence*). The increasing frequency of high water levels can have severe impacts in many locations depending on exposure (*high confidence*). Sea level rise is projected to continue beyond 2100 in all RCP scenarios. For a high emissions scenario (RCP8.5), projections of global sea level rise by 2100 are greater than in AR5 due to a larger contribution from the Antarctic Ice Sheet (*medium confidence*). In coming centuries under RCP8.5, sea-level rise is projected to exceed rates of several centimetres per year resulting in multi-metre rise (*medium confidence*), while for RCP2.6 sea level rise is projected to be limited to around 1 m in 2300 (*low confidence*). Extreme sea levels and coastal hazards will be exacerbated by projected increases in tropical cyclone intensity and precipitation (*high confidence*). Projected changes in waves and tides vary locally in whether they amplify or ameliorate these hazards (*medium confidence*). {Cross-Chapter Box 5 in Chapter 1, Cross-Chapter Box 8 in Chapter 3, 4.1, 4.2, 5.2.2, 6.3.1, Figures SPM.1, SPM.4, SPM.5}

B.3.1 The global mean sea level (GMSL) rise under RCP2.6 is projected to be 0.39 m (0.26–0.53 m, *likely* range) for the period 2081–2100, and 0.43 m (0.29–0.59 m, *likely* range) in 2100 with respect to 1986–2005. For RCP8.5, the corresponding GMSL rise is 0.71 m (0.51–0.92 m, *likely* range) for 2081–2100 and 0.84 m (0.61–1.10 m, *likely* range) in 2100. Mean sea level rise projections are higher by 0.1 m compared to AR5 under RCP8.5 in 2100, and the *likely* range extends beyond 1 m in 2100 due to a larger projected ice loss from the Antarctic Ice Sheet (*medium confidence*). The uncertainty at the end of the century is mainly determined by the ice sheets, especially in Antarctica. {4.2.3, Figures SPM.1, SPM.5}

B.3.2 Sea level projections show regional differences around GMSL. Processes not driven by recent climate change, such as local subsidence caused by natural processes and human activities, are important to relative sea level changes at the coast (*high confidence*). While the relative importance of climate-driven sea level rise is projected to increase over time, local processes need to be considered for projections and impacts of sea level (*high confidence*). {SPM A.3.4, 4.2.1, 4.2.2, Figure SPM.5}

B.3.3 The rate of global mean sea level rise is projected to reach 15 mm yr^{-1} (10–20 mm yr^{-1}, *likely* range) under RCP8.5 in 2100, and to exceed several centimetres per year in the 22nd century. Under RCP2.6, the rate is projected to reach 4 mm yr^{-1} (2–6 mm yr^{-1}, *likely* range) in 2100. Model studies indicate multi-meter rise in sea level by 2300 (2.3–5.4 m for RCP8.5 and 0.6–1.07 m under RCP2.6) (*low confidence*), indicating the importance of reduced emissions for limiting sea level rise. Processes controlling the timing of future ice-shelf loss and the extent of ice sheet instabilities could increase Antarctica's contribution to sea level rise to values substantially higher than the *likely* range on century and longer time-scales (*low confidence*). Considering the consequences of sea level rise that a collapse of parts of the Antarctic Ice Sheet entails, this high impact risk merits attention. {Cross-Chapter Box 5 in Chapter 1, Cross-Chapter Box 8 in Chapter 3, 4.1, 4.2.3}

B.3.4 Global mean sea level rise will cause the frequency of extreme sea level events at most locations to increase. Local sea levels that historically occurred once per century (historical centennial events) are projected to occur at least annually at most locations by 2100 under all RCP scenarios (*high confidence*). Many low-lying megacities and small islands (including SIDS) are projected to experience historical centennial events at least annually by 2050 under RCP2.6, RCP4.5 and RCP8.5. The year when the historical centennial event becomes an annual event in the mid-latitudes occurs soonest in RCP8.5, next in RCP4.5 and latest in RCP2.6. The increasing frequency of high water levels can have severe impacts in many locations depending on the level of exposure (*high confidence*). {4.2.3, 6.3, Figures SPM.4, SPM.5}

B.3.5 Significant wave heights (the average height from trough to crest of the highest one-third of waves) are projected to increase across the Southern Ocean and tropical eastern Pacific (*high confidence*) and Baltic Sea (*medium confidence*) and decrease over the North Atlantic and Mediterranean Sea under RCP8.5 (*high confidence*). Coastal tidal amplitudes and patterns are projected to change due to sea level rise and coastal adaptation measures (*very likely*). Projected changes in waves arising from changes in weather patterns, and changes in tides due to sea level rise, can locally enhance or ameliorate coastal hazards (*medium confidence)*. {6.3.1, 5.2.2}

B.3.6 The average intensity of tropical cyclones, the proportion of Category 4 and 5 tropical cyclones and the associated average precipitation rates are projected to increase for a 2ºC global temperature rise above any baseline period (*medium confidence*). Rising mean sea levels will contribute to higher extreme sea levels associated with tropical cyclones (*very high confidence*). Coastal hazards will be exacerbated by an increase in the average intensity, magnitude of storm surge and precipitation rates of tropical cyclones. There are greater increases projected under RCP8.5 than under RCP2.6 from around mid-century to 2100 (*medium confidence*). There is *low confidence* in changes in the future frequency of tropical cyclones at the global scale. {6.3.1}

Projected Risks for Ecosystems

B.4 Future land cryosphere changes will continue to alter terrestrial and freshwater ecosystems in high mountain and polar regions with major shifts in species distributions resulting in changes in ecosystem structure and functioning, and eventual loss of globally unique biodiversity (*medium confidence*). Wildfire is projected to increase significantly for the rest of this century across most tundra and boreal regions, and also in some mountain regions (*medium confidence*). {2.3.3, Box 3.4, 3.4.3}

B.4.1 In high mountain regions, further upslope migration by lower-elevation species, range contractions, and increased mortality will lead to population declines of many alpine species, especially glacier- or snow-dependent species (*high confidence*), with local and eventual global species loss (*medium confidence*). The persistence of alpine species and sustaining ecosystem services depends on appropriate conservation and adaptation measures (*high confidence*). {2.3.3}

B.4.2 On Arctic land, a loss of globally unique biodiversity is projected as limited refugia exist for some High-Arctic species and hence they are outcompeted by more temperate species (*medium confidence*). Woody shrubs and trees are projected to expand to cover 24–52% of Arctic tundra by 2050 (*medium confidence*). The boreal forest is projected to expand at its northern edge, while diminishing at its southern edge where it is replaced by lower biomass woodland/shrublands *(medium confidence*). {3.4.3, Box 3.4}

B.4.3 Permafrost thaw and decrease in snow will affect Arctic and mountain hydrology and wildfire, with impacts on vegetation and wildlife (*medium confidence)*. About 20% of Arctic land permafrost is vulnerable to abrupt permafrost thaw and ground subsidence, which is projected to increase small lake area by over 50% by 2100 for RCP8.5 (*medium confidence*). Even as the overall regional water cycle is projected to intensify, including increased precipitation, evapotranspiration, and river discharge to the Arctic Ocean, decreases in snow and permafrost may lead to soil drying with consequences for ecosystem productivity and disturbances (*medium confidence*). Wildfire is projected to increase for the rest of this century across most tundra and boreal regions, and also in some mountain regions, while interactions between climate and shifting vegetation will influence future fire intensity and frequency (*medium confidence*). {2.3.3, 3.4.1, 3.4.2, 3.4.3, SPM B.1}

B.5 A decrease in global biomass of marine animal communities, their production, and fisheries catch potential, and a shift in species composition are projected over the 21st century in ocean ecosystems from the surface to the deep seafloor under all emission scenarios (*medium confidence*). The rate and magnitude of decline are projected to be highest in the tropics (*high confidence*), whereas impacts remain diverse in polar regions (*medium confidence*) and increase for high emissions scenarios. Ocean acidification (*medium confidence*), oxygen loss (*medium confidence*) and reduced sea ice extent (*medium confidence*) as well as non-climatic human activities (*medium confidence*) have the potential to exacerbate these warming-induced ecosystem impacts. {3.2.3, 3.3.3, 5.2.2, 5.2.3, 5.2.4, 5.4.1, Figure SPM.3}

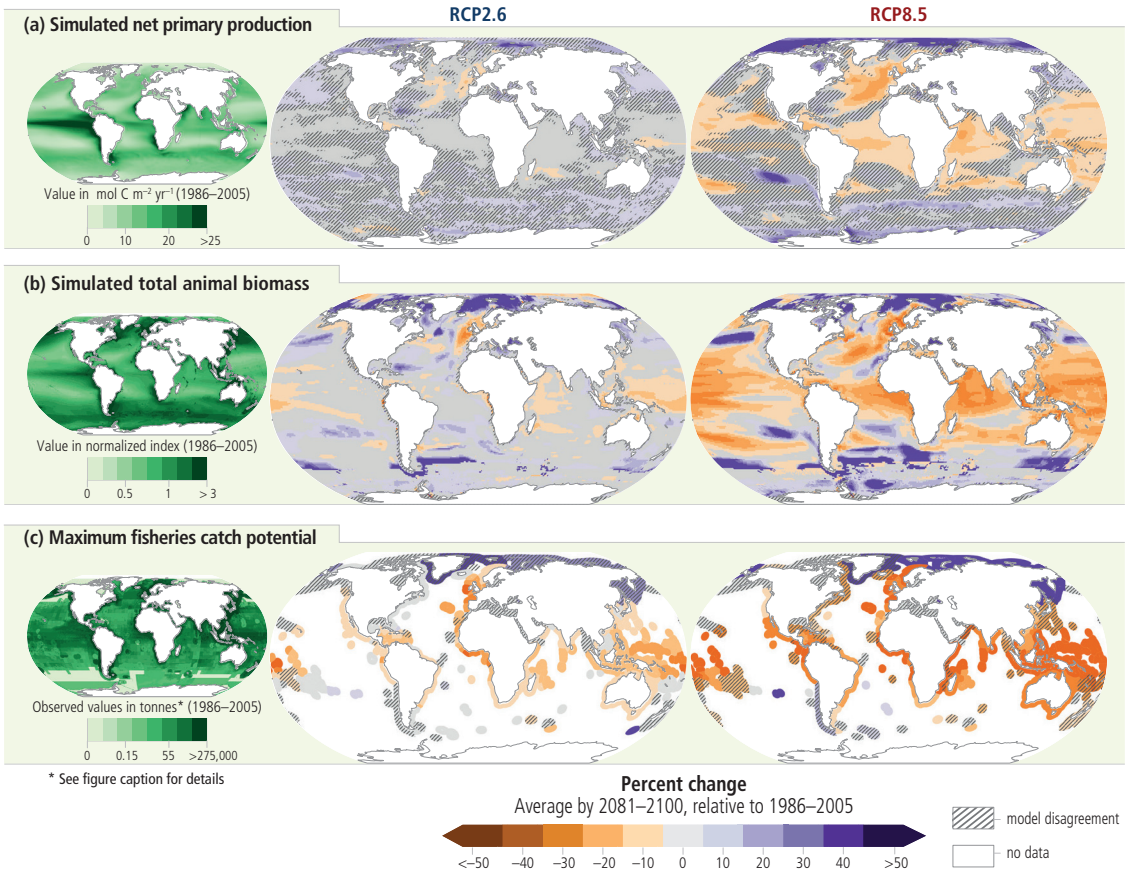
B.5.1 Projected ocean warming and changes in net primary production alter biomass, production and community structure of marine ecosystems. The global-scale biomass of marine animals across the foodweb is projected to decrease by 15.0 ± 5.9% (*very likely* range) and the maximum catch potential of fisheries by 20.5–24.1% by the end of the 21st century relative to 1986–2005 under RCP8.5 (*medium confidence*). These changes are projected to be *very likely* three to four times larger under RCP8.5 than RCP2.6. {3.2.3, 3.3.3, 5.2.2, 5.2.3, 5.4.1, Figure SPM.3}

B.5.2 Under enhanced stratification reduced nutrient supply is projected to cause tropical ocean net primary production to decline by 7–16% (*very likely* range) for RCP8.5 by 2081–2100 (*medium confidence*). In tropical regions, marine animal biomass and production are projected to decrease more than the global average under all emissions scenarios in the 21st century (*high confidence*). Warming and sea ice changes are projected to increase marine net primary production in the Arctic (*medium confidence*) and around Antarctica (*low confidence*), modified by changing nutrient supply due to shifts in upwelling and stratification. Globally, the sinking flux of organic matter from the upper ocean is projected to decrease, linked largely due to changes in net primary production (*high confidence*). As a result, 95% or more of the deep sea (3000–6000 m depth) seafloor area and cold-water coral ecosystems are projected to experience declines in benthic biomass under RCP8.5 (*medium confidence*). {3.2.3, 5.2.2. 5.2.4, Figure SPM.1}

B.5.3 Warming, ocean acidification, reduced seasonal sea ice extent and continued loss of multi-year sea ice are projected to impact polar marine ecosystems through direct and indirect effects on habitats, populations and their viability (*medium confidence*). The geographical range of Arctic marine species, including marine mammals, birds and fish is projected to contract, while the range of some sub-Arctic fish communities is projected to expand, further increasing pressure on high-Arctic species (*medium confidence*). In the Southern Ocean, the habitat of Antarctic krill, a key prey species for penguins, seals and whales, is projected to contract southwards under both RCP2.6 and RCP8.5 (*medium confidence*). {3.2.2, 3.2.3, 5.2.3}

B.5.4 Ocean warming, oxygen loss, acidification and a decrease in flux of organic carbon from the surface to the deep ocean are projected to harm habitat-forming cold-water corals, which support high biodiversity, partly through decreased calcification, increased dissolution of skeletons, and bioerosion (*medium confidence*). Vulnerability and risks are highest where and when temperature and oxygen conditions both reach values outside species' tolerance ranges (*medium confidence*). {Box 5.2, Figure SPM.3}

Projected changes, impacts and risks for ocean ecosystems as a result of climate change



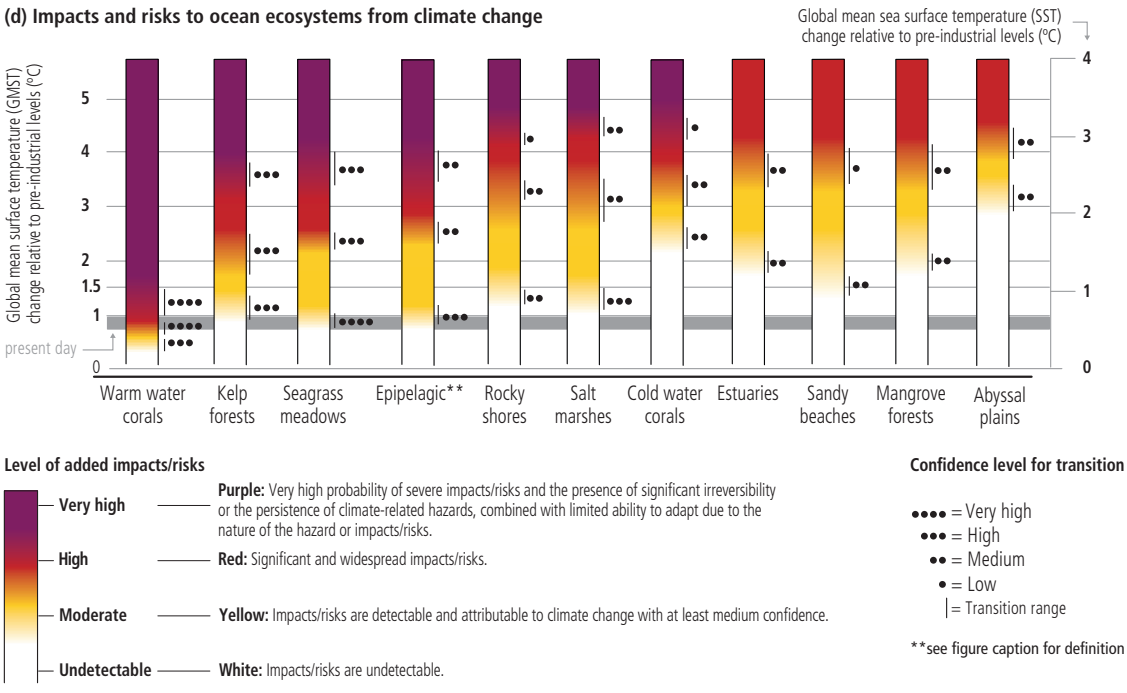


Figure SPM.3 | Projected changes, impacts and risks for ocean regions and ecosystems.

Figure SPM.3 (continued): **(a)** depth integrated net primary production (NPP from CMIP5[27]), **(b)** total animal biomass (depth integrated, including fishes and invertebrates from FISHMIP[28]), **(c)** maximum fisheries catch potential and **(d)** impacts and risks for coastal and open ocean ecosystems. The three left panels represent the simulated (a,b) and observed (c) mean values for the recent past (1986–2005), the middle and right panels represent projected changes (%) by 2081–2100 relative to recent past under low (RCP2.6) and high (RCP8.5) greenhouse gas emissions scenario {Box SPM.1}, respectively. Total animal biomass in the recent past (b, left panel) represents the projected total animal biomass by each spatial pixel relative to the global average. (c) *Average observed fisheries catch in the recent past (based on data from the Sea Around Us global fisheries database); projected changes in maximum fisheries catch potential in shelf seas are based on the average outputs from two fisheries and marine ecosystem models. To indicate areas of model inconsistency, shaded areas represent regions where models disagree in the direction of change for more than: (a) and (b) 3 out of 10 model projections, and (c) one out of two models. Although unshaded, the projected change in the Arctic and Antarctic regions in (b) total animal biomass and (c) fisheries catch potential have *low confidence* due to uncertainties associated with modelling multiple interacting drivers and ecosystem responses. Projections presented in (b) and (c) are driven by changes in ocean physical and biogeochemical conditions e.g., temperature, oxygen level, and net primary production projected from CMIP5 Earth system models. **The epipelagic refers to the uppermost part of the ocean with depth <200 m from the surface where there is enough sunlight to allow photosynthesis. (d) Assessment of risks for coastal and open ocean ecosystems based on observed and projected climate impacts on ecosystem structure, functioning and biodiversity. Impacts and risks are shown in relation to changes in Global Mean Surface Temperature (GMST) relative to pre-industrial level. Since assessments of risks and impacts are based on global mean Sea Surface Temperature (SST), the corresponding SST levels are shown[29]. The assessment of risk transitions is described in Chapter 5 Sections 5.2, 5.3, 5.2.5 and 5.3.7 and Supplementary Materials SM5.3, Table SM5.6, Table SM5.8 and other parts of the underlying report. The figure indicates assessed risks at approximate warming levels and increasing climate-related hazards in the ocean: ocean warming, acidification, deoxygenation, increased density stratification, changes in carbon fluxes, sea level rise, and increased frequency and/or intensity of extreme events. The assessment considers the natural adaptive capacity of the ecosystems, their exposure and vulnerability. Impact and risk levels do not consider risk reduction strategies such as human interventions, or future changes in non-climatic drivers. Risks for ecosystems were assessed by considering biological, biogeochemical, geomorphological and physical aspects. Higher risks associated with compound effects of climate hazards include habitat and biodiversity loss, changes in species composition and distribution ranges, and impacts/risks on ecosystem structure and functioning, including changes in animal/plant biomass and density, productivity, carbon fluxes, and sediment transport. As part of the assessment, literature was compiled and data extracted into a summary table. A multi-round expert elicitation process was undertaken with independent evaluation of threshold judgement, and a final consensus discussion. Further information on methods and underlying literature can be found in Chapter 5, Sections 5.2 and 5.3 and Supplementary Material. {3.2.3, 3.2.4, 5.2, 5.3, 5.2.5, 5.3.7, SM5.6, SM5.8, Figure 5.16, Cross Chapter Box 1 in Chapter 1 Table CCB1}

B.6 Risks of severe impacts on biodiversity, structure and function of coastal ecosystems are projected to be higher for elevated temperatures under high compared to low emissions scenarios in the 21st century and beyond. Projected ecosystem responses include losses of species habitat and diversity, and degradation of ecosystem functions. The capacity of organisms and ecosystems to adjust and adapt is higher at lower emissions scenarios (*high confidence*). For sensitive ecosystems such as seagrass meadows and kelp forests, high risks are projected if global warming exceeds 2ºC above pre-industrial temperature, combined with other climate-related hazards (*high confidence*). Warm-water corals are at high risk already and are projected to transition to very high risk even if global warming is limited to 1.5ºC (*very high confidence*). {4.3.3, 5.3, 5.5, Figure SPM.3}

B.6.1 All coastal ecosystems assessed are projected to face increasing risk level, from moderate to high risk under RCP2.6 to high to very high risk under RCP8.5 by 2100. Intertidal rocky shore ecosystems are projected to be at very high risk by 2100 under RCP8.5 (*medium confidence*) due to exposure to warming, especially during marine heatwaves, as well as to acidification, sea level rise, loss of calcifying species and biodiversity (*high confidence*). Ocean acidification challenges these ecosystems and further limits their habitat suitability (*medium confidence*) by inhibiting recovery through reduced calcification and enhanced bioerosion. The decline of kelp forests is projected to continue in temperate regions due to warming, particularly under the projected intensification of marine heatwaves, with high risk of local extinctions under RCP8.5 (*medium confidence*). {5.3, 5.3.5, 5.3.6, 5.3.7, 6.4.2, Figure SPM.3}

B.6.2 Seagrass meadows and saltmarshes and associated carbon stores are at moderate risk at 1.5ºC global warming and increase with further warming (*medium confidence).* Globally, 20–90% of current coastal wetlands are projected to be lost by 2100, depending on projected sea level rise, regional differences and wetland types, especially where vertical growth is already constrained by reduced sediment supply and landward migration is constrained by steep topography or human modification of shorelines (*high confidence*). {4.3.3, 5.3.2, Figure SPM.3, SPM A.6.1}

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27 NPP is estimated from the Coupled Models Intercomparison Project 5 (CMIP5).

28 Total animal biomass is from the Fisheries and Marine Ecosystem Models Intercomparison Project (FISHMIP).

29 The conversion between GMST and SST is based on a scaling factor of 1.44 derived from changes in an ensemble of RCP8.5 simulations; this scaling factor has an uncertainty of about 4% due to differences between the RCP2.6 and RCP8.5 scenarios. {Table SPM.1}

B.6.3 Ocean warming, sea level rise and tidal changes are projected to expand salinization and hypoxia in estuaries (*high confidence*) with high risks for some biota leading to migration, reduced survival, and local extinction under high emission scenarios (*medium confidence*). These impacts are projected to be more pronounced in more vulnerable eutrophic and shallow estuaries with low tidal range in temperate and high latitude regions (*medium confidence*). {5.2.2, 5.3.1, Figure SPM.3}

B.6.4 Almost all warm-water coral reefs are projected to suffer significant losses of area and local extinctions, even if global warming is limited to 1.5ºC (*high confidence*). The species composition and diversity of remaining reef communities is projected to differ from present-day reefs (*very high confidence*). {5.3.4, 5.4.1, Figure SPM.3}

Projected Risks for People and Ecosystem Services

B.7 Future cryosphere changes on land are projected to affect water resources and their uses, such as hydropower (*high confidence*) and irrigated agriculture in and downstream of high mountain areas (*medium confidence*), as well as livelihoods in the Arctic (*medium confidence*). Changes in floods, avalanches, landslides, and ground destabilization are projected to increase risk for infrastructure, cultural, tourism, and recreational assets (*medium confidence*). {2.3, 2.3.1, 3.4.3}

B.7.1 Disaster risks to human settlements and livelihood options in high mountain areas and the Arctic are expected to increase (*medium confidence*), due to future changes in hazards such as floods, fires, landslides, avalanches, unreliable ice and snow conditions, and increased exposure of people and infrastructure (*high confidence*). Current engineered risk reduction approaches are projected to be less effective as hazards change in character (*medium confidence*). Significant risk reduction and adaptation strategies help avoid increased impacts from mountain flood and landslide hazards as exposure and vulnerability are increasing in many mountain regions during this century (*high confidence*). {2.3.2, 3.4.3, 3.5.2}

B.7.2 Permafrost thaw-induced subsidence of the land surface is projected to impact overlying urban and rural communication and transportation infrastructure in the Arctic and in high mountain areas (*medium confidence*). The majority of Arctic infrastructure is located in regions where permafrost thaw is projected to intensify by mid-century. Retrofitting and redesigning infrastructure has the potential to halve the costs arising from permafrost thaw and related climate-change impacts by 2100 (*medium confidence*). {2.3.4, 3.4.1, 3.4.3}

B.7.3 High mountain tourism, recreation and cultural assets are projected to be negatively affected by future cryospheric changes (*high confidence*). Current snowmaking technologies are projected to be less effective in reducing risks to ski tourism in a warmer climate in most parts of Europe, North America, and Japan, in particular at 2ºC global warming and beyond (*high confidence*). {2.3.5, 2.3.6}

B.8 Future shifts in fish distribution and decreases in their abundance and fisheries catch potential due to climate change are projected to affect income, livelihoods, and food security of marine resource-dependent communities (*medium confidence*). Long-term loss and degradation of marine ecosystems compromises the ocean's role in cultural, recreational, and intrinsic values important for human identity and well-being (*medium confidence*). {3.2.4, 3.4.3, 5.4.1, 5.4.2, 6.4}

B.8.1 Projected geographical shifts and decreases of global marine animal biomass and fish catch potential are more pronounced under RCP8.5 relative to RCP2.6 elevating the risk for income and livelihoods of dependent human communities, particularly in areas that are economically vulnerable (*medium confidence*). The projected redistribution of resources and abundance increases the risk of conflicts among fisheries, authorities or communities (*medium confidence*). Challenges to fisheries governance are widespread under RCP8.5 with regional hotspots such as the Arctic and tropical Pacific Ocean (*medium confidence*). {3.5.2, 5.4.1, 5.4.2, 5.5.2, 5.5.3, 6.4.2, Figure SPM.3}

B.8.2 The decline in warm-water coral reefs is projected to greatly compromise the services they provide to society, such as food provision (*high confidence*), coastal protection (*high confidence*) and tourism (*medium confidence*). Increases in the risks for seafood security (*medium confidence*) associated with decreases in seafood availability are projected to elevate the risk to nutritional health in some communities highly dependent on seafood (*medium confidence*), such as those in the Arctic, West Africa, and Small Island Developing States. Such impacts compound any risks from other shifts in diets and food systems caused by social and economic changes and climate change over land (*medium confidence*). {3.4.3, 5.4.2, 6.4.2}

B.8.3 Global warming compromises seafood safety (*medium confidence*) through human exposure to elevated bioaccumulation of persistent organic pollutants and mercury in marine plants and animals (*medium confidence*), increasing prevalence of waterborne *Vibrio* pathogens (*medium confidence*), and heightened likelihood of harmful algal blooms (*medium confidence*). These risks are projected to be particularly large for human communities with high consumption of seafood, including coastal Indigenous communities (*medium confidence*), and for economic sectors such as fisheries, aquaculture, and tourism (*high confidence*). {3.4.3, 5.4.2, Box 5.3}

B.8.4 Climate change impacts on marine ecosystems and their services put key cultural dimensions of lives and livelihoods at risk (*medium confidence*), including through shifts in the distribution or abundance of harvested species and diminished access to fishing or hunting areas. This includes potentially rapid and irreversible loss of culture and local knowledge and Indigenous knowledge, and negative impacts on traditional diets and food security, aesthetic aspects, and marine recreational activities (*medium confidence*). {3.4.3, 3.5.3, 5.4.2}

B.9 Increased mean and extreme sea level, alongside ocean warming and acidification, are projected to exacerbate risks for human communities in low-lying coastal areas (*high confidence*). In Arctic human communities without rapid land uplift, and in urban atoll islands, risks are projected to be moderate to high even under a low emissions scenario (RCP2.6) (*medium confidence*), including reaching adaptation limits (*high confidence*). Under a high emissions scenario (RCP8.5), delta regions and resource rich coastal cities are projected to experience moderate to high risk levels after 2050 under current adaptation (*medium confidence*). Ambitious adaptation including transformative governance is expected to reduce risk (*high confidence*), but with context-specific benefits. {4.3.3, 4.3.4, SM4.3, 6.9.2, Cross-Chapter Box 9, Figure SPM.5}

B.9.1 In the absence of more ambitious adaptation efforts compared to today, and under current trends of increasing exposure and vulnerability of coastal communities, risks, such as erosion and land loss, flooding, salinization, and cascading impacts due to mean sea level rise and extreme events are projected to significantly increase throughout this century under all greenhouse gas emissions scenarios (*very high confidence*). Under the same assumptions, annual coastal flood damages are projected to increase by 2–3 orders of magnitude by 2100 compared to today (*high confidence*). {4.3.3, 4.3.4, Box 6.1, 6.8, SM.4.3, Figures SPM.4, SPM.5}

B.9.2 High to very high risks are approached for vulnerable communities in coral reef environments, urban atoll islands and low-lying Arctic locations from sea level rise well before the end of this century in case of high emissions scenarios. This entails adaptation limits being reached, which are the points at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions (*high confidence*). Reaching adaptation limits (e.g., biophysical, geographical, financial, technical, social, political, and institutional) depends on the emissions scenario and context-specific risk tolerance, and is projected to expand to more areas beyond 2100, due to the long-term commitment of sea level rise (*medium confidence*). Some island nations are *likely* to become uninhabitable due to climate-related ocean and cryosphere change (*medium confidence*), but habitability thresholds remain extremely difficult to assess. {4.3.4, 4.4.2, 4.4.3, 5.5.2, Cross-Chapter Box 9, SM.4.3, SPM C.1, Glossary, Figure SPM.5}

B.9.3 Globally, a slower rate of climate-related ocean and cryosphere change provides greater adaptation opportunities (*high confidence*). While there is *high confidence* that ambitious adaptation, including governance for transformative change, has the potential to reduce risks in many locations, such benefits can vary between locations. At global scale, coastal protection can reduce flood risk by 2–3 orders of magnitude during the 21st century, but depends on investments on the order of tens to several hundreds of billions of US$ per year (*high confidence*). While such investments are generally cost efficient for densely populated urban areas, rural and poorer areas may be challenged to afford such investments with relative annual costs for some small island states amounting to several percent of GDP (*high confidence*). Even with major adaptation efforts, residual risks and associated losses are projected to occur (*medium confidence*), but context-specific limits to adaptation and residual risks remain difficult to assess. {4.1.3, 4.2.2.4, 4.3.1, 4.3.2, 4.3.4., 4.4.3, 6.9.1, 6.9.2, Cross-Chapter Boxes 1–2 in Chapter 1, SM.4.3, Figure SPM.5}

Extreme sea level events

Due to projected global mean sea level (GMSL) rise, local sea levels that historically occurred once per century (historical centennial events, HCEs) are projected to become at least annual events at most locations during the 21st century. The height of a HCE varies widely, and depending on the level of exposure can already cause severe impacts. Impacts can continue to increase with rising frequency of HCEs.

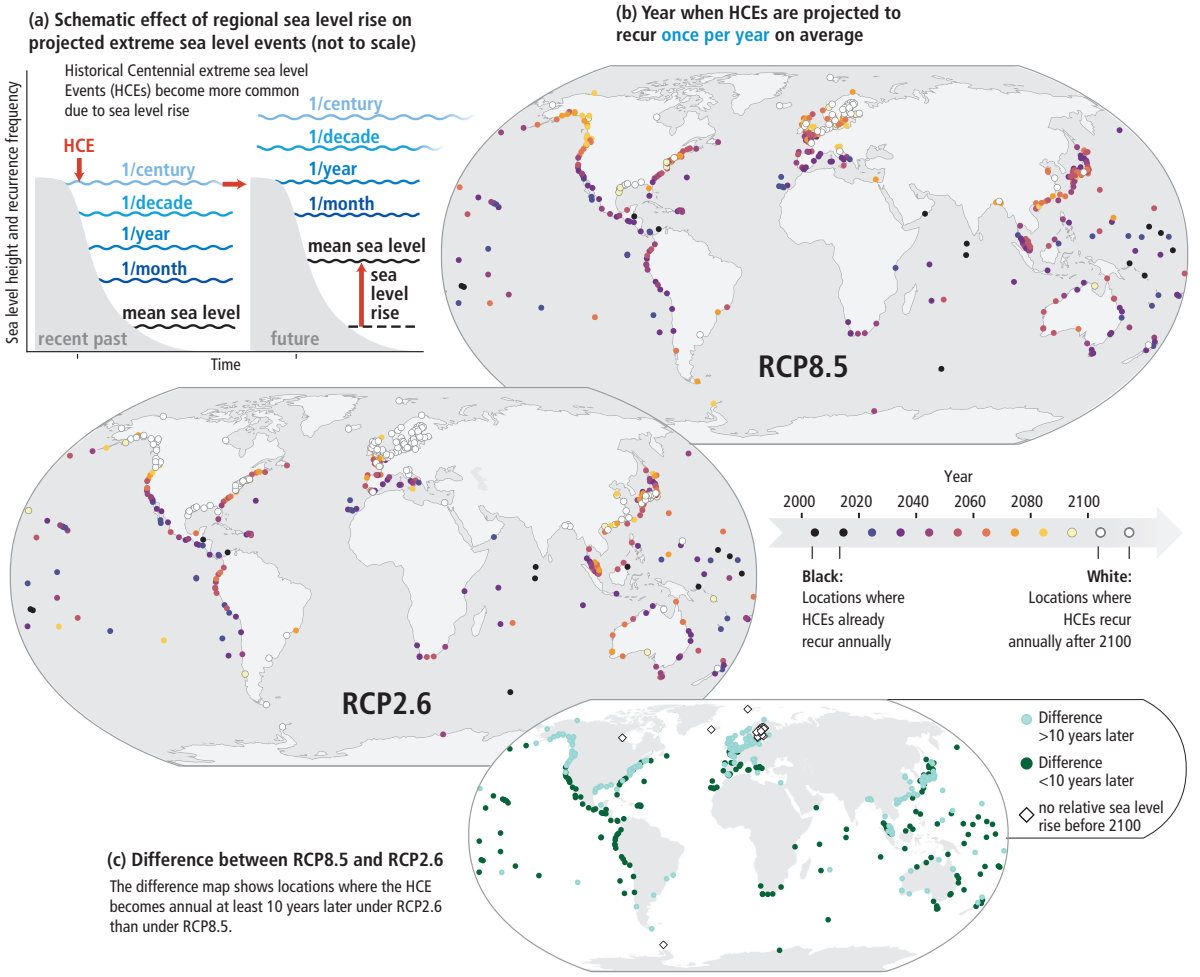


Figure SPM.4 | The effect of regional sea level rise on extreme sea level events at coastal locations. **(a)** Schematic illustration of extreme sea level events and their average recurrence in the recent past (1986–2005) and the future. As a consequence of mean sea level rise, local sea levels that historically occurred once per century (historical centennial events, HCEs) are projected to recur more frequently in the future. **(b)** The year in which HCEs are expected to recur once per year on average under RCP8.5 and RCP2.6, at the 439 individual coastal locations where the observational record is sufficient. The absence of a circle indicates an inability to perform an assessment due to a lack of data but does not indicate absence of exposure and risk. The darker the circle, the earlier this transition is expected. The *likely* range is ±10 years for locations where this transition is expected before 2100. White circles (33% of locations under RCP2.6 and 10% under RCP8.5) indicate that HCEs are not expected to recur once per year before 2100. **(c)** An indication at which locations this transition of HCEs to annual events is projected to occur more than 10 years later under RCP2.6 compared to RCP8.5. As the scenarios lead to small differences by 2050 in many locations results are not shown here for RCP4.5 but they are available in Chapter 4. {4.2.3, Figure 4.10, Figure 4.12}

C. Implementing Responses to Ocean and Cryosphere Change

Challenges

C.1 Impacts of climate-related changes in the ocean and cryosphere increasingly challenge current governance efforts to develop and implement adaptation responses from local to global scales, and in some cases pushing them to their limits. People with the highest exposure and vulnerability are often those with lowest capacity to respond (*high confidence*). {1.5, 1.7, Cross-Chapter Boxes 2–3 in Chapter 1, 2.3.1, 2.3.2, 2.3.3, 2.4, 3.2.4, 3.4.3, 3.5.2, 3.5.3, 4.1, 4.3.3, 4.4.3, 5.5.2, 5.5.3, 6.9}

C.1.1 The temporal scales of climate change impacts in ocean and cryosphere and their societal consequences operate on time horizons which are longer than those of governance arrangements (e.g., planning cycles, public and corporate decision making cycles, and financial instruments). Such temporal differences challenge the ability of societies to adequately prepare for and respond to long-term changes including shifts in the frequency and intensity of extreme events (*high confidence*). Examples include changing landslides and floods in high mountain regions and risks to important species and ecosystems in the Arctic, as well as to low-lying nations and islands, small island nations, other coastal regions and to coral reef ecosystems. {2.3.2, 3.5.2, 3.5.4, 4.4.3, 5.2, 5.3, 5.4, 5.5.1, 5.5.2, 5.5.3, 6.9}

C.1.2 Governance arrangements (e.g., marine protected areas, spatial plans and water management systems) are, in many contexts, too fragmented across administrative boundaries and sectors to provide integrated responses to the increasing and cascading risks from climate-related changes in the ocean and/or cryosphere (*high confidence*). The capacity of governance systems in polar and ocean regions to respond to climate change impacts has strengthened recently, but this development is not sufficiently rapid or robust to adequately address the scale of increasing projected risks (*high confidence*). In high mountains, coastal regions and small islands, there are also difficulties in coordinating climate adaptation responses, due to the many interactions of climatic and non-climatic risk drivers (such as inaccessibility, demographic and settlement trends, or land subsidence caused by local activities) across scales, sectors and policy domains (*high confidence*). {2.3.1, 3.5.3, 4.4.3, 5.4.2, 5.5.2, 5.5.3, Box 5.6, 6.9, Cross-Chapter Box 3 in Chapter 1}

C.1.3 There are a broad range of identified barriers and limits for adaptation to climate change in ecosystems (*high confidence*). Limitations include the space that ecosystems require, non-climatic drivers and human impacts that need to be addressed as part of the adaptation response, the lowering of adaptive capacity of ecosystems because of climate change, and the slower ecosystem recovery rates relative to the recurrence of climate impacts, availability of technology, knowledge and financial support, and existing governance arrangements (*medium confidence*). {3.5.4, 5.5.2}

C.1.4 Financial, technological, institutional and other barriers exist for implementing responses to current and projected negative impacts of climate-related changes in the ocean and cryosphere, impeding resilience building and risk reduction measures (*high confidence*). Whether such barriers reduce adaptation effectiveness or correspond to adaptation limits depends on context specific circumstances, the rate and scale of climate changes and on the ability of societies to turn their adaptive capacity into effective adaptation responses. Adaptive capacity continues to differ between as well as within communities and societies (*high confidence*). People with highest exposure and vulnerability to current and future hazards from ocean and cryosphere changes are often also those with lowest adaptive capacity, particularly in low-lying islands and coasts, Arctic and high mountain regions with development challenges (*high confidence*). {2.3.1, 2.3.2, 2.3.7, Box 2.4, 3.5.2, 4.3.4, 4.4.2, 4.4.3, 5.5.2, 6.9, Cross-Chapter Boxes 2 and 3 in Chapter 1, Cross-Chapter Box 9}

Strengthening Response Options

C.2 The far-reaching services and options provided by ocean and cryosphere-related ecosystems can be supported by protection, restoration, precautionary ecosystem-based management of renewable resource use, and the reduction of pollution and other stressors (*high confidence*). Integrated water management (*medium confidence*) and ecosystem-based adaptation (*high confidence*) approaches lower climate risks locally and provide multiple societal benefits. However, ecological, financial, institutional and governance constraints for such actions exist (*high confidence*), and in many contexts ecosystem-based adaptation will only be effective under the lowest levels of warming (*high confidence*). {2.3.1, 2.3.3, 3.2.4, 3.5.2, 3.5.4, 4.4.2, 5.2.2, 5.4.2, 5.5.1, 5.5.2, Figure SPM.5}

C.2.1 Networks of protected areas help maintain ecosystem services, including carbon uptake and storage, and enable future ecosystem-based adaptation options by facilitating the poleward and altitudinal movements of species, populations, and ecosystems that occur in response to warming and sea level rise (*medium confidence*). Geographic barriers, ecosystem degradation, habitat fragmentation and barriers to regional cooperation limit the potential for such networks to support future species range shifts in marine, high mountain and polar land regions (*high confidence*). {2.3.3, 3.2.3, 3.3.2, 3.5.4, 5.5.2, Box 3.4}

C.2.2 Terrestrial and marine habitat restoration, and ecosystem management tools such as assisted species relocation and coral gardening, can be locally effective in enhancing ecosystem-based adaptation (*high confidence*). Such actions are most successful when they are community-supported, are science-based whilst also using local knowledge and Indigenous knowledge, have long-term support that includes the reduction or removal of non-climatic stressors, and under the lowest levels of warming (*high confidence*). For example, coral reef restoration options may be ineffective if global warming exceeds 1.5ºC, because corals are already at high risk (*very high confidence*) at current levels of warming. {2.3.3, 4.4.2, 5.3.7, 5.5.1, 5.5.2, Box 5.5, Figure SPM.3}

C.2.3 Strengthening precautionary approaches, such as rebuilding overexploited or depleted fisheries, and responsiveness of existing fisheries management strategies reduces negative climate change impacts on fisheries, with benefits for regional economies and livelihoods (*medium confidence*). Fisheries management that regularly assesses and updates measures over time, informed by assessments of future ecosystem trends, reduces risks for fisheries (*medium confidence*) but has limited ability to address ecosystem change. {3.2.4, 3.5.2, 5.4.2, 5.5.2, 5.5.3, Figure SPM.5}

C.2.4 Restoration of vegetated coastal ecosystems, such as mangroves, tidal marshes and seagrass meadows (coastal 'blue carbon' ecosystems), could provide climate change mitigation through increased carbon uptake and storage of around 0.5% of current global emissions annually (*medium confidence*). Improved protection and management can reduce carbon emissions from these ecosystems. Together, these actions also have multiple other benefits, such as providing storm protection, improving water quality, and benefiting biodiversity and fisheries (*high confidence*). Improving the quantification of carbon storage and greenhouse gas fluxes of these coastal ecosystems will reduce current uncertainties around measurement, reporting and verification (*high confidence*). {Box 4.3, 5.4, 5.5.1, 5.5.2, Annex I: Glossary}

C.2.5 Ocean renewable energy can support climate change mitigation, and can comprise energy extraction from offshore winds, tides, waves, thermal and salinity gradient and algal biofuels. The emerging demand for alternative energy sources is expected to generate economic opportunities for the ocean renewable energy sector (*high confidence*), although their potential may also be affected by climate change (*low confidence*). {5.4.2, 5.5.1, Figure 5.23}

C.2.6 Integrated water management approaches across multiple scales can be effective at addressing impacts and leveraging opportunities from cryosphere changes in high mountain areas. These approaches also support water resource management through the development and optimization of multi-purpose storage and release of water from reservoirs (*medium confidence*), with consideration of potentially negative impacts to ecosystems and communities. Diversification of tourism activities throughout the year supports adaptation in high mountain economies (*medium confidence*). {2.3.1, 2.3.5}

C.3 Coastal communities face challenging choices in crafting context-specific and integrated responses to sea level rise that balance costs, benefits and trade-offs of available options and that can be adjusted over time (*high confidence*). All types of options, including protection, accommodation, ecosystem-based adaptation, coastal advance and retreat, wherever possible, can play important roles in such integrated responses (*high confidence*). {4.4.2, 4.4.3, 4.4.4, 6.9.1, Cross-Chapter Box 9, Figure SPM.5}

C.3.1 The higher the sea levels rise, the more challenging is coastal protection, mainly due to economic, financial and social barriers rather than due to technical limits (*high confidence*). In the coming decades, reducing local drivers of exposure and vulnerability such as coastal urbanization and human-induced subsidence constitute effective responses (*high confidence*). Where space is limited, and the value of exposed assets is high (e.g., in cities), hard protection (e.g., dikes) is *likely* to be a cost-efficient response option during the 21st century taking into account the specifics of the context (*high confidence*), but resource-limited areas may not be able to afford such investments. Where space is available, ecosystem-based adaptation can reduce coastal risk and provide multiple other benefits such as carbon storage, improved water quality, biodiversity conservation and livelihood support (*medium confidence*). {4.3.2, 4.4.2, Box 4.1, Cross-Chapter Box 9, Figure SPM.5}

C.3.2 Some coastal accommodation measures, such as early warning systems and flood-proofing of buildings, are often both low cost and highly cost-efficient under current sea levels (*high confidence*). Under projected sea level rise and increase in coastal hazards some of these measures become less effective unless combined with other measures (*high confidence*). All types of options, including protection, accommodation, ecosystem-based adaptation, coastal advance and planned relocation, if alternative localities are available, can play important roles in such integrated responses (*high confidence*). Where the community affected is small, or in the aftermath of a disaster, reducing risk by coastal planned relocations is worth considering if safe alternative localities are available. Such planned relocation can be socially, culturally, financially and politically constrained (*very high confidence*). {4.4.2, Box 4.1, Cross-Chapter Box 9, SPM B.3}

C.3.3 Responses to sea level rise and associated risk reduction present society with profound governance challenges, resulting from the uncertainty about the magnitude and rate of future sea level rise, vexing trade-offs between societal goals (e.g., safety, conservation, economic development, intra- and inter-generational equity), limited resources, and conflicting interests and values among diverse stakeholders (*high confidence*). These challenges can be eased using locally appropriate combinations of decision analysis, land-use planning, public participation, diverse knowledge systems and conflict resolution approaches that are adjusted over time as circumstances change (*high confidence*). {Cross-Chapter Box 5 in Chapter 1, 4.4.3, 4.4.4, 6.9}

C.3.4 Despite the large uncertainties about the magnitude and rate of post 2050 sea level rise, many coastal decisions with time horizons of decades to over a century are being made now (e.g., critical infrastructure, coastal protection works, city planning) and can be improved by taking relative sea level rise into account, favouring flexible responses (i.e., those that can be adapted over time) supported by monitoring systems for early warning signals, periodically adjusting decisions (i.e., adaptive decision making), using robust decision-making approaches, expert judgement, scenario-building, and multiple knowledge systems (*high confidence*). The sea level rise range that needs to be considered for planning and implementing coastal responses depends on the risk tolerance of

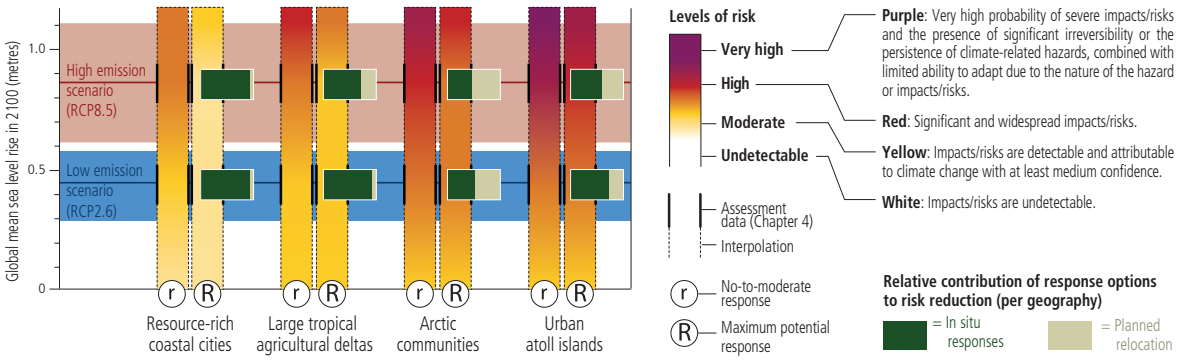
stakeholders. Stakeholders with higher risk tolerance (e.g., those planning for investments that can be very easily adapted to unforeseen conditions) often prefer to use the *likely* range of projections, while stakeholders with a lower risk tolerance (e.g., those deciding on critical infrastructure) also consider global and local mean sea level above the upper end of the *likely* range (globally 1.1 m under RCP8.5 by 2100) and from methods characterised by lower confidence such as from expert elicitation. {1.8.1, 1.9.2, 4.2.3, 4.4.4, Figure 4.2, Cross-Chapter Box 5 in Chapter 1, Figure SPM.5, SPM B.3}

Sea level rise risk and responses

The term response is used here instead of adaptation because some responses, such as retreat, may or may not be considered to be adaptation.

(a) Risk in 2100 under different sea level rise and response scenarios

Risk for illustrative geographies based on mean sea level changes *(medium confidence)*



In this assessment, the term response refers to in situ responses to sea level rise (hard engineered coastal defenses, restoration of degraded ecosystems, subsidence limitation) and planned relocation. Planned relocation in this assessment refers to proactive managed retreat or resettlement only at a local scale, and according to the specificities of a particular context (e.g., in urban atoll islands: within the island, in a neighbouring island or in artificially raised islands). Forced displacement and international migration are not considered in this assessment.

The illustrative geographies are based on a limited number of case studies well covered by the peer reviewed literature. The realisation of risk will depend on context specifities.

Sea level rise scenarios: RCP4.5 and RCP6.0 are not considered in this risk assessment because the literature underpinning this assessment is only available for RCP2.6 and RCP8.5.

(b) Benefits of responses to sea level rise and mitigation

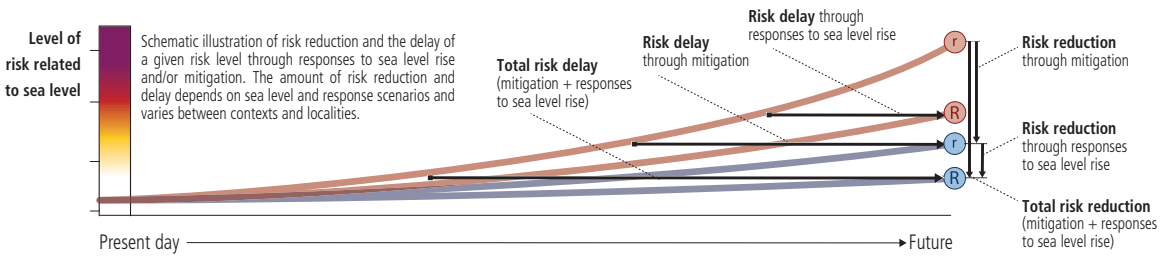


Figure SPM.5 | a, b

(c) Responses to rising mean and extreme sea levels

The table illustrates responses and their characteristics. It is not exhaustive. Whether a response is applicable depends on geography and context.

Confidence levels (assessed for effectiveness): ●●●● = Very High ●●●= High ●● = Medium ●= Low

Responses		Potential effectiveness in terms of reducing sea level rise (SLR) risks (technical/biophysical limits)	Advantages (beyond risk reduction)	Co–benefits	Drawbacks	Economic efficiency	Governance challenges
Hard protection		Up to multiple metres of SLR {4.4.2.2.4} ●●●	Predictable levels of safety {4.4.2.2.4}	Multifunctional dikes such as for recreation, or other land use {4.4.2.2.5}	Destruction of habitat through coastal squeeze, flooding & erosion downdrift, lock–in, disastrous consequence in case of defence failure {4.3.2.4, 4.4.2.2.5}	High if the value of assets behind protection is high, as found in many urban and densely populated coastal areas {4.4.2.2.7}	Often unaffordable for poorer areas. Conflicts between objectives (e.g., conservation, safety and tourism), conflicts about the distribution of public budgets, lack of finance {4.3.3.2, 4.4.2.2.6}
Sediment–based protection		Effective but depends on sediment availability {4.4.2.2.4} ●●●	High flexibility {4.4.2.2.4}	Preservation of beaches for recreation/ tourism {4.4.2.2.5}	Destruction of habitat, where sediment is sourced {4.4.2.2.5}	High if tourism revenues are high {4.4.2.2.7}	Conflicts about the distribution of public budgets {4.4.2.2.6}
Ecosystem based adaptation	**Coral conservation**	Effective up to 0.5 cm yr^{-1} SLR. ●● Strongly limited by ocean warming and acidification. Constrained at 1.5°C warming and lost at 2°C at many places. {4.3.3.5.2, 4.4.2.3.2, 5.3.4} ●●●	Opportunity for community involvement, {4.4.2.3.1}	Habitat gain, biodiversity, carbon sequestration, income from tourism, enhanced fishery productivity, improved water quality. Provision of food, medicine, fuel, wood and cultural benefits {4.4.2.3.5}	Long–term effectiveness depends on ocean warming, acidification and emission scenarios {4.3.3.5.2., 4.4.2.3.2}	Limited evidence on benefit–cost ratios; Depends on population density and the availability of land {4.4.2.3.7}	Permits for implementation are difficult to obtain. Lack of finance. Lack of enforcement of conservation policies. EbA options dismissed due to short–term economic interest, availability of land {4.4.2.3.6}
	Coral restoration						
	Wetland conservation (Marshes, Mangroves)	Effective up to 0.5–1 cm yr^{-1} SLR, ●● decreased at 2°C {4.3.3.5.1, 4.4.2.3.2, 5.3.7} ●●●			Safety levels less predictable, development benefits not realized {4.4.2.3.5, 4.4.2.3.2}		
	Wetland restoration (Marshes, Mangroves)				Safety levels less predictable, a lot of land required, barriers for landward expan–sion of ecosystems has to be removed {4.4.2.3.5, 4.4.2.3.2}		
Coastal advance		Up to multiple metres of SLR {4.4.2.2.4} ●●●	Predictable levels of safety {4.4.2.2.4}	Generates land and land sale revenues that can be used to finance adaptation {4.4.2.4.5}	Groundwater salinisa–tion, enhanced erosion and loss of coastal ecosystems and habitat {4.4.2.4.5}	Very high if land prices are high as found in many urban coasts {4.4.2.4.7}	Often unaffordable for poorer areas. Social conflicts with regards to access and distribution of new land {4.4.2.4.6}
Coastal accommodation (Flood–proofing buildings, early warning systems for flood events, etc.)		Very effective for small SLR {4.4.2.5.4} ●●●	Mature technology; sediments deposited during floods can raise elevation {4.4.2.5.5}	Maintains landscape connectivity {4.4.2.5.5}	Does not prevent flooding/impacts {4.4.2.5.5}	Very high for early warning systems and building–scale measures {4.4.2.5.7}	Early warning systems require effective insti–tutional arrangements {4.4.2.6.6}
Retreat	**Planned relocation**	Effective if alternative safe localities are available {4.4.2.6.4} ●●●	Sea level risks at origin can be eliminated {4.4.2.6.4}	Access to improved services (health, education, housing), job opportunities and economic growth {4.4.2.6.5}	Loss of social cohesion, cultural identity and well–being. Depressed services (health, education, housing), job opportunities and economic growth {4.4.2.6.5}	Limited evidence {4.4.2.6.7}	Reconciling the divergent interests arising from relocating people from point of origin and destination {4.4.2.6.6}
	Forced displacement	Addresses only immediate risk at place of origin	Not applicable	Not applicable	Range from loss of life to loss of livelihoods and sovereignty {4.4.2.6.5}	Not applicable	Raises complex humanitarian questions on livelihoods, human rights and equity {4.4.2.6.6}

(d) Choosing and enabling sea level rise responses

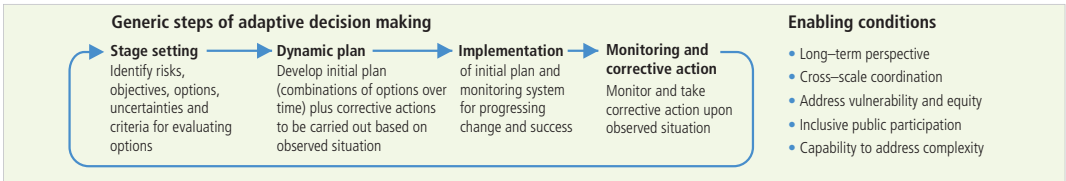


Figure SPM.5 | c, d

Figure SPM.5 | Sea level rise risks and responses. The term response is used here instead of adaptation because some responses, such as retreat, may or may not be considered to be adaptation. **(a)** shows the combined risk of coastal flooding, erosion and salinization for illustrative geographies in 2100, due to changing mean and extreme sea levels under RCP2.6 and RCP8.5 and under two response scenarios. Risks under RCPs 4.5 and 6.0 were not assessed due to a lack of literature for the assessed geographies. The assessment does not account for changes in extreme sea level beyond those directly induced by mean sea level rise; risk levels could increase if other changes in extreme sea levels were considered (e.g., due to changes in cyclone intensity). Panel a) considers a socioeconomic scenario with relatively stable coastal population density over the century. {SM4.3.2} Risks to illustrative geographies have been assessed based on relative sea level changes projected for a set of specific examples: New York City, Shanghai and Rotterdam for resource-rich coastal cities covering a wide range of response experiences; South Tarawa, Fongafale and Male' for urban atoll islands; Mekong and Ganges-Brahmaputra-Meghna for large tropical agricultural deltas; and Bykovskiy, Shishmaref, Kivalina, Tuktoyaktuk and Shingle Point for Arctic communities located in regions remote from rapid glacio-isostatic adjustment. {4.2, 4.3.4, SM4.2} The assessment distinguishes between two contrasting response scenarios. "No-to-moderate response" describes efforts as of today (i.e., no further significant action or new types of actions). "Maximum potential response" represents a combination of responses implemented to their full extent and thus significant additional efforts compared to today, assuming minimal financial, social and political barriers. The assessment has been conducted for each sea level rise and response scenario, as indicated by the burning embers in the figure; in-between risk levels are interpolated. {4.3.3} The assessment criteria include exposure and vulnerability (density of assets, level of degradation of terrestrial and marine buffer ecosystems), coastal hazards (flooding, shoreline erosion, salinization), in-situ responses (hard engineered coastal defenses, ecosystem restoration or creation of new natural buffers areas, and subsidence management) and planned relocation. Planned relocation refers to managed retreat or resettlement as described in Chapter 4, i.e., proactive and local-scale measures to reduce risk by relocating people, assets and infrastructure. Forced displacement is not considered in this assessment. Panel **(a)** also highlights the relative contributions of in-situ responses and planned relocation to the total risk reduction. **(b)** schematically illustrates the risk reduction (vertical arrows) and risk delay (horizontal arrows) through mitigation and/or responses to sea level rise. **(c)** summarizes and assesses responses to sea level rise in terms of their effectiveness, costs, co-benefits, drawbacks, economic efficiency and associated governance challenges. {4.4.2} **(d)** presents generic steps of an adaptive decision-making approach, as well as key enabling conditions for responses to sea level rise. {4.4.4, 4.4.5}

Enabling Conditions

C.4 Enabling climate resilience and sustainable development depends critically on urgent and ambitious emissions reductions coupled with coordinated sustained and increasingly ambitious adaptation actions (*very high confidence*). Key enablers for implementing effective responses to climate-related changes in the ocean and cryosphere include intensifying cooperation and coordination among governing authorities across spatial scales and planning horizons. Education and climate literacy, monitoring and forecasting, use of all available knowledge sources, sharing of data, information and knowledge, finance, addressing social vulnerability and equity, and institutional support are also essential. Such investments enable capacity-building, social learning, and participation in context-specific adaptation, as well as the negotiation of trade-offs and realisation of co-benefits in reducing short-term risks and building long-term resilience and sustainability. (*high confidence*). This report reflects the state of science for ocean and cryosphere for low levels of global warming (1.5°C), as also assessed in earlier IPCC and IPBES reports. {1.1, 1.5, 1.8.3, 2.3.1, 2.3.2, 2.4, Figure 2.7, 2.5, 3.5.2, 3.5.4, 4.4, 5.2.2, Box 5.3, 5.4.2, 5.5.2, 6.4.3, 6.5.3, 6.8, 6.9, Cross-Chapter Box 9, Figure SPM.5}

C.4.1 In light of observed and projected changes in the ocean and cryosphere, many nations will face challenges to adapt, even with ambitious mitigation (*very high confidence*). In a high emissions scenario, many ocean- and cryosphere-dependent communities are projected to face adaptation limits (e.g. biophysical, geographical, financial, technical, social, political and institutional) during the second half of the 21st century. Low emission pathways, for comparison, limit the risks from ocean and cryosphere changes in this century and beyond and enable more effective responses (*high confidence*), whilst also creating co-benefits. Profound economic and institutional transformative change will enable Climate Resilient Development Pathways in the ocean and cryosphere context (*high confidence*). {1.1, 1.4–1.7, Cross-Chapter Boxes 1–3 in Chapter 1, 2.3.1, 2.4, Box 3.2, Figure 3.4, Cross-Chapter Box 7 in Chapter 3, 3.4.3, 4.2.2, 4.2.3, 4.3.4, 4.4.2, 4.4.3, 4.4.6, 5.4.2, 5.5.3, 6.9.2, Cross-Chapter Box 9, Figure SPM.5}

C.4.2 Intensifying cooperation and coordination among governing authorities across scales, jurisdictions, sectors, policy domains and planning horizons can enable effective responses to changes in the ocean, cryosphere and to sea level rise (*high confidence*). Regional cooperation, including treaties and conventions, can support adaptation action; however, the extent to which responding to impacts and losses arising from changes

in the ocean and cryosphere is enabled through regional policy frameworks is currently limited *(high confidence*). Institutional arrangements that provide strong multiscale linkages with local and Indigenous communities benefit adaptation (*high confidence*). Coordination and complementarity between national and transboundary regional policies can support efforts to address risks to resource security and management, such as water and fisheries (*medium confidence*). {2.3.1, 2.3.2, 2.4, Box 2.4, 2.5, 3.5.2, 3.5.3, 3.5.4, 4.4.4, 4.4.5, Table 4.9, 5.5.2, 6.9.2}

C.4.3 Experience to date – for example, in responding to sea level rise, water-related risks in some high mountains, and climate change risks in the Arctic – also reveal the enabling influence of taking a long-term perspective when making short-term decisions, explicitly accounting for uncertainty of context-specific risks beyond 2050 (*high confidence*), and building governance capabilities to tackle complex risks (*medium confidence*). {2.3.1, 3.5.4, 4.4.4, 4.4.5, Table 4.9, 5.5.2, 6.9, Figure SPM.5}

C.4.4 Investments in education and capacity building at various levels and scales facilitates social learning and long-term capability for context-specific responses to reduce risk and enhance resilience (*high confidence*). Specific activities include utilization of multiple knowledge systems and regional climate information into decision making, and the engagement of local communities, Indigenous peoples, and relevant stakeholders in adaptive governance arrangements and planning frameworks (*medium confidence).* Promotion of climate literacy and drawing on local, Indigenous and scientific knowledge systems enables public awareness, understanding and social learning about locality-specific risk and response potential (*high confidence*). Such investments can develop, and in many cases transform existing institutions and enable informed, interactive and adaptive governance arrangements (*high confidence*). {1.8.3, 2.3.2, Figure 2.7, Box 2.4, 2.4, 3.5.2, 3.5.4, 4.4.4, 4.4.5, Table 4.9, 5.5.2, 6.9}

C.4.5 Context-specific monitoring and forecasting of changes in the ocean and the cryosphere informs adaptation planning and implementation, and facilitates robust decisions on trade-offs between short- and long-term gains (*medium confidence*). Sustained long-term monitoring, sharing of data, information and knowledge and improved context-specific forecasts, including early warning systems to predict more extreme El Niño/La Niña events, tropical cyclones, and marine heatwaves, help to manage negative impacts from ocean changes such as losses in fisheries, and adverse impacts on human health, food security, agriculture, coral reefs, aquaculture, wildfire, tourism, conservation, drought and flood (*high confidence*). {2.4, 2.5, 3.5.2, 4.4.4, 5.5.2, 6.3.1, 6.3.3, 6.4.3, 6.5.3, 6.9}

C.4.6 Prioritising measures to address social vulnerability and equity underpins efforts to promote fair and just climate resilience and sustainable development (*high confidence*), and can be helped by creating safe community settings for meaningful public participation, deliberation and conflict resolution (*medium confidence*). {Box 2.4, 4.4.4, 4.4.5, Table 4.9, Figure SPM.5}

C.4.7 This assessment of the ocean and cryosphere in a changing climate reveals the benefits of ambitious mitigation and effective adaptation for sustainable development and, conversely, the escalating costs and risks of delayed action. The potential to chart Climate Resilient Development Pathways varies within and among ocean, high mountain and polar land regions. Realising this potential depends on transformative change. This highlights the urgency of prioritising timely, ambitious, coordinated and enduring action (*very high confidence*). {1.1, 1.8, Cross-Chapter Box 1 in Chapter 1, 2.3, 2.4, 3.5, 4.2.1, 4.2.2, 4.3.4, 4.4, Table 4.9, 5.5, 6.9, Cross-Chapter Box 9, Figure SPM.5}

Summary for Policymakers

SPM

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Introduction

This Summary for Policymakers (SPM) presents key findings of the Working Group I (WGI) contribution to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6)[1] on the physical science basis of climate change. The report builds upon the 2013 Working Group I contribution to the IPCC's Fifth Assessment Report (AR5) and the 2018–2019 IPCC Special Reports[2] of the AR6 cycle and incorporates subsequent new evidence from climate science.[3]

This SPM provides a high-level summary of the understanding of the current state of the climate, including how it is changing and the role of human influence, the state of knowledge about possible climate futures, climate information relevant to regions and sectors, and limiting human-induced climate change.

Based on scientific understanding, key findings can be formulated as statements of fact or associated with an assessed level of confidence indicated using the IPCC calibrated language.[4]

The scientific basis for each key finding is found in chapter sections of the main Report and in the integrated synthesis presented in the Technical Summary (hereafter TS), and is indicated in curly brackets. The AR6 WGI Interactive Atlas facilitates exploration of these key synthesis findings, and supporting climate change information, across the WGI reference regions.[5]

A. The Current State of the Climate

Since AR5, improvements in observationally based estimates and information from paleoclimate archives provide a comprehensive view of each component of the climate system and its changes to date. New climate model simulations, new analyses, and methods combining multiple lines of evidence lead to improved understanding of human influence on a wider range of climate variables, including weather and climate extremes. The time periods considered throughout this section depend upon the availability of observational products, paleoclimate archives and peer-reviewed studies.

A.1 It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred. {2.2, 2.3, Cross-Chapter Box 2.3, 3.3, 3.4, 3.5, 3.6, 3.8, 5.2, 5.3, 6.4, 7.3, 8.3, 9.2, 9.3, 9.5, 9.6, Cross-Chapter Box 9.1} (Figure SPM.1, Figure SPM.2)

A.1.1 Observed increases in well-mixed greenhouse gas (GHG) concentrations since around 1750 are unequivocally caused by human activities. Since 2011 (measurements reported in AR5), concentrations have continued to increase in the atmosphere, reaching annual averages of 410 parts per million (ppm) for carbon dioxide (CO_2), 1866 parts per billion (ppb) for methane (CH_4), and 332 ppb for nitrous oxide (N_2O) in 2019.[6] Land and ocean have taken up a near-constant proportion (globally about 56% per year) of CO_2 emissions from human activities over the past six decades, with regional differences (*high confidence*).[7]
{2.2, 5.2, 7.3, TS.2.2, Box TS.5}

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1 Decision IPCC/XLVI-2.

2 The three Special Reports are: Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (SR1.5); Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL); IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC).

3 The assessment covers scientific literature accepted for publication by 31 January 2021.

4 Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or result: virtually certain 99–100% probability; very likely 90–100%; likely 66–100%; about as likely as not 33–66%; unlikely 0–33%; very unlikely 0–10%; and exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%; more likely than not >50–100%; and extremely unlikely 0–5%) are also used when appropriate. Assessed likelihood is typeset in italics, for example, *very likely*. This is consistent with AR5. In this Report, unless stated otherwise, square brackets [x to y] are used to provide the assessed *very likely* range, or 90% interval.

5 The Interactive Atlas is available at https://interactive-atlas.ipcc.ch

6 Other GHG concentrations in 2019 were: perfluorocarbons (PFCs) – 109 parts per trillion (ppt) CF_4 equivalent; sulphur hexafluoride (SF_6) – 10 ppt; nitrogen trifluoride (NF_3) – 2 ppt; hydrofluorocarbons (HFCs) – 237 ppt HFC-134a equivalent; other Montreal Protocol gases (mainly chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs)) – 1032 ppt CFC-12 equivalent). Increases from 2011 are 19 ppm for CO_2, 63 ppb for CH_4 and 8 ppb for N_2O.

7 Land and ocean are not substantial sinks for other GHGs.

A.1.2 Each of the last four decades has been successively warmer than any decade that preceded it since 1850. Global surface temperature[8] in the first two decades of the 21st century (2001–2020) was 0.99 [0.84 to 1.10] °C higher than 1850–1900.[9] Global surface temperature was 1.09 [0.95 to 1.20] °C higher in 2011–2020 than 1850–1900, with larger increases over land (1.59 [1.34 to 1.83] °C) than over the ocean (0.88 [0.68 to 1.01] °C). The estimated increase in global surface temperature since AR5 is principally due to further warming since 2003–2012 (+0.19 [0.16 to 0.22] °C). Additionally, methodological advances and new datasets contributed approximately 0.1°C to the updated estimate of warming in AR6.[10]
{2.3, Cross-Chapter Box 2.3} (Figure SPM.1)

A.1.3 The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019[11] is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is *very likely* that well-mixed GHGs were the main driver[12] of tropospheric warming since 1979 and *extremely likely* that human-caused stratospheric ozone depletion was the main driver of cooling of the lower stratosphere between 1979 and the mid-1990s.
{3.3, 6.4, 7.3, TS.2.3, Cross-Section Box TS.1} (Figure SPM.2)

A.1.4 Globally averaged precipitation over land has *likely* increased since 1950, with a faster rate of increase since the 1980s (*medium confidence*). It is *likely* that human influence contributed to the pattern of observed precipitation changes since the mid-20th century and *extremely likely* that human influence contributed to the pattern of observed changes in near-surface ocean salinity. Mid-latitude storm tracks have *likely* shifted poleward in both hemispheres since the 1980s, with marked seasonality in trends (*medium confidence*). For the Southern Hemisphere, human influence *very likely* contributed to the poleward shift of the closely related extratropical jet in austral summer.
{2.3, 3.3, 8.3, 9.2, TS.2.3, TS.2.4, Box TS.6}

A.1.5 Human influence is *very likely* the main driver of the global retreat of glaciers since the 1990s and the decrease in Arctic sea ice area between 1979–1988 and 2010–2019 (decreases of about 40% in September and about 10% in March). There has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability. Human influence *very likely* contributed to the decrease in Northern Hemisphere spring snow cover since 1950. It is *very likely* that human influence has contributed to the observed surface melting of the Greenland Ice Sheet over the past two decades, but there is only *limited evidence*, with *medium agreement*, of human influence on the Antarctic Ice Sheet mass loss.
{2.3, 3.4, 8.3, 9.3, 9.5, TS.2.5}

A.1.6 It is *virtually certain* that the global upper ocean (0–700 m) has warmed since the 1970s and *extremely likely* that human influence is the main driver. It is *virtually certain* that human-caused CO_2 emissions are the main driver of current global acidification of the surface open ocean. There is *high confidence* that oxygen levels have dropped in many upper ocean regions since the mid-20th century and *medium confidence* that human influence contributed to this drop.
{2.3, 3.5, 3.6, 5.3, 9.2, TS.2.4}

A.1.7 Global mean sea level increased by 0.20 [0.15 to 0.25] m between 1901 and 2018. The average rate of sea level rise was 1.3 [0.6 to 2.1] mm yr^{-1} between 1901 and 1971, increasing to 1.9 [0.8 to 2.9] mm yr^{-1} between 1971 and 2006, and further increasing to 3.7 [3.2 to 4.2] mm yr^{-1} between 2006 and 2018 (*high confidence*). Human influence was *very likely* the main driver of these increases since at least 1971.
{2.3, 3.5, 9.6, Cross-Chapter Box 9.1, Box TS.4}

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8 The term 'global surface temperature' is used in reference to both global mean surface temperature and global surface air temperature throughout this SPM. Changes in these quantities are assessed with *high confidence* to differ by at most 10% from one another, but conflicting lines of evidence lead to *low confidence* in the sign (direction) of any difference in long-term trend. {Cross-Section Box TS.1}

9 The period 1850–1900 represents the earliest period of sufficiently globally complete observations to estimate global surface temperature and, consistent with AR5 and SR1.5, is used as an approximation for pre-industrial conditions.

10 Since AR5, methodological advances and new datasets have provided a more complete spatial representation of changes in surface temperature, including in the Arctic. These and other improvements have also increased the estimate of global surface temperature change by approximately 0.1°C, but this increase does not represent additional physical warming since AR5.

11 The period distinction with A.1.2 arises because the attribution studies consider this slightly earlier period. The observed warming to 2010–2019 is 1.06 [0.88 to 1.21] °C.

12 Throughout this SPM, 'main driver' means responsible for more than 50% of the change.

A.1.8 Changes in the land biosphere since 1970 are consistent with global warming: climate zones have shifted poleward in both hemispheres, and the growing season has on average lengthened by up to two days per decade since the 1950s in the Northern Hemisphere extratropics (*high confidence*). {2.3, TS.2.6}

Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years

Changes in global surface temperature relative to 1850–1900

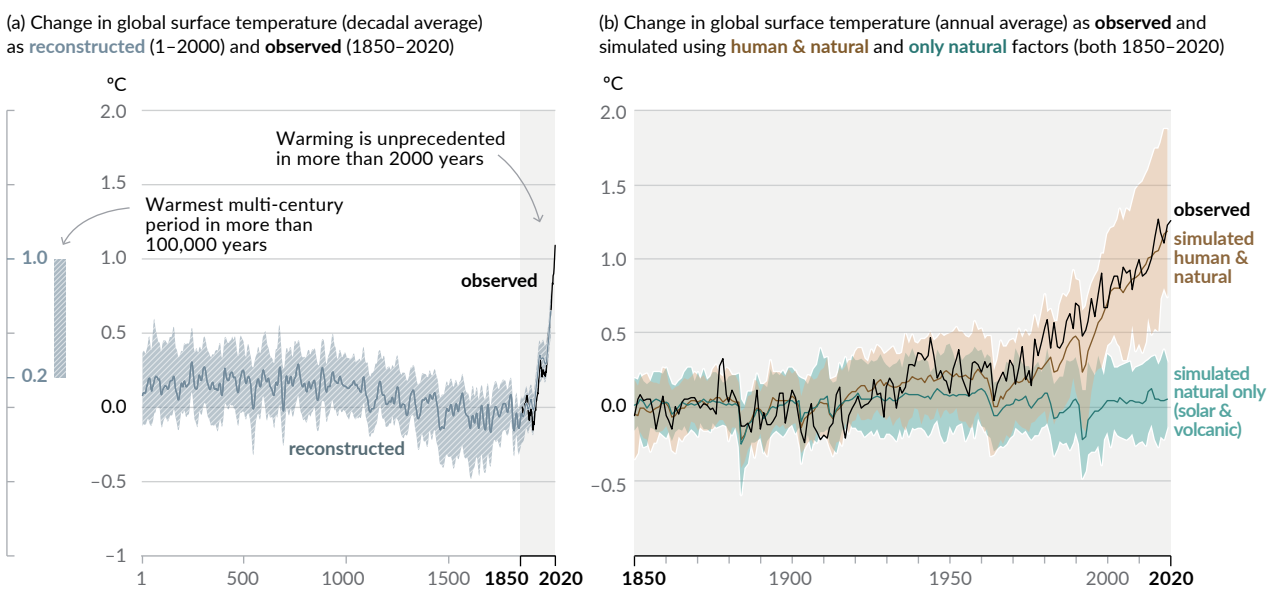

Figure SPM.1 | History of global temperature change and causes of recent warming

Panel (a) Changes in global surface temperature reconstructed from paleoclimate archives (solid grey line, years 1–2000) **and from direct observations** (solid black line, 1850–2020), both relative to 1850–1900 and decadally averaged. The vertical bar on the left shows the estimated temperature (*very likely* range) during the warmest multi-century period in at least the last 100,000 years, which occurred around 6500 years ago during the current interglacial period (Holocene). The Last Interglacial, around 125,000 years ago, is the next most recent candidate for a period of higher temperature. These past warm periods were caused by slow (multi-millennial) orbital variations. The grey shading with white diagonal lines shows the *very likely* ranges for the temperature reconstructions.

Panel (b) Changes in global surface temperature over the past 170 years (black line) relative to 1850–1900 and annually averaged, compared to Coupled Model Intercomparison Project Phase 6 (CMIP6) climate model simulations (see Box SPM.1) of the temperature response to both human and natural drivers (brown) and to only natural drivers (solar and volcanic activity, green). Solid coloured lines show the multi-model average, and coloured shades show the *very likely* range of simulations. (See Figure SPM.2 for the assessed contributions to warming).

{2.3.1; Cross-Chapter Box 2.3; 3.3; TS.2.2; Cross-Section Box TS.1, Figure 1a}

Observed warming is driven by emissions from human activities, with greenhouse gas warming partly masked by aerosol cooling

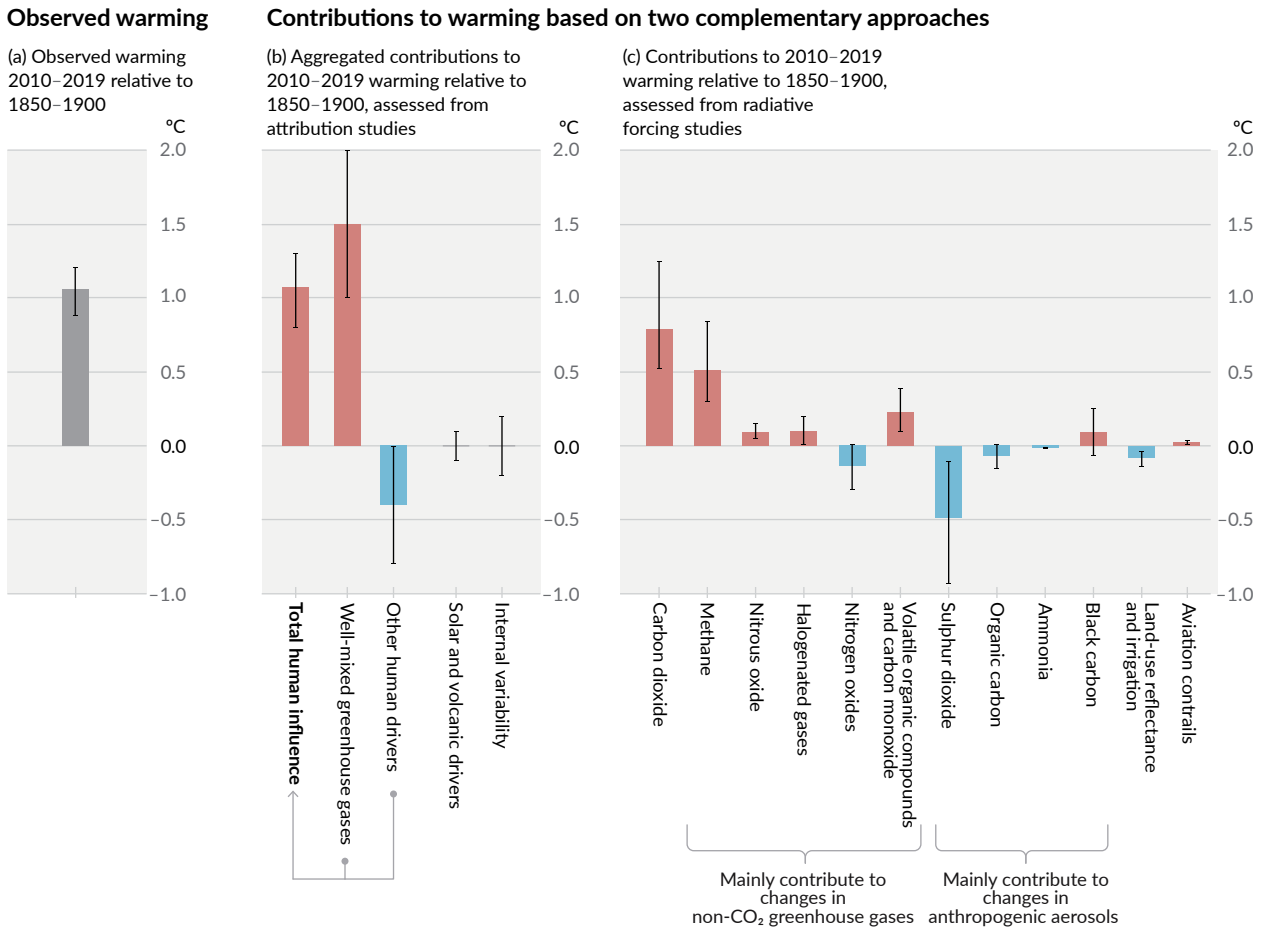

Figure SPM.2 | Assessed contributions to observed warming in 2010–2019 relative to 1850–1900

Panel (a) Observed global warming (increase in global surface temperature). Whiskers show the *very likely* range.

Panel (b) Evidence from attribution studies, which synthesize information from climate models and observations. The panel shows temperature change attributed to: total human influence; changes in well-mixed greenhouse gas concentrations; other human drivers due to aerosols, ozone and land-use change (land-use reflectance); solar and volcanic drivers; and internal climate variability. Whiskers show *likely* ranges.

Panel (c) Evidence from the assessment of radiative forcing and climate sensitivity. The panel shows temperature changes from individual components of human influence: emissions of greenhouse gases, aerosols and their precursors; land-use changes (land-use reflectance and irrigation); and aviation contrails. Whiskers show *very likely* ranges. Estimates account for both direct emissions into the atmosphere and their effect, if any, on other climate drivers. For aerosols, both direct effects (through radiation) and indirect effects (through interactions with clouds) are considered.

{Cross-Chapter Box 2.3, 3.3.1, 6.4.2, 7.3}

A.2 The scale of recent changes across the climate system as a whole – and the present state of many aspects of the climate system – are unprecedented over many centuries to many thousands of years. {2.2, 2.3, Cross-Chapter Box 2.1, 5.1} (Figure SPM.1)

A.2.1 In 2019, atmospheric CO_2 concentrations were higher than at any time in at least 2 million years (*high confidence*), and concentrations of CH_4 and N_2O were higher than at any time in at least 800,000 years (*very high confidence*). Since 1750, increases in CO_2 (47%) and CH_4 (156%) concentrations far exceed – and increases in N_2O (23%) are similar to – the natural multi-millennial changes between glacial and interglacial periods over at least the past 800,000 years (*very high confidence*). {2.2, 5.1, TS.2.2}

A.2.2 Global surface temperature has increased faster since 1970 than in any other 50-year period over at least the last 2000 years (*high confidence*). Temperatures during the most recent decade (2011–2020) exceed those of the most recent multi-century warm period, around 6500 years ago[13] [0.2°C to 1°C relative to 1850–1900] (*medium confidence*). Prior to that, the next most recent warm period was about 125,000 years ago, when the multi-century temperature [0.5°C to 1.5°C relative to 1850–1900] overlaps the observations of the most recent decade (*medium confidence*). {2.3, Cross-Chapter Box 2.1, Cross-Section Box TS.1} (Figure SPM.1)

A.2.3 In 2011–2020, annual average Arctic sea ice area reached its lowest level since at least 1850 (*high confidence*). Late summer Arctic sea ice area was smaller than at any time in at least the past 1000 years (*medium confidence*). The global nature of glacier retreat since the 1950s, with almost all of the world's glaciers retreating synchronously, is unprecedented in at least the last 2000 years (*medium confidence*). {2.3, TS.2.5}

A.2.4 Global mean sea level has risen faster since 1900 than over any preceding century in at least the last 3000 years (*high confidence*). The global ocean has warmed faster over the past century than since the end of the last deglacial transition (around 11,000 years ago) (*medium confidence*). A long-term increase in surface open ocean pH occurred over the past 50 million years (*high confidence*). However, surface open ocean pH as low as recent decades is unusual in the last 2 million years (*medium confidence*). {2.3, TS.2.4, Box TS.4}

A.3 Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since AR5. {2.3, 3.3, 8.2, 8.3, 8.4, 8.5, 8.6, Box 8.1, Box 8.2, Box 9.2, 10.6, 11.2, 11.3, 11.4, 11.6, 11.7, 11.8, 11.9, 12.3} (Figure SPM.3)

A.3.1 It is *virtually certain* that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe, with *high confidence* that human-induced climate change is the main driver[14] of these changes. Some recent hot extremes observed over the past decade would have been *extremely unlikely* to occur without human influence on the climate system. Marine heatwaves have approximately doubled in frequency since the 1980s (*high confidence*), and human influence has *very likely* contributed to most of them since at least 2006. {Box 9.2, 11.2, 11.3, 11.9, TS.2.4, TS.2.6, Box TS.10} (Figure SPM.3)

A.3.2 The frequency and intensity of heavy precipitation events have increased since the 1950s over most land area for which observational data are sufficient for trend analysis (*high confidence*), and human-induced climate change is *likely* the main driver. Human-induced climate change has contributed to increases in agricultural and ecological droughts[15] in some regions due to increased land evapotranspiration[16] (*medium confidence*). {8.2, 8.3, 11.4, 11.6, 11.9, TS.2.6, Box TS.10} (Figure SPM.3)

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13 As stated in section B.1, even under the very low emissions scenario SSP1-1.9, temperatures are assessed to remain elevated above those of the most recent decade until at least 2100 and therefore warmer than the century-scale period 6500 years ago.

14 As indicated in footnote 12, throughout this SPM, 'main driver' means responsible for more than 50% of the change.

15 Agricultural and ecological drought (depending on the affected biome): a period with abnormal soil moisture deficit, which results from combined shortage of precipitation and excess evapotranspiration, and during the growing season impinges on crop production or ecosystem function in general (see Annex VII: Glossary). Observed changes in meteorological droughts (precipitation deficits) and hydrological droughts (streamflow deficits) are distinct from those in agricultural and ecological droughts and are addressed in the underlying AR6 material (Chapter 11).

16 The combined processes through which water is transferred to the atmosphere from open water and ice surfaces, bare soils and vegetation that make up the Earth's surface (Glossary).

A.3.3 Decreases in global land monsoon precipitation[17] from the 1950s to the 1980s are partly attributed to human-caused Northern Hemisphere aerosol emissions, but increases since then have resulted from rising GHG concentrations and decadal to multi-decadal internal variability (*medium confidence*). Over South Asia, East Asia and West Africa, increases in monsoon precipitation due to warming from GHG emissions were counteracted by decreases in monsoon precipitation due to cooling from human-caused aerosol emissions over the 20th century (*high confidence*). Increases in West African monsoon precipitation since the 1980s are partly due to the growing influence of GHGs and reductions in the cooling effect of human-caused aerosol emissions over Europe and North America (*medium confidence*).
{2.3, 3.3, 8.2, 8.3, 8.4, 8.5, 8.6, Box 8.1, Box 8.2, 10.6, Box TS.13}

A.3.4 It is *likely* that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades, and it is *very likely* that the latitude where tropical cyclones in the western North Pacific reach their peak intensity has shifted northward; these changes cannot be explained by internal variability alone (*medium confidence*). There is *low confidence* in long-term (multi-decadal to centennial) trends in the frequency of all-category tropical cyclones. Event attribution studies and physical understanding indicate that human-induced climate change increases heavy precipitation associated with tropical cyclones (*high confidence*), but data limitations inhibit clear detection of past trends on the global scale.
{8.2, 11.7, Box TS.10}

A.3.5 Human influence has *likely* increased the chance of compound extreme events[18] since the 1950s. This includes increases in the frequency of concurrent heatwaves and droughts on the global scale (*high confidence*), fire weather in some regions of all inhabited continents (*medium confidence*), and compound flooding in some locations (*medium confidence*).
{11.6, 11.7, 11.8, 12.3, 12.4, TS.2.6, Table TS.5, Box TS.10}

17 The global monsoon is defined as the area in which the annual range (local summer minus local winter) of precipitation is greater than 2.5 mm day^{-1} (Glossary). Global land monsoon precipitation refers to the mean precipitation over land areas within the global monsoon.

18 Compound extreme events are the combination of multiple drivers and/or hazards that contribute to societal or environmental risk (Glossary). Examples are concurrent heatwaves and droughts, compound flooding (e.g., a storm surge in combination with extreme rainfall and/or river flow), compound fire weather conditions (i.e., a combination of hot, dry and windy conditions), or concurrent extremes at different locations.

Climate change is already affecting every inhabited region across the globe, with human influence contributing to many observed changes in weather and climate extremes

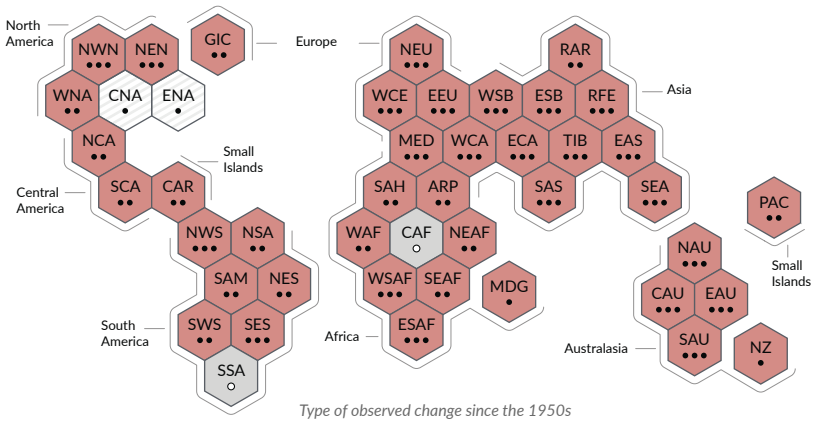
(a) Synthesis of assessment of observed change in **hot extremes** and confidence in human contribution to the observed changes in the world's regions

Type of observed change
in hot extremes

- Increase (41)
- Decrease (0)
- Low agreement in the type of change (2)
- Limited data and/or literature (2)

Confidence in human contribution
to the observed change

- ●●● High
- ●● Medium
- ● Low due to limited agreement
- ○ Low due to limited evidence



Type of observed change since the 1950s

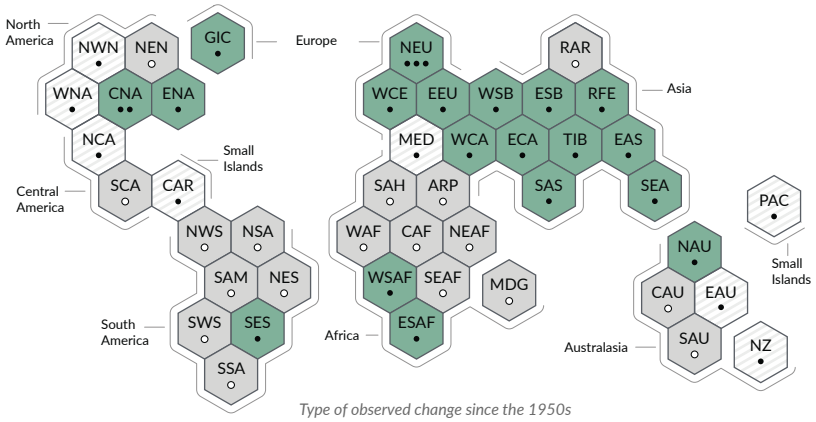
(b) Synthesis of assessment of observed change in **heavy precipitation** and confidence in human contribution to the observed changes in the world's regions

Type of observed change
in heavy precipitation

- Increase (19)
- Decrease (0)
- Low agreement in the type of change (8)
- Limited data and/or literature (18)

Confidence in human contribution
to the observed change

- ●●● High
- ●● Medium
- ● Low due to limited agreement
- ○ Low due to limited evidence



Type of observed change since the 1950s

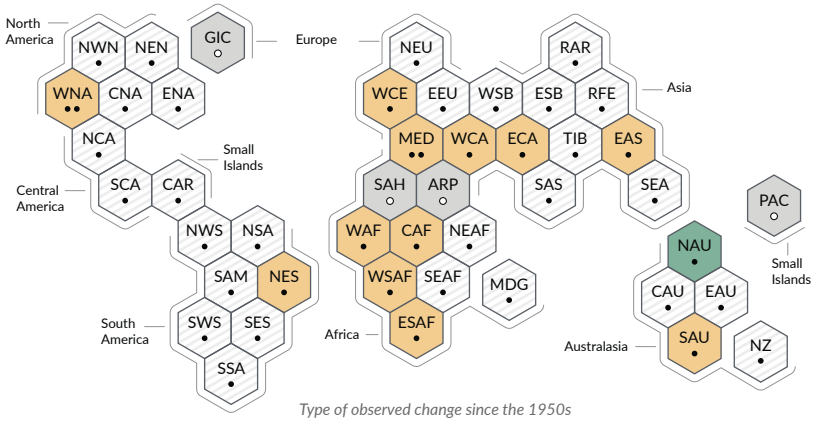
(c) Synthesis of assessment of observed change in **agricultural and ecological drought** and confidence in human contribution to the observed changes in the world's regions

Type of observed change
in agricultural and ecological drought

- Increase (12)
- Decrease (1)
- Low agreement in the type of change (28)
- Limited data and/or literature (4)

Confidence in human contribution
to the observed change

- ●●● High
- ●● Medium
- ● Low due to limited agreement
- ○ Low due to limited evidence



Type of observed change since the 1950s

Each hexagon corresponds to one of the IPCC AR6 WGI reference regions

NWN *North-Western North America*

IPCC AR6 WGI reference regions: **North America:** ***NWN*** *(North-Western North America),* ***NEN*** *(North-Eastern North America),* ***WNA*** *(Western North America),* ***CNA*** *(Central North America),* ***ENA*** *(Eastern North America),* **Central America:** ***NCA*** *(Northern Central America),* ***SCA*** *(Southern Central America),* ***CAR*** *(Caribbean),* **South America:** ***NWS*** *(North-Western South America),* ***NSA*** *(Northern South America),* ***NES*** *(North-Eastern South America),* ***SAM*** *(South American Monsoon),* ***SWS*** *(South-Western South America),* ***SES*** *(South-Eastern South America),* ***SSA*** *(Southern South America),* **Europe:** ***GIC*** *(Greenland/Iceland),* ***NEU*** *(Northern Europe),* ***WCE*** *(Western and Central Europe),* ***EEU*** *(Eastern Europe),* ***MED*** *(Mediterranean),* **Africa:** ***MED*** *(Mediterranean),* ***SAH*** *(Sahara),* ***WAF*** *(Western Africa),* ***CAF*** *(Central Africa),* ***NEAF*** *(North Eastern Africa),* ***SEAF*** *(South Eastern Africa),* ***WSAF*** *(West Southern Africa),* ***ESAF*** *(East Southern Africa),* ***MDG*** *(Madagascar),* **Asia:** ***RAR*** *(Russian Arctic),* ***WSB*** *(West Siberia),* ***ESB*** *(East Siberia),* ***RFE*** *(Russian Far East),* ***WCA*** *(West Central Asia),* ***ECA*** *(East Central Asia),* ***TIB*** *(Tibetan Plateau),* ***EAS*** *(East Asia),* ***ARP*** *(Arabian Peninsula),* ***SAS*** *(South Asia),* ***SEA*** *(South East Asia),* **Australasia:** ***NAU*** *(Northern Australia),* ***CAU*** *(Central Australia),* ***EAU*** *(Eastern Australia),* ***SAU*** *(Southern Australia),* ***NZ*** *(New Zealand),* **Small Islands:** ***CAR*** *(Caribbean),* ***PAC*** *(Pacific Small Islands)*

Figure SPM.3 | Synthesis of assessed observed and attributable regional changes

The IPCC AR6 WGI inhabited regions are displayed as **hexagons** with identical size in their approximate geographical location (see legend for regional acronyms). All assessments are made for each region as a whole and for the 1950s to the present. Assessments made on different time scales or more local spatial scales might differ from what is shown in the figure. The **colours** in each panel represent the four outcomes of the assessment on observed changes. Striped hexagons (white and light-grey) are used where there is *low agreement* in the type of change for the region as a whole, and grey hexagons are used when there is limited data and/or literature that prevents an assessment of the region as a whole. Other colours indicate at least *medium confidence* in the observed change. The **confidence level** for the human influence on these observed changes is based on assessing trend detection and attribution and event attribution literature, and it is indicated by the number of dots: three dots for *high confidence*, two dots for *medium confidence* and one dot for *low confidence* (single, filled dot: limited agreement; single, empty dot: limited evidence).

Panel (a) For hot extremes, the evidence is mostly drawn from changes in metrics based on daily maximum temperatures; regional studies using other indices (heatwave duration, frequency and intensity) are used in addition. Red hexagons indicate regions where there is at least *medium confidence* in an observed increase in hot extremes.

Panel (b) For heavy precipitation, the evidence is mostly drawn from changes in indices based on one-day or five-day precipitation amounts using global and regional studies. Green hexagons indicate regions where there is at least *medium confidence* in an observed increase in heavy precipitation.

Panel (c) Agricultural and ecological droughts are assessed based on observed and simulated changes in total column soil moisture, complemented by evidence on changes in surface soil moisture, water balance (precipitation minus evapotranspiration) and indices driven by precipitation and atmospheric evaporative demand. Yellow hexagons indicate regions where there is at least *medium confidence* in an observed increase in this type of drought, and green hexagons indicate regions where there is at least *medium confidence* in an observed decrease in agricultural and ecological drought.

For all regions, Table TS.5 shows a broader range of observed changes besides the ones shown in this figure. Note that Southern South America (SSA) is the only region that does not display observed changes in the metrics shown in this figure, but is affected by observed increases in mean temperature, decreases in frost and increases in marine heatwaves.

{11.9, Atlas 1.3.3, Figure Atlas.2, Table TS.5; Box TS.10, Figure 1}

A.4 Improved knowledge of climate processes, paleoclimate evidence and the response of the climate system to increasing radiative forcing gives a best estimate of equilibrium climate sensitivity of 3°C, with a narrower range compared to AR5. {2.2, 7.3, 7.4, 7.5, Box 7.2, 9.4, 9.5, 9.6, Cross-Chapter Box 9.1}

A.4.1 Human-caused radiative forcing of 2.72 [1.96 to 3.48] W m^{-2} in 2019 relative to 1750 has warmed the climate system. This warming is mainly due to increased GHG concentrations, partly reduced by cooling due to increased aerosol concentrations. The radiative forcing has increased by 0.43 W m^{-2} (19%) relative to AR5, of which 0.34 W m^{-2} is due to the increase in GHG concentrations since 2011. The remainder is due to improved scientific understanding and changes in the assessment of aerosol forcing, which include decreases in concentration and improvement in its calculation (*high confidence*). {2.2, 7.3, TS.2.2, TS.3.1}

A.4.2 Human-caused net positive radiative forcing causes an accumulation of additional energy (heating) in the climate system, partly reduced by increased energy loss to space in response to surface warming. The observed average rate of heating of the climate system increased from 0.50 [0.32 to 0.69] W m^{-2} for the period 1971–2006[19] to 0.79 [0.52 to 1.06] W m^{-2} for the period 2006–2018[20] (*high confidence*). Ocean warming accounted for 91% of the heating in the climate system, with land warming, ice loss and atmospheric warming accounting for about 5%, 3% and 1%, respectively (*high confidence*). {7.2, Box 7.2, TS.3.1}

A.4.3 Heating of the climate system has caused global mean sea level rise through ice loss on land and thermal expansion from ocean warming. Thermal expansion explained 50% of sea level rise during 1971–2018, while ice loss from glaciers contributed 22%, ice sheets 20% and changes in land-water storage 8%. The rate of ice-sheet loss increased by a factor of four between 1992–1999 and 2010–2019. Together, ice-sheet and glacier mass loss were the dominant contributors to global mean sea level rise during 2006–2018 (*high confidence*). {9.4, 9.5, 9.6, Cross-Chapter Box 9.1}

A.4.4 The equilibrium climate sensitivity is an important quantity used to estimate how the climate responds to radiative forcing. Based on multiple lines of evidence,[21] the *very likely* range of equilibrium climate sensitivity is between 2°C (*high confidence*) and 5°C (*medium confidence*). The AR6 assessed best estimate is 3°C with a *likely* range of 2.5°C to 4°C (*high confidence*), compared to 1.5°C to 4.5°C in AR5, which did not provide a best estimate. {7.4, 7.5, TS.3.2}

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19 Cumulative energy increase of 282 [177 to 387] ZJ over 1971–2006 (1 ZJ = 10^{21} joules).

20 Cumulative energy increase of 152 [100 to 205] ZJ over 2006–2018.

21 Understanding of climate processes, the instrumental record, paleoclimates and model-based emergent constraints (Glossary).

B. Possible Climate Futures

A set of five new illustrative emissions scenarios is considered consistently across this Report to explore the climate response to a broader range of greenhouse gas (GHG), land-use and air pollutant futures than assessed in AR5. This set of scenarios drives climate model projections of changes in the climate system. These projections account for solar activity and background forcing from volcanoes. Results over the 21st century are provided for the near term (2021–2040), mid-term (2041–2060) and long term (2081–2100) relative to 1850–1900, unless otherwise stated.

Box SPM.1 | Scenarios, Climate Models and Projections

Box SPM.1.1: This Report assesses the climate response to five illustrative scenarios that cover the range of possible future development of anthropogenic drivers of climate change found in the literature. They start in 2015, and include scenarios[22] with high and very high GHG emissions (SSP3-7.0 and SSP5-8.5) and CO_2 emissions that roughly double from current levels by 2100 and 2050, respectively, scenarios with intermediate GHG emissions (SSP2-4.5) and CO_2 emissions remaining around current levels until the middle of the century, and scenarios with very low and low GHG emissions and CO_2 emissions declining to net zero around or after 2050, followed by varying levels of net negative CO_2 emissions[23] (SSP1-1.9 and SSP1-2.6), as illustrated in Figure SPM.4. Emissions vary between scenarios depending on socio-economic assumptions, levels of climate change mitigation and, for aerosols and non-methane ozone precursors, air pollution controls. Alternative assumptions may result in similar emissions and climate responses, but the socio-economic assumptions and the feasibility or likelihood of individual scenarios are not part of the assessment.
{1.6, Cross-Chapter Box 1.4, TS.1.3} (Figure SPM.4)

Box SPM.1.2: This Report assesses results from climate models participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6) of the World Climate Research Programme. These models include new and better representations of physical, chemical and biological processes, as well as higher resolution, compared to climate models considered in previous IPCC assessment reports. This has improved the simulation of the recent mean state of most large-scale indicators of climate change and many other aspects across the climate system. Some differences from observations remain, for example in regional precipitation patterns. The CMIP6 historical simulations assessed in this Report have an ensemble mean global surface temperature change within 0.2°C of the observations over most of the historical period, and observed warming is within the *very likely* range of the CMIP6 ensemble. However, some CMIP6 models simulate a warming that is either above or below the assessed *very likely* range of observed warming.
{1.5, Cross-Chapter Box 2.2, 3.3, 3.8, TS.1.2, Cross-Section Box TS.1} (Figure SPM.1b, Figure SPM.2)

Box SPM.1.3: The CMIP6 models considered in this Report have a wider range of climate sensitivity than in CMIP5 models and the AR6 assessed *very likely* range, which is based on multiple lines of evidence. These CMIP6 models also show a higher average climate sensitivity than CMIP5 and the AR6 assessed best estimate. The higher CMIP6 climate sensitivity values compared to CMIP5 can be traced to an amplifying cloud feedback that is larger in CMIP6 by about 20%.
{Box 7.1, 7.3, 7.4, 7.5, TS.3.2}

Box SPM.1.4: For the first time in an IPCC report, assessed future changes in global surface temperature, ocean warming and sea level are constructed by combining multi-model projections with observational constraints based on past simulated warming, as well as the AR6 assessment of climate sensitivity. For other quantities, such robust methods do not yet exist to constrain the projections. Nevertheless, robust projected geographical patterns of many variables can be identified at a given level of global warming, common to all scenarios considered and independent of timing when the global warming level is reached.
{1.6, 4.3, 4.6, Box 4.1, 7.5, 9.2, 9.6, Cross-Chapter Box 11.1, Cross-Section Box TS.1}

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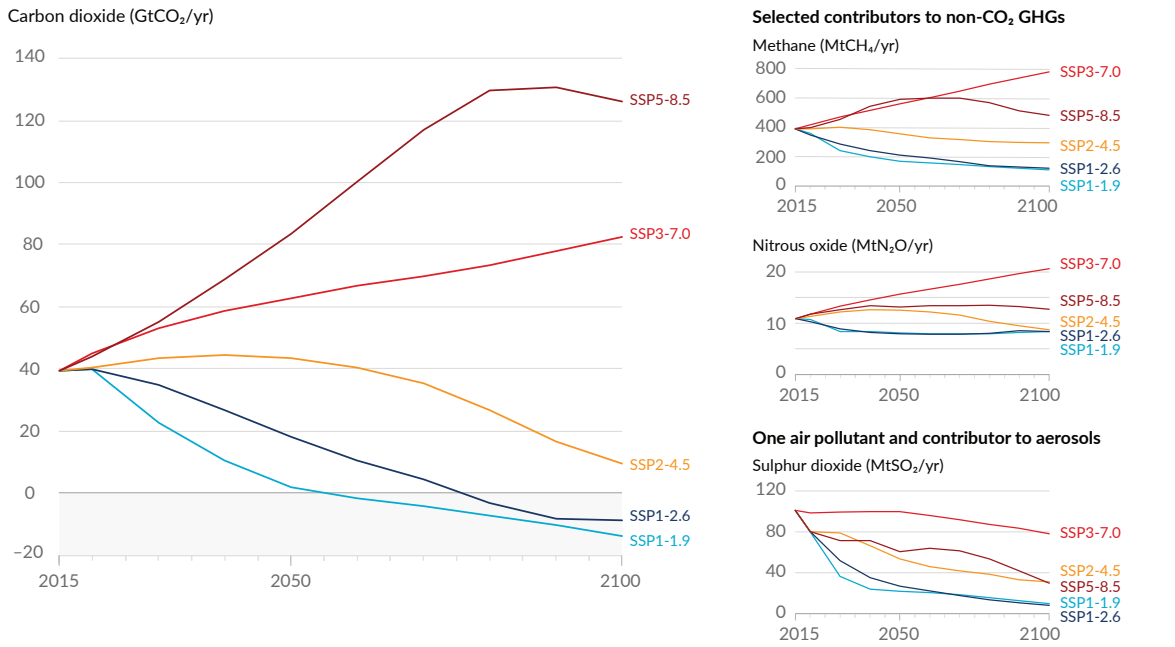
22 Throughout this Report, the five illustrative scenarios are referred to as SSPx-y, where 'SSPx' refers to the Shared Socio-economic Pathway or 'SSP' describing the socio-economic trends underlying the scenario, and 'y' refers to the approximate level of radiative forcing (in watts per square metre, or W m^{-2}) resulting from the scenario in the year 2100. A detailed comparison to scenarios used in earlier IPCC reports is provided in Section TS.1.3, and Sections 1.6 and 4.6. The SSPs that underlie the specific forcing scenarios used to drive climate models are not assessed by WGI. Rather, the SSPx-y labelling ensures traceability to the underlying literature in which specific forcing pathways are used as input to the climate models. IPCC is neutral with regard to the assumptions underlying the SSPs, which do not cover all possible scenarios. Alternative scenarios may be considered or developed.

23 Net negative CO_2 emissions are reached when anthropogenic removals of CO_2 exceed anthropogenic emissions (Glossary).

Box SPM.1 (continued)

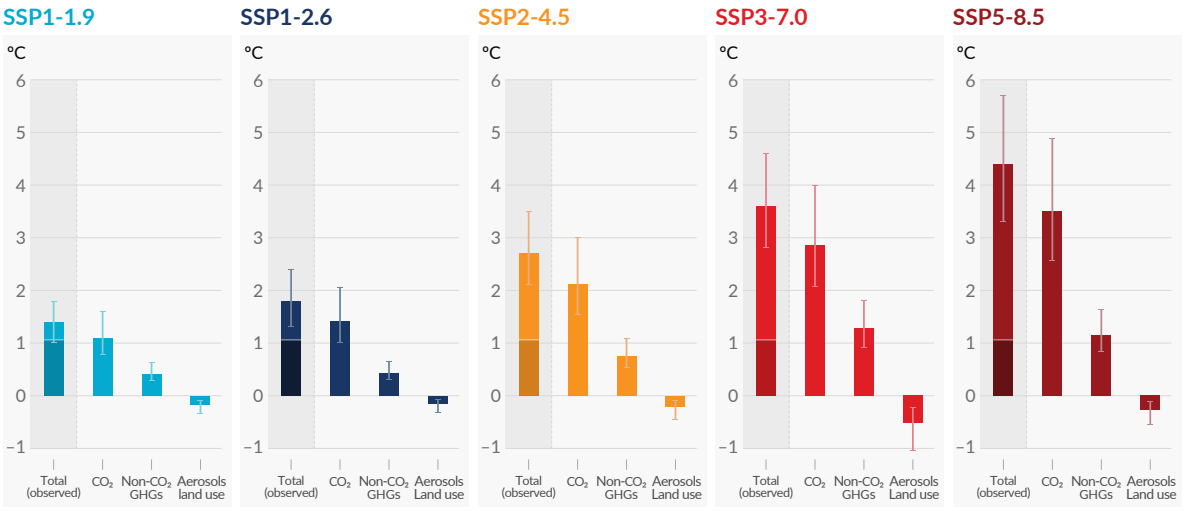
Future emissions cause future additional warming, with total warming dominated by past and future CO_2 emissions

(a) Future annual emissions of CO_2 (left) and of a subset of key non-CO_2 drivers (right), across five illustrative scenarios



(b) Contribution to global surface temperature increase from different emissions, with a dominant role of CO_2 emissions

Change in global surface temperature in 2081–2100 relative to 1850–1900 (°C)



Total warming (observed warming to date in darker shade), warming from CO_2, warming from non-CO_2 GHGs and cooling from changes in aerosols and land use

Figure SPM.4 | Future anthropogenic emissions of key drivers of climate change and warming contributions by groups of drivers for the five illustrative scenarios used in this report

The five scenarios are SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5.

Panel (a) Annual anthropogenic (human-caused) emissions over the 2015–2100 period. Shown are emissions trajectories for carbon dioxide (CO_2) from all sectors ($GtCO_2$/yr) (left graph) and for a subset of three key non-CO_2 drivers considered in the scenarios: methane (CH_4, $MtCH_4$/yr, top-right graph); nitrous oxide (N_2O, MtN_2O/yr, middle-right graph); and sulphur dioxide (SO_2, $MtSO_2$/yr, bottom-right graph, contributing to anthropogenic aerosols in panel (b).

Panel (b) Warming contributions by groups of anthropogenic drivers and by scenario are shown as the change in global surface temperature (°C) in 2081–2100 relative to 1850–1900, with indication of the observed warming to date. Bars and whiskers represent median values and the *very likely* range, respectively. Within each scenario bar plot, the bars represent: total global warming (°C; 'total' bar) (see Table SPM.1); warming contributions (°C) from changes in CO_2 ('CO_2' bar) and from non-CO_2 greenhouse gases (GHGs; 'non-CO_2 GHGs' bar: comprising well-mixed greenhouse gases and ozone); and net cooling from other anthropogenic drivers ('aerosols and land use' bar: anthropogenic aerosols, changes in reflectance due to land-use and irrigation changes, and contrails from aviation) (see Figure SPM.2, panel c, for the warming contributions to date for individual drivers). The best estimate for observed warming in 2010–2019 relative to 1850–1900 (see Figure SPM.2, panel a) is indicated in the darker column in the 'total' bar. Warming contributions in panel (b) are calculated as explained in Table SPM.1 for the total bar. For the other bars, the contribution by groups of drivers is calculated with a physical climate emulator of global surface temperature that relies on climate sensitivity and radiative forcing assessments.

{Cross-Chapter Box 1.4; 4.6; Figure 4.35; 6.7; Figures 6.18, 6.22 and 6.24; 7.3; Cross-Chapter Box 7.1; Figure 7.7; Box TS.7; Figures TS.4 and TS.15}

B.1 Global surface temperature will continue to increase until at least mid-century under all emissions scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades. {2.3, Cross-Chapter Box 2.3, Cross-Chapter Box 2.4, 4.3, 4.4, 4.5} (Figure SPM.1, Figure SPM.4, Figure SPM.8, Table SPM.1, Box SPM.1)

B.1.1 Compared to 1850–1900, global surface temperature averaged over 2081–2100 is *very likely* to be higher by 1.0°C to 1.8°C under the very low GHG emissions scenario considered (SSP1-1.9), by 2.1°C to 3.5°C in the intermediate GHG emissions scenario (SSP2-4.5) and by 3.3°C to 5.7°C under the very high GHG emissions scenario (SSP5-8.5).[24] The last time global surface temperature was sustained at or above 2.5°C higher than 1850–1900 was over 3 million years ago (*medium confidence*).
{2.3, Cross-Chapter Box 2.4, 4.3, 4.5, Box TS.2, Box TS.4, Cross-Section Box TS.1} (Table SPM.1)

Table SPM.1 | Changes in global surface temperature, which are assessed based on multiple lines of evidence, for selected 20-year time periods and the five illustrative emissions scenarios considered. Temperature differences relative to the average global surface temperature of the period 1850–1900 are reported in °C. This includes the revised assessment of observed historical warming for the AR5 reference period 1986–2005, which in AR6 is higher by 0.08 [–0.01 to +0.12] °C than in AR5 (see footnote 10). Changes relative to the recent reference period 1995–2014 may be calculated approximately by subtracting 0.85°C, the best estimate of the observed warming from 1850–1900 to 1995–2014.
{Cross-Chapter Box 2.3, 4.3, 4.4, Cross-Section Box TS.1}

	Near term, 2021–2040		Mid-term, 2041–2060		Long term, 2081–2100	
Scenario	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)
SSP1-1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP2-4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP3-7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5	1.6	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

B.1.2 Based on the assessment of multiple lines of evidence, global warming of 2°C, relative to 1850–1900, would be exceeded during the 21st century under the high and very high GHG emissions scenarios considered in this report (SSP3-7.0 and SSP5-8.5, respectively). Global warming of 2°C would *extremely likely* be exceeded in the intermediate GHG emissions scenario (SSP2-4.5). Under the very low and low GHG emissions scenarios, global warming of 2°C is *extremely unlikely* to be exceeded (SSP1-1.9) or *unlikely* to be exceeded (SSP1-2.6).[25] Crossing the 2°C global warming level in the mid-term period (2041–2060) is *very likely* to occur under the very high GHG emissions scenario (SSP5-8.5), *likely* to occur under the high GHG emissions scenario (SSP3-7.0), and *more likely than not* to occur in the intermediate GHG emissions scenario (SSP2-4.5).[26]
{4.3, Cross-Section Box TS.1} (Table SPM.1, Figure SPM.4, Box SPM.1)

24 Changes in global surface temperature are reported as running 20-year averages, unless stated otherwise.

25 SSP1-1.9 and SSP1-2.6 are scenarios that start in 2015 and have very low and low GHG emissions, respectively, and CO_2 emissions declining to net zero around or after 2050, followed by varying levels of net negative CO_2 emissions.

26 Crossing is defined here as having the assessed global surface temperature change, averaged over a 20-year period, exceed a particular global warming level.

B.1.3 Global warming of 1.5°C relative to 1850–1900 would be exceeded during the 21st century under the intermediate, high and very high GHG emissions scenarios considered in this report (SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively). Under the five illustrative scenarios, in the near term (2021–2040), the 1.5°C global warming level is *very likely* to be exceeded under the very high GHG emissions scenario (SSP5-8.5), *likely* to be exceeded under the intermediate and high GHG emissions scenarios (SSP2-4.5 and SSP3-7.0), *more likely than not* to be exceeded under the low GHG emissions scenario (SSP1-2.6) and *more likely than not* to be reached under the very low GHG emissions scenario (SSP1-1.9).[27] Furthermore, for the very low GHG emissions scenario (SSP1-1.9), it is *more likely than not* that global surface temperature would decline back to below 1.5°C toward the end of the 21st century, with a temporary overshoot of no more than 0.1°C above 1.5°C global warming.
{4.3, Cross-Section Box TS.1} (Table SPM.1, Figure SPM.4)

B.1.4 Global surface temperature in any single year can vary above or below the long-term human-induced trend, due to substantial natural variability.[28] The occurrence of individual years with global surface temperature change above a certain level, for example 1.5°C or 2°C, relative to 1850–1900 does not imply that this global warming level has been reached.[29]
{Cross-Chapter Box 2.3, 4.3, 4.4, Box 4.1, Cross-Section Box TS.1} (Table SPM.1, Figure SPM.1, Figure SPM.8)

B.2 Many changes in the climate system become larger in direct relation to increasing global warming. They include increases in the frequency and intensity of hot extremes, marine heatwaves, heavy precipitation, and, in some regions, agricultural and ecological droughts; an increase in the proportion of intense tropical cyclones; and reductions in Arctic sea ice, snow cover and permafrost.
{4.3, 4.5, 4.6, 7.4, 8.2, 8.4, Box 8.2, 9.3, 9.5, Box 9.2, 11.1, 11.2, 11.3, 11.4, 11.6, 11.7, 11.9, Cross-Chapter Box 11.1, 12.4, 12.5, Cross-Chapter Box 12.1, Atlas.4, Atlas.5, Atlas.6, Atlas.7, Atlas.8, Atlas.9, Atlas.10, Atlas.11} (Figure SPM.5, Figure SPM.6, Figure SPM.8)

B.2.1 It is *virtually certain* that the land surface will continue to warm more than the ocean surface (*likely* 1.4 to 1.7 times more). It is *virtually certain* that the Arctic will continue to warm more than global surface temperature, with *high confidence* above two times the rate of global warming.
{2.3, 4.3, 4.5, 4.6, 7.4, 11.1, 11.3, 11.9, 12.4, 12.5, Cross-Chapter Box 12.1, Atlas.4, Atlas.5, Atlas.6, Atlas.7, Atlas.8, Atlas.9, Atlas.10, Atlas.11, Cross-Section Box TS.1, TS.2.6} (Figure SPM.5)

B.2.2 With every additional increment of global warming, changes in extremes continue to become larger. For example, every additional 0.5°C of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves (*very likely*), and heavy precipitation (*high confidence*), as well as agricultural and ecological droughts[30] in some regions (*high confidence*). Discernible changes in intensity and frequency of meteorological droughts, with more regions showing increases than decreases, are seen in some regions for every additional 0.5°C of global warming (*medium confidence*). Increases in frequency and intensity of hydrological droughts become larger with increasing global warming in some regions (*medium confidence*). There will be an increasing occurrence of some extreme events unprecedented in the observational record with additional global warming, even at 1.5°C of global warming. Projected percentage changes in frequency are larger for rarer events (*high confidence*).
{8.2, 11.2, 11.3, 11.4, 11.6, 11.9, Cross-Chapter Box 11.1, Cross-Chapter Box 12.1, TS.2.6} (Figure SPM.5, Figure SPM.6)

B.2.3 Some mid-latitude and semi-arid regions, and the South American Monsoon region, are projected to see the highest increase in the temperature of the hottest days, at about 1.5 to 2 times the rate of global warming (*high confidence*). The Arctic is projected to experience the highest increase in the temperature of the coldest days, at about three times the rate of global warming (*high confidence*). With additional global warming, the frequency of marine heatwaves will continue to increase (*high confidence*), particularly in the tropical ocean and the Arctic (*medium confidence*).
{Box 9.2, 11.1, 11.3, 11.9, Cross-Chapter Box 11.1, Cross-Chapter Box 12.1, 12.4, TS.2.4, TS.2.6} (Figure SPM.6)

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27 The AR6 assessment of when a given global warming level is first exceeded benefits from the consideration of the illustrative scenarios, the multiple lines of evidence entering the assessment of future global surface temperature response to radiative forcing, and the improved estimate of historical warming. The AR6 assessment is thus not directly comparable to the SR1.5 SPM, which reported *likely* reaching 1.5°C global warming between 2030 and 2052, from a simple linear extrapolation of warming rates of the recent past. When considering scenarios similar to SSP1-1.9 instead of linear extrapolation, the SR1.5 estimate of when 1.5°C global warming is first exceeded is close to the best estimate reported here.

28 Natural variability refers to climatic fluctuations that occur without any human influence, that is, internal variability combined with the response to external natural factors such as volcanic eruptions, changes in solar activity and, on longer time scales, orbital effects and plate tectonics (Glossary).

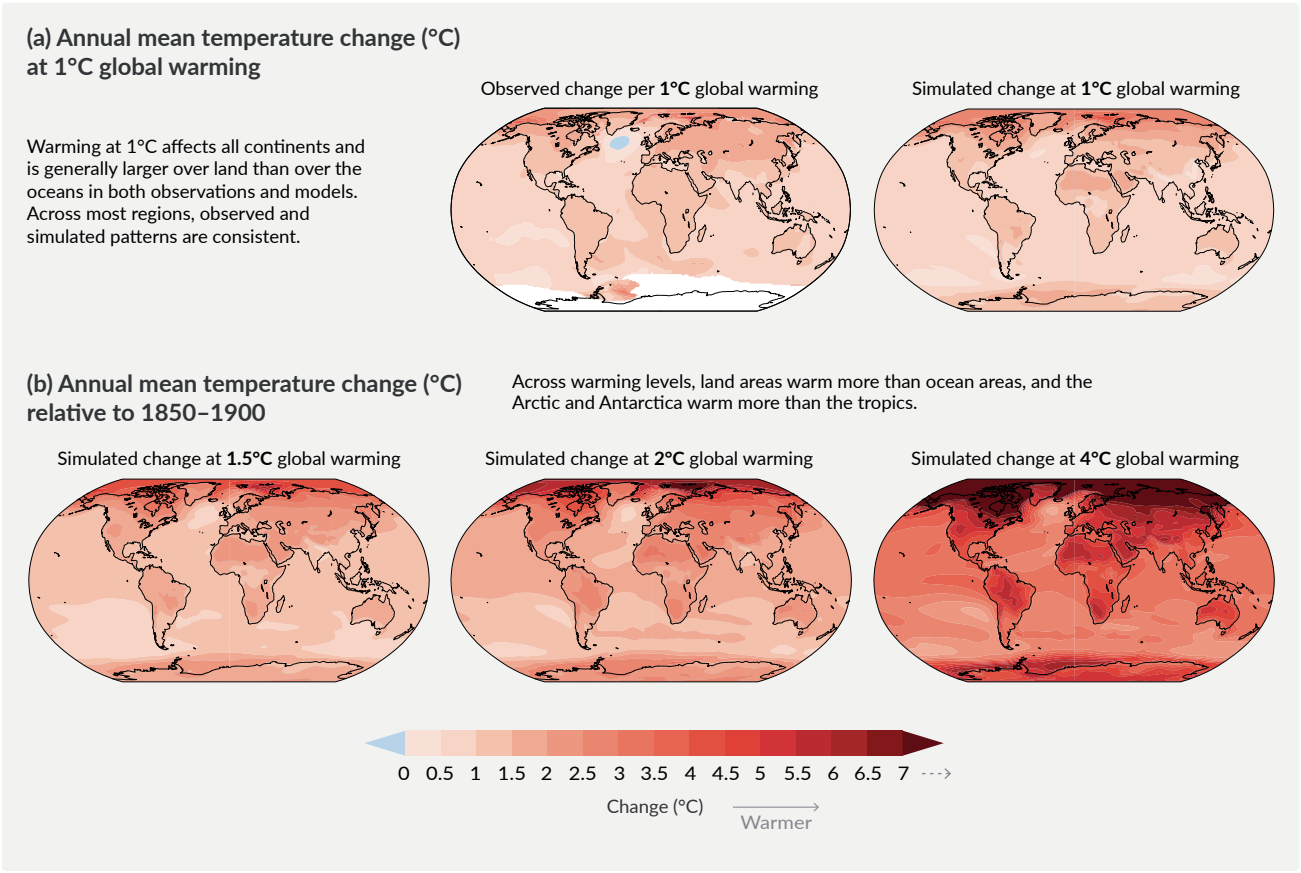
29 The internal variability in any single year is estimated to be about ±0.25°C (5–95% range, *high confidence*).

30 Projected changes in agricultural and ecological droughts are primarily assessed based on total column soil moisture. See footnote 15 for definition and relation to precipitation and evapotranspiration.

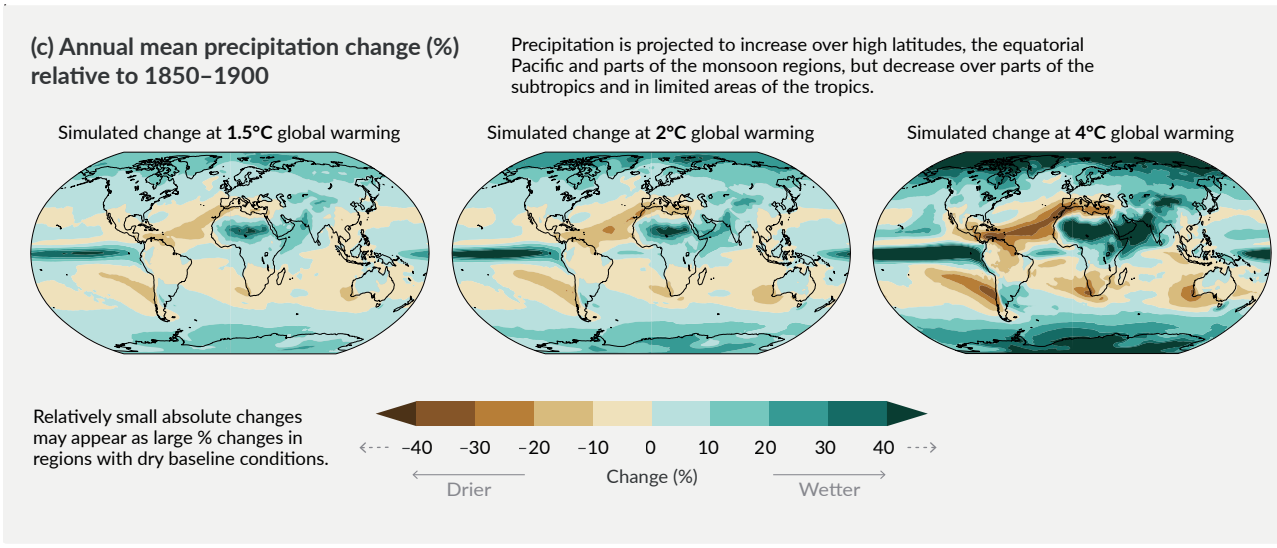
B.2.4 It is *very likely* that heavy precipitation events will intensify and become more frequent in most regions with additional global warming. At the global scale, extreme daily precipitation events are projected to intensify by about 7% for each 1°C of global warming (*high confidence*). The proportion of intense tropical cyclones (Category 4–5) and peak wind speeds of the most intense tropical cyclones are projected to increase at the global scale with increasing global warming (*high confidence*). {8.2, 11.4, 11.7, 11.9, Cross-Chapter Box 11.1, Box TS.6, TS.4.3.1} (Figure SPM.5, Figure SPM.6)

B.2.5 Additional warming is projected to further amplify permafrost thawing and loss of seasonal snow cover, of land ice and of Arctic sea ice (*high confidence*). The Arctic is *likely* to be practically sea ice-free in September[31] at least once before 2050 under the five illustrative scenarios considered in this report, with more frequent occurrences for higher warming levels. There is *low confidence* in the projected decrease of Antarctic sea ice. {4.3, 4.5, 7.4, 8.2, 8.4, Box 8.2, 9.3, 9.5, 12.4, Cross-Chapter Box 12.1, Atlas.5, Atlas.6, Atlas.8, Atlas.9, Atlas.11, TS.2.5} (Figure SPM.8)

With every increment of global warming, changes get larger in regional mean temperature, precipitation and soil moisture



31 Monthly average sea ice area of less than 1 million km², which is about 15% of the average September sea ice area observed in 1979–1988.



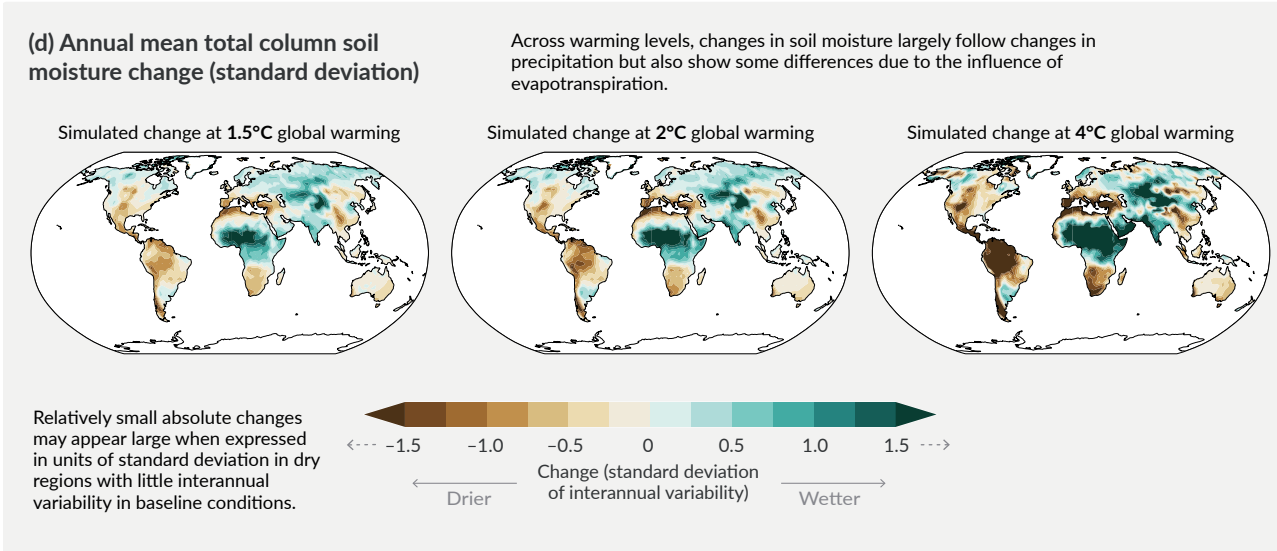


Figure SPM.5 | Changes in annual mean surface temperature, precipitation, and soil moisture

Panel (a) Comparison of observed and simulated annual mean surface temperature change. The **left map** shows the observed changes in annual mean surface temperature in the period 1850–2020 per °C of global warming (°C). The local (i.e., grid point) observed annual mean surface temperature changes are linearly regressed against the global surface temperature in the period 1850–2020. Observed temperature data are from Berkeley Earth, the dataset with the largest coverage and highest horizontal resolution. Linear regression is applied to all years for which data at the corresponding grid point is available. The regression method was used to take into account the complete observational time series and thereby reduce the role of internal variability at the grid point level. White indicates areas where time coverage was 100 years or less and thereby too short to calculate a reliable linear regression. The **right map** is based on model simulations and shows change in annual multi-model mean simulated temperatures at a global warming level of 1°C (20-year mean global surface temperature change relative to 1850–1900). The triangles at each end of the colour bar indicate out-of-bound values, that is, values above or below the given limits.

Panel (b) Simulated annual mean temperature change (°C), panel (c) precipitation change (%), and panel (d) total column soil moisture change (standard deviation of interannual variability) at global warming levels of 1.5°C, 2°C and 4°C (20-year mean global surface temperature change relative to 1850–1900). Simulated changes correspond to Coupled Model Intercomparison Project Phase 6 (CMIP6) multi-model mean change (median change for soil moisture) at the corresponding global warming level, that is, the same method as for the right map in panel (a).

In **panel (c)**, high positive percentage changes in dry regions may correspond to small absolute changes. In **panel (d)**, the unit is the standard deviation of interannual variability in soil moisture during 1850–1900. Standard deviation is a widely used metric in characterizing drought severity. A projected reduction in mean soil moisture by one standard deviation corresponds to soil moisture conditions typical of droughts that occurred about once every six years during 1850–1900. In panel (d), large changes in dry regions with little interannual variability in the baseline conditions can correspond to small absolute change. The triangles at each end of the colour bars indicate out-of-bound values, that is, values above or below the given limits. Results from all models reaching the corresponding warming level in any of the five illustrative scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) are averaged. Maps of annual mean temperature and precipitation changes at a global warming level of 3°C are available in Figure 4.31 and Figure 4.32 in Section 4.6. Corresponding maps of panels (b), (c) and (d), including hatching to indicate the level of model agreement at grid-cell level, are found in Figures 4.31, 4.32 and 11.19, respectively; as highlighted in Cross-Chapter Box Atlas.1, grid-cell level hatching is not informative for larger spatial scales (e.g., over AR6 reference regions) where the aggregated signals are less affected by small-scale variability, leading to an increase in robustness.

{Figure 1.14, 4.6.1, Cross-Chapter Box 11.1, Cross-Chapter Box Atlas.1, TS.1.3.2, Figures TS.3 and TS.5}

Projected changes in extremes are larger in frequency and intensity with every additional increment of global warming

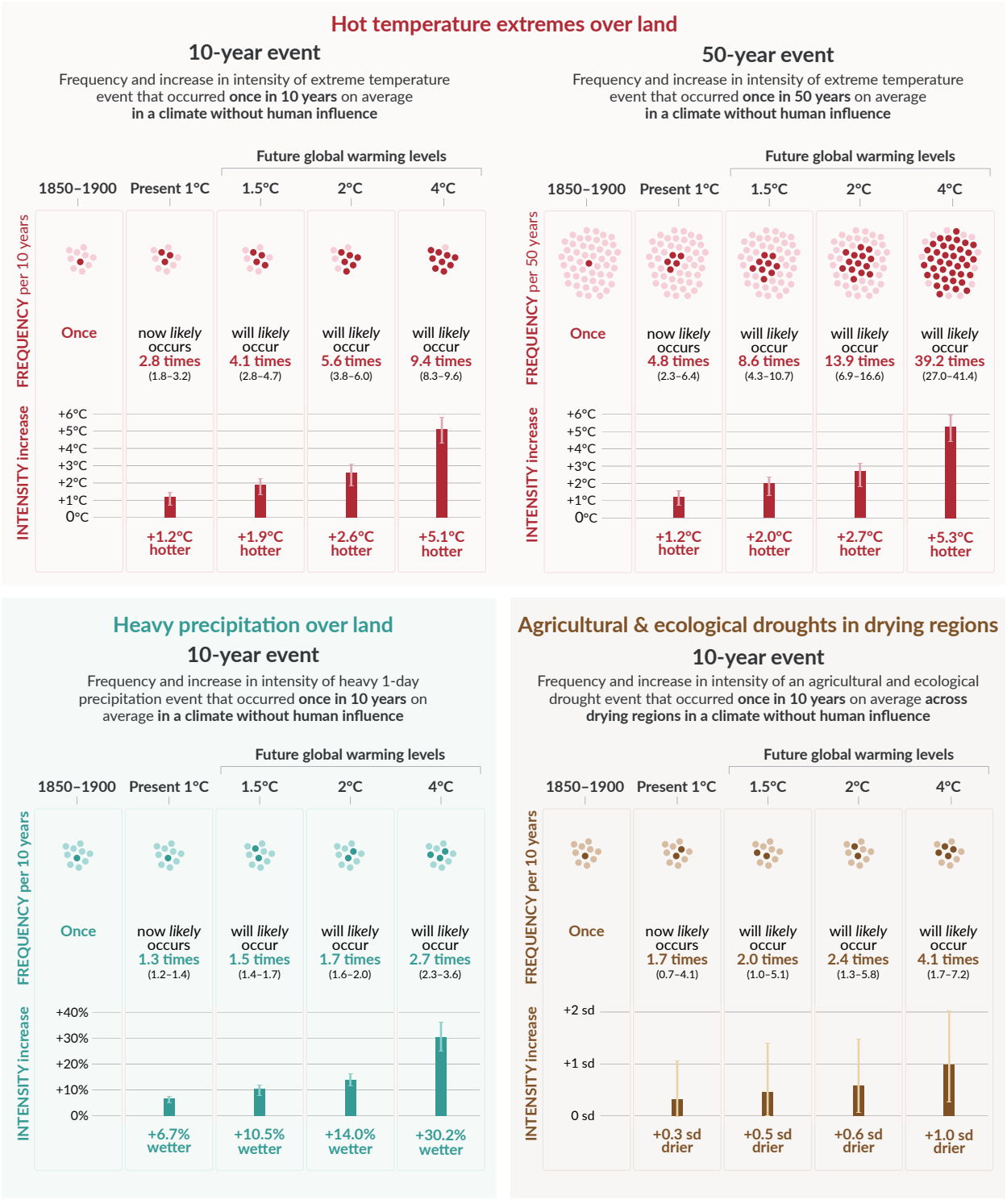


Figure SPM.6 | Projected changes in the intensity and frequency of hot temperature extremes over land, extreme precipitation over land, and agricultural and ecological droughts in drying regions

Projected changes are shown at global warming levels of 1°C, 1.5°C, 2°C, and 4°C and are relative to 1850–1900,[9] representing a climate without human influence. The figure depicts frequencies and increases in intensity of 10- or 50-year extreme events from the base period (1850–1900) under different global warming levels.

Hot temperature extremes are defined as the daily maximum temperatures over land that were exceeded on average once in a decade (10-year event) or once in 50 years (50-year event) during the 1850–1900 reference period. **Extreme precipitation events** are defined as the daily precipitation amount over land that

was exceeded on average once in a decade during the 1850–1900 reference period. **Agricultural and ecological drought events** are defined as the annual average of total column soil moisture below the 10th percentile of the 1850–1900 base period. These extremes are defined on model grid box scale. For hot temperature extremes and extreme precipitation, results are shown for the global land. For agricultural and ecological drought, results are shown for drying regions only, which correspond to the AR6 regions in which there is at least *medium confidence* in a projected increase in agricultural and ecological droughts at the 2°C warming level compared to the 1850–1900 base period in the Coupled Model Intercomparison Project Phase 6 (CMIP6). These regions include Western North America, Central North America, Northern Central America, Southern Central America, Caribbean, Northern South America, North-Eastern South America, South American Monsoon, South-Western South America, Southern South America, Western and Central Europe, Mediterranean, West Southern Africa, East Southern Africa, Madagascar, Eastern Australia, and Southern Australia (Caribbean is not included in the calculation of the figure because of the too-small number of full land grid cells). The non-drying regions do not show an overall increase or decrease in drought severity. Projections of changes in agricultural and ecological droughts in the CMIP Phase 5 (CMIP5) multi-model ensemble differ from those in CMIP6 in some regions, including in parts of Africa and Asia. Assessments of projected changes in meteorological and hydrological droughts are provided in Chapter 11.

In the **'frequency' section**, each year is represented by a dot. The dark dots indicate years in which the extreme threshold is exceeded, while light dots are years when the threshold is not exceeded. Values correspond to the medians (in bold) and their respective 5–95% range based on the multi-model ensemble from simulations of CMIP6 under different Shared Socio-economic Pathway scenarios. For consistency, the number of dark dots is based on the rounded-up median. In the **'intensity' section**, medians and their 5–95% range, also based on the multi-model ensemble from simulations of CMIP6, are displayed as dark and light bars, respectively. Changes in the intensity of hot temperature extremes and extreme precipitation are expressed as degree Celsius and percentage. As for agricultural and ecological drought, intensity changes are expressed as fractions of standard deviation of annual soil moisture.

{11.1; 11.3; 11.4; 11.6; 11.9; Figures 11.12, 11.15, 11.6, 11.7, and 11.18}

B.3 Continued global warming is projected to further intensify the global water cycle, including its variability, global monsoon precipitation and the severity of wet and dry events. {4.3, 4.4, 4.5, 4.6, 8.2, 8.3, 8.4, 8.5, Box 8.2, 11.4, 11.6, 11.9, 12.4, Atlas.3} (Figure SPM.5, Figure SPM.6)

B.3.1 There is strengthened evidence since AR5 that the global water cycle will continue to intensify as global temperatures rise (*high confidence*), with precipitation and surface water flows projected to become more variable over most land regions within seasons (*high confidence*) and from year to year (*medium confidence*). The average annual global land precipitation is projected to increase by 0–5% under the very low GHG emissions scenario (SSP1-1.9), 1.5–8% for the intermediate GHG emissions scenario (SSP2-4.5) and 1–13% under the very high GHG emissions scenario (SSP5-8.5) by 2081–2100 relative to 1995–2014 (*likely* ranges). Precipitation is projected to increase over high latitudes, the equatorial Pacific and parts of the monsoon regions, but decrease over parts of the subtropics and limited areas in the tropics in SSP2-4.5, SSP3-7.0 and SSP5-8.5 (*very likely*). The portion of the global land experiencing detectable increases or decreases in seasonal mean precipitation is projected to increase (*medium confidence*). There is *high confidence* in an earlier onset of spring snowmelt, with higher peak flows at the expense of summer flows in snow-dominated regions globally.
{4.3, 4.5, 4.6, 8.2, 8.4, Atlas.3, TS.2.6, TS.4.3, Box TS.6} (Figure SPM.5)

B.3.2 A warmer climate will intensify very wet and very dry weather and climate events and seasons, with implications for flooding or drought (*high confidence*), but the location and frequency of these events depend on projected changes in regional atmospheric circulation, including monsoons and mid-latitude storm tracks. It is *very likely* that rainfall variability related to the El Niño–Southern Oscillation is projected to be amplified by the second half of the 21st century in the SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios.
{4.3, 4.5, 4.6, 8.2, 8.4, 8.5, 11.4, 11.6, 11.9, 12.4, TS.2.6, TS.4.2, Box TS.6} (Figure SPM.5, Figure SPM.6)

B.3.3 Monsoon precipitation is projected to increase in the mid- to long term at the global scale, particularly over South and South East Asia, East Asia and West Africa apart from the far west Sahel (*high confidence*). The monsoon season is projected to have a delayed onset over North and South America and West Africa (*high confidence*) and a delayed retreat over West Africa (*medium confidence*).
{4.4, 4.5, 8.2, 8.3, 8.4, Box 8.2, Box TS.13}

B.3.4 A projected southward shift and intensification of Southern Hemisphere summer mid-latitude storm tracks and associated precipitation is *likely* in the long term under high GHG emissions scenarios (SSP3-7.0, SSP5-8.5), but in the near term the effect of stratospheric ozone recovery counteracts these changes (*high confidence*). There is *medium confidence* in a continued poleward shift of storms and their precipitation in the North Pacific, while there is *low confidence* in projected changes in the North Atlantic storm tracks.
{4.4, 4.5, 8.4, TS.2.3, TS.4.2}

B.4 Under scenarios with increasing CO_2 emissions, the ocean and land carbon sinks are projected to be less effective at slowing the accumulation of CO_2 in the atmosphere. {4.3, 5.2, 5.4, 5.5, 5.6} (Figure SPM.7)

B.4.1 While natural land and ocean carbon sinks are projected to take up, in absolute terms, a progressively larger amount of CO_2 under higher compared to lower CO_2 emissions scenarios, they become less effective, that is, the proportion of emissions taken up by land and ocean decrease with increasing cumulative CO_2 emissions. This is projected to result in a higher proportion of emitted CO_2 remaining in the atmosphere (*high confidence*).
{5.2, 5.4, Box TS.5} (Figure SPM.7)

B.4.2 Based on model projections, under the intermediate GHG emissions scenario that stabilizes atmospheric CO_2 concentrations this century (SSP2-4.5), the rates of CO_2 taken up by the land and ocean are projected to decrease in the second half of the 21st century (*high confidence*). Under the very low and low GHG emissions scenarios (SSP1-1.9, SSP1-2.6), where CO_2 concentrations peak and decline during the 21st century, the land and ocean begin to take up less carbon in response to declining atmospheric CO_2 concentrations (*high confidence*) and turn into a weak net source by 2100 under SSP1-1.9 (*medium confidence*). It is *very unlikely* that the combined global land and ocean sink will turn into a source by 2100 under scenarios without net negative emissions (SSP2-4.5, SSP3-7.0, SSP5-8.5).[32]
{4.3, 5.4, 5.5, 5.6, Box TS.5, TS.3.3}

B.4.3 The magnitude of feedbacks between climate change and the carbon cycle becomes larger but also more uncertain in high CO_2 emissions scenarios (*very high confidence*). However, climate model projections show that the uncertainties in atmospheric CO_2 concentrations by 2100 are dominated by the differences between emissions scenarios (*high confidence*). Additional ecosystem responses to warming not yet fully included in climate models, such as CO_2 and CH_4 fluxes from wetlands, permafrost thaw and wildfires, would further increase concentrations of these gases in the atmosphere (*high confidence*).
{5.4, Box TS.5, TS.3.2}

The proportion of CO_2 emissions taken up by land and ocean carbon sinks is smaller in scenarios with higher cumulative CO_2 emissions

Total cumulative CO_2 emissions **taken up by land and ocean** (colours) and remaining in the atmosphere (grey) under the five illustrative scenarios from 1850 to 2100

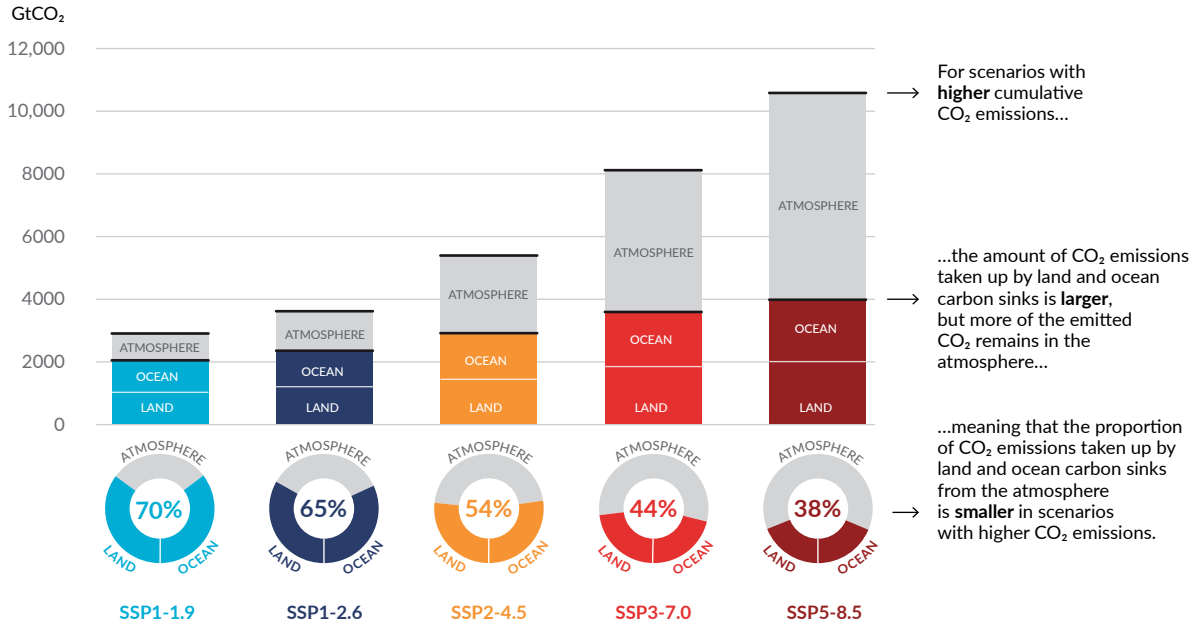


Figure SPM.7 | Cumulative anthropogenic CO_2 emissions taken up by land and ocean sinks by 2100 under the five illustrative scenarios

The cumulative anthropogenic (human-caused) carbon dioxide (CO_2) emissions taken up by the land and ocean sinks under the five illustrative scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) are simulated from 1850 to 2100 by Coupled Model Intercomparison Project Phase 6 (CMIP6) climate models in the concentration-driven simulations. Land and ocean carbon sinks respond to past, current and future emissions; therefore, cumulative sinks from 1850 to 2100 are presented here. During the historical period (1850–2019) the observed land and ocean sink took up 1430 $GtCO_2$ (59% of the emissions).

32 These projected adjustments of carbon sinks to stabilization or decline of atmospheric CO_2 are accounted for in calculations of remaining carbon budgets.

The bar chart illustrates the projected amount of cumulative anthropogenic CO_2 emissions ($GtCO_2$) between 1850 and 2100 remaining in the atmosphere (grey part) and taken up by the land and ocean (coloured part) in the year 2100. **The doughnut chart** illustrates the proportion of the cumulative anthropogenic CO_2 emissions taken up by the land and ocean sinks and remaining in the atmosphere in the year 2100. Values in % indicate the proportion of the cumulative anthropogenic CO_2 emissions taken up by the combined land and ocean sinks in the year 2100. The overall anthropogenic carbon emissions are calculated by adding the net global land-use emissions from the CMIP6 scenario database to the other sectoral emissions calculated from climate model runs with prescribed CO_2 concentrations.[33] Land and ocean CO_2 uptake since 1850 is calculated from the net biome productivity on land, corrected for CO_2 losses due to land-use change by adding the land-use change emissions, and net ocean CO_2 flux.

{5.2.1; Table 5.1; 5.4.5; Figure 5.25; Box TS.5; Box TS.5, Figure 1}

B.5 Many changes due to past and future greenhouse gas emissions are irreversible for centuries to millennia, especially changes in the ocean, ice sheets and global sea level. {2.3, Cross-Chapter Box 2.4, 4.3, 4.5, 4.7, 5.3, 9.2, 9.4, 9.5, 9.6, Box 9.4} (Figure SPM.8)

B.5.1 Past GHG emissions since 1750 have committed the global ocean to future warming (*high confidence*). Over the rest of the 21st century, *likely* ocean warming ranges from 2–4 (SSP1-2.6) to 4–8 times (SSP5-8.5) the 1971–2018 change. Based on multiple lines of evidence, upper ocean stratification (*virtually certain*), ocean acidification (*virtually certain*) and ocean deoxygenation (*high confidence*) will continue to increase in the 21st century, at rates dependent on future emissions. Changes are irreversible on centennial to millennial time scales in global ocean temperature (*very high confidence*), deep-ocean acidification (*very high confidence*) and deoxygenation (*medium confidence*).
{4.3, 4.5, 4.7, 5.3, 9.2, TS.2.4} (Figure SPM.8)

B.5.2 Mountain and polar glaciers are committed to continue melting for decades or centuries (*very high confidence*). Loss of permafrost carbon following permafrost thaw is irreversible at centennial time scales (*high confidence*). Continued ice loss over the 21st century is *virtually certain* for the Greenland Ice Sheet and *likely* for the Antarctic Ice Sheet. There is *high confidence* that total ice loss from the Greenland Ice Sheet will increase with cumulative emissions. There is *limited evidence* for low-likelihood, high-impact outcomes (resulting from ice-sheet instability processes characterized by deep uncertainty and in some cases involving tipping points) that would strongly increase ice loss from the Antarctic Ice Sheet for centuries under high GHG emissions scenarios.[34]
{4.3, 4.7, 5.4, 9.4, 9.5, Box 9.4, Box TS.1, TS.2.5}

B.5.3 It is *virtually certain* that global mean sea level will continue to rise over the 21st century. Relative to 1995–2014, the *likely* global mean sea level rise by 2100 is 0.28–0.55 m under the very low GHG emissions scenario (SSP1-1.9); 0.32–0.62 m under the low GHG emissions scenario (SSP1-2.6); 0.44–0.76 m under the intermediate GHG emissions scenario (SSP2-4.5); and 0.63–1.01 m under the very high GHG emissions scenario (SSP5-8.5); and by 2150 is 0.37–0.86 m under the very low scenario (SSP1-1.9); 0.46–0.99 m under the low scenario (SSP1-2.6); 0.66–1.33 m under the intermediate scenario (SSP2-4.5); and 0.98–1.88 m under the very high scenario (SSP5-8.5) (*medium confidence*).[35] Global mean sea level rise above the *likely* range – approaching 2 m by 2100 and 5 m by 2150 under a very high GHG emissions scenario (SSP5-8.5) (*low confidence*) – cannot be ruled out due to deep uncertainty in ice-sheet processes.
{4.3, 9.6, Box 9.4, Box TS.4} (Figure SPM.8)

B.5.4 In the longer term, sea level is committed to rise for centuries to millennia due to continuing deep-ocean warming and ice-sheet melt and will remain elevated for thousands of years (*high confidence*). Over the next 2000 years, global mean sea level will rise by about 2 to 3 m if warming is limited to 1.5°C, 2 to 6 m if limited to 2°C and 19 to 22 m with 5°C of warming, and it will continue to rise over subsequent millennia (*low confidence*). Projections of multi-millennial global mean sea level rise are consistent with reconstructed levels during past warm climate periods: *likely* 5–10 m higher than today around 125,000 years ago, when global temperatures were *very likely* 0.5°C–1.5°C higher than 1850–1900; and *very likely* 5–25 m higher roughly 3 million years ago, when global temperatures were 2.5°C–4°C higher (*medium confidence*).
{2.3, Cross-Chapter Box 2.4, 9.6, Box TS.2, Box TS.4, Box TS.9}

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33 The other sectoral emissions are calculated as the residual of the net land and ocean CO_2 uptake and the prescribed atmospheric CO_2 concentration changes in the CMIP6 simulations. These calculated emissions are net emissions and do not separate gross anthropogenic emissions from removals, which are included implicitly.

34 Low-likelihood, high-impact outcomes are those whose probability of occurrence is low or not well known (as in the context of deep uncertainty) but whose potential impacts on society and ecosystems could be high. A tipping point is a critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly. (Glossary) {1.4, Cross-Chapter Box 1.3, 4.7}

35 To compare to the 1986–2005 baseline period used in AR5 and SROCC, add 0.03 m to the global mean sea level rise estimates. To compare to the 1900 baseline period used in Figure SPM.8, add 0.16 m.

Human activities affect all the major climate system components, with some responding over decades and others over centuries

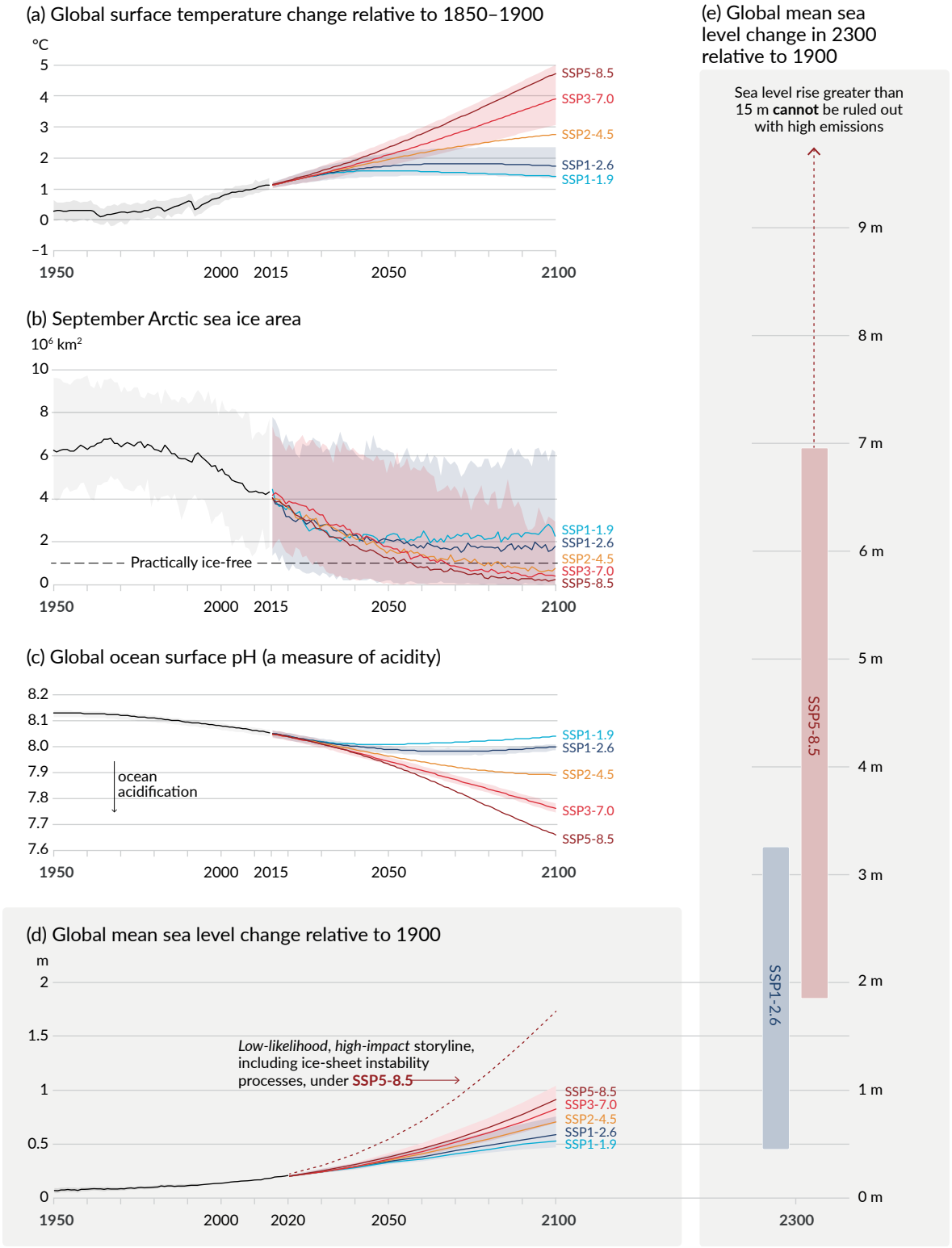

Figure SPM.8 | Selected indicators of global climate change under the five illustrative scenarios used in this Report

The projections for each of the five scenarios are shown in colour. Shades represent uncertainty ranges – more detail is provided for each panel below. The black curves represent the historical simulations (panels a, b, c) or the observations (panel d). Historical values are included in all graphs to provide context for the projected future changes.

Panel (a) Global surface temperature changes in °C relative to 1850–1900. These changes were obtained by combining Coupled Model Intercomparison Project Phase 6 (CMIP6) model simulations with observational constraints based on past simulated warming, as well as an updated assessment of equilibrium climate sensitivity (see Box SPM.1). Changes relative to 1850–1900 based on 20-year averaging periods are calculated by adding 0.85°C (the observed global surface temperature increase from 1850–1900 to 1995–2014) to simulated changes relative to 1995–2014. *Very likely* ranges are shown for SSP1-2.6 and SSP3-7.0.

Panel (b) September Arctic sea ice area in 10^6 km^2 based on CMIP6 model simulations. *Very likely* ranges are shown for SSP1-2.6 and SSP3-7.0. The Arctic is projected to be practically ice-free near mid-century under intermediate and high GHG emissions scenarios.

Panel (c) Global ocean surface pH (a measure of acidity) based on CMIP6 model simulations. *Very likely* ranges are shown for SSP1-2.6 and SSP3-7.0.

Panel (d) Global mean sea level change in metres, relative to 1900. The historical changes are observed (from tide gauges before 1992 and altimeters afterwards), and the future changes are assessed consistently with observational constraints based on emulation of CMIP, ice-sheet, and glacier models. *Likely* ranges are shown for SSP1-2.6 and SSP3-7.0. Only *likely* ranges are assessed for sea level changes due to difficulties in estimating the distribution of deeply uncertain processes. The dashed curve indicates the potential impact of these deeply uncertain processes. It shows the 83rd percentile of SSP5-8.5 projections that include low-likelihood, high-impact ice-sheet processes that cannot be ruled out; because of *low confidence* in projections of these processes, this curve does not constitute part of a *likely* range. Changes relative to 1900 are calculated by adding 0.158 m (observed global mean sea level rise from 1900 to 1995–2014) to simulated and observed changes relative to 1995–2014.

Panel (e) Global mean sea level change at 2300 in metres relative to 1900. Only SSP1-2.6 and SSP5-8.5 are projected at 2300, as simulations that extend beyond 2100 for the other scenarios are too few for robust results. The 17th–83rd percentile ranges are shaded. The dashed arrow illustrates the 83rd percentile of SSP5-8.5 projections that include low-likelihood, high-impact ice-sheet processes that cannot be ruled out.

Panels (b) and (c) are based on single simulations from each model, and so include a component of internal variability. Panels (a), (d) and (e) are based on long-term averages, and hence the contributions from internal variability are small.

{4.3; Figures 4.2, 4.8, and 4.11; 9.6; Figure 9.27; Figures TS.8 and TS.11; Box TS.4, Figure 1}

C. Climate Information for Risk Assessment and Regional Adaptation

Physical climate information addresses how the climate system responds to the interplay between human influence, natural drivers and internal variability. Knowledge of the climate response and the range of possible outcomes, including low-likelihood, high impact outcomes, informs climate services, the assessment of climate-related risks, and adaptation planning. Physical climate information at global, regional and local scales is developed from multiple lines of evidence, including observational products, climate model outputs and tailored diagnostics.

C.1 Natural drivers and internal variability will modulate human-caused changes, especially at regional scales and in the near term, with little effect on centennial global warming. These modulations are important to consider in planning for the full range of possible changes.

{1.4, 2.2, 3.3, Cross-Chapter Box 3.1, 4.4, 4.6, Cross-Chapter Box 4.1, Box 7.2, 8.3, 8.5, 9.2, 10.3, 10.4, 10.6, 11.3, 12.5, Atlas.4, Atlas.5, Atlas.8, Atlas.9, Atlas.10, Atlas.11, Cross-Chapter Box Atlas.2}

C.1.1 The historical global surface temperature record highlights that decadal variability has both enhanced and masked underlying human-caused long-term changes, and this variability will continue into the future (*very high confidence*). For example, internal decadal variability and variations in solar and volcanic drivers partially masked human-caused surface global warming during 1998–2012, with pronounced regional and seasonal signatures (*high confidence*). Nonetheless, the heating of the climate system continued during this period, as reflected in both the continued warming of the global ocean (*very high confidence*) and in the continued rise of hot extremes over land (*medium confidence*).
{1.4, 3.3, Cross-Chapter Box 3.1, 4.4, Box 7.2, 9.2, 11.3, Cross-Section Box TS.1} (Figure SPM.1)

C.1.2 Projected human-caused changes in mean climate and climatic impact-drivers (CIDs),[36] including extremes, will be either amplified or attenuated by internal variability (*high confidence*).[37] Near-term cooling at any particular location with respect to present climate could occur and would be consistent with the global surface temperature increase due to human influence (*high confidence*).
{1.4, 4.4, 4.6, 10.4, 11.3, 12.5, Atlas.5, Atlas.10, Atlas.11, TS.4.2}

36 Climatic impact-drivers (CIDs) are physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems. Depending on system tolerance, CIDs and their changes can be detrimental, beneficial, neutral, or a mixture of each across interacting system elements and regions (Glossary). CID types include heat and cold, wet and dry, wind, snow and ice, coastal and open ocean.

37 The main internal variability phenomena include El Niño–Southern Oscillation, Pacific Decadal Variability and Atlantic Multi-decadal Variability through their regional influence.

C.1.3 Internal variability has largely been responsible for the amplification and attenuation of the observed human-caused decadal-to-multi-decadal mean precipitation changes in many land regions (*high confidence*). At global and regional scales, near-term changes in monsoons will be dominated by the effects of internal variability (*medium confidence*). In addition to the influence of internal variability, near-term projected changes in precipitation at global and regional scales are uncertain because of model uncertainty and uncertainty in forcings from natural and anthropogenic aerosols (*medium confidence*).
{1.4, 4.4, 8.3, 8.5, 10.3, 10.4, 10.5, 10.6, Atlas.4, Atlas.8, Atlas.9, Atlas.10, Atlas.11, Cross-Chapter Box Atlas.2, TS.4.2, Box TS.6, Box TS.13}

C.1.4 Based on paleoclimate and historical evidence, it is *likely* that at least one large explosive volcanic eruption would occur during the 21st century.[38] Such an eruption would reduce global surface temperature and precipitation, especially over land, for one to three years, alter the global monsoon circulation, modify extreme precipitation and change many CIDs (*medium confidence*). If such an eruption occurs, this would therefore temporarily and partially mask human-caused climate change.
{2.2, 4.4, Cross-Chapter Box 4.1, 8.5, TS.2.1}

C.2 With further global warming, every region is projected to increasingly experience concurrent and multiple changes in climatic impact-drivers. Changes in several climatic impact-drivers would be more widespread at 2°C compared to 1.5°C global warming and even more widespread and/or pronounced for higher warming levels.
{8.2, 9.3, 9.5, 9.6, Box 10.3, 11.3, 11.4, 11.5, 11.6, 11.7, 11.9, Box 11.3, Box 11.4, Cross-Chapter Box 11.1, 12.2, 12.3, 12.4, 12.5, Cross-Chapter Box 12.1, Atlas.4, Atlas.5, Atlas.6, Atlas.7, Atlas.8, Atlas.9, Atlas.10, Atlas.11} (Table SPM.1, Figure SPM.9)

C.2.1 All regions[39] are projected to experience further increases in hot climatic impact-drivers (CIDs) and decreases in cold CIDs (*high confidence*). Further decreases are projected in permafrost; snow, glaciers and ice sheets; and lake and Arctic sea ice (*medium* to *high confidence*).[40] These changes would be larger at 2°C global warming or above than at 1.5°C (*high confidence*). For example, extreme heat thresholds relevant to agriculture and health are projected to be exceeded more frequently at higher global warming levels (*high confidence*).
{9.3, 9.5, 11.3, 11.9, Cross-Chapter Box 11.1, 12.3, 12.4, 12.5, Cross-Chapter Box 12.1, Atlas.4, Atlas.5, Atlas.6, Atlas.7, Atlas.8, Atlas.9, Atlas.10, Atlas.11, TS.4.3} (Table SPM.1, Figure SPM.9)

C.2.2 At 1.5°C global warming, heavy precipitation and associated flooding are projected to intensify and be more frequent in most regions in Africa and Asia (*high confidence*), North America (*medium* to *high confidence*)[40] and Europe (*medium confidence*). Also, more frequent and/or severe agricultural and ecological droughts are projected in a few regions in all inhabited continents except Asia compared to 1850–1900 (*medium confidence*); increases in meteorological droughts are also projected in a few regions (*medium confidence*). A small number of regions are projected to experience increases or decreases in mean precipitation (*medium confidence*).
{11.4, 11.5, 11.6, 11.9, Atlas.4, Atlas.5, Atlas.7, Atlas.8, Atlas.9, Atlas.10, Atlas.11, TS.4.3} (Table SPM.1)

C.2.3 At 2°C global warming and above, the level of confidence in and the magnitude of the change in droughts and heavy and mean precipitation increase compared to those at 1.5°C. Heavy precipitation and associated flooding events are projected to become more intense and frequent in the Pacific Islands and across many regions of North America and Europe (*medium* to *high confidence*).[40] These changes are also seen in some regions in Australasia and Central and South America (*medium confidence*). Several regions in Africa, South America and Europe are projected to experience an increase in frequency and/or severity of agricultural and ecological droughts with *medium* to *high confidence*;[40] increases are also projected in Australasia, Central and North America, and the Caribbean with *medium confidence*. A small number of regions in Africa, Australasia, Europe and North America are also projected to be affected by increases in hydrological droughts, and several regions are projected to be affected by increases or decreases in meteorological droughts, with more regions displaying an increase (*medium confidence*). Mean precipitation is projected to increase in all polar, northern European and northern North American regions, most Asian regions and two regions of South America (*high confidence*).
{11.4, 11.6, 11.9, Cross-Chapter Box 11.1, 12.4, 12.5, Cross-Chapter Box 12.1, Atlas.5, Atlas.7, Atlas.8, Atlas.9, Atlas.11, TS.4.3} (Table SPM.1, Figure SPM.5, Figure SPM.6, Figure SPM.9)

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38 Based on 2500 year reconstructions, eruptions more negative than –1 W m^{-2} occur on average twice per century.

39 Regions here refer to the AR6 WGI reference regions used in this Report to summarize information in sub-continental and oceanic regions. Changes are compared to averages over the last 20–40 years unless otherwise specified. {1.4, 12.4, Atlas.1}.

40 The specific level of confidence or likelihood depends on the region considered. Details can be found in the Technical Summary and the underlying Report.

C.2.4 More CIDs across more regions are projected to change at 2°C and above compared to 1.5°C global warming (*high confidence*). Region-specific changes include intensification of tropical cyclones and/or extratropical storms (*medium confidence*), increases in river floods (*medium* to *high confidence*),[40] reductions in mean precipitation and increases in aridity (*medium* to *high confidence*),[40] and increases in fire weather (*medium* to *high confidence*).[40] There is *low confidence* in most regions in potential future changes in other CIDs, such as hail, ice storms, severe storms, dust storms, heavy snowfall and landslides.
{11.7, 11.9, Cross-Chapter Box 11.1, 12.4, 12.5, Cross-Chapter Box 12.1, Atlas.4, Atlas.6, Atlas.7, Atlas.8, Atlas.10, TS.4.3.1, TS.4.3.2, TS.5} (Table SPM.1, Figure SPM.9)

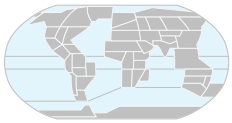
C.2.5 It is *very likely* to *virtually certain*[40] that regional mean relative sea level rise will continue throughout the 21st century, except in a few regions with substantial geologic land uplift rates. Approximately two-thirds of the global coastline has a projected regional relative sea level rise within ±20% of the global mean increase (*medium confidence*). Due to relative sea level rise, extreme sea level events that occurred once per century in the recent past are projected to occur at least annually at more than half of all tide gauge locations by 2100 (*high confidence*). Relative sea level rise contributes to increases in the frequency and severity of coastal flooding in low-lying areas and to coastal erosion along most sandy coasts (*high confidence*).
{9.6, 12.4, 12.5, Cross-Chapter Box 12.1, Box TS.4, TS.4.3} (Figure SPM.9)

C.2.6 Cities intensify human-induced warming locally, and further urbanization together with more frequent hot extremes will increase the severity of heatwaves (*very high confidence*). Urbanization also increases mean and heavy precipitation over and/or downwind of cities (*medium confidence*) and resulting runoff intensity (*high confidence*). In coastal cities, the combination of more frequent extreme sea level events (due to sea level rise and storm surge) and extreme rainfall/riverflow events will make flooding more probable (*high confidence*).
{8.2, Box 10.3, 11.3, 12.4, Box TS.14}

C.2.7 Many regions are projected to experience an increase in the probability of compound events with higher global warming (*high confidence*). In particular, concurrent heatwaves and droughts are *likely* to become more frequent. Concurrent extremes at multiple locations, including in crop-producing areas, become more frequent at 2°C and above compared to 1.5°C global warming (*high confidence*).
{11.8, Box 11.3, Box 11.4, 12.3, 12.4, Cross-Chapter Box 12.1, TS.4.3} (Table SPM.1)

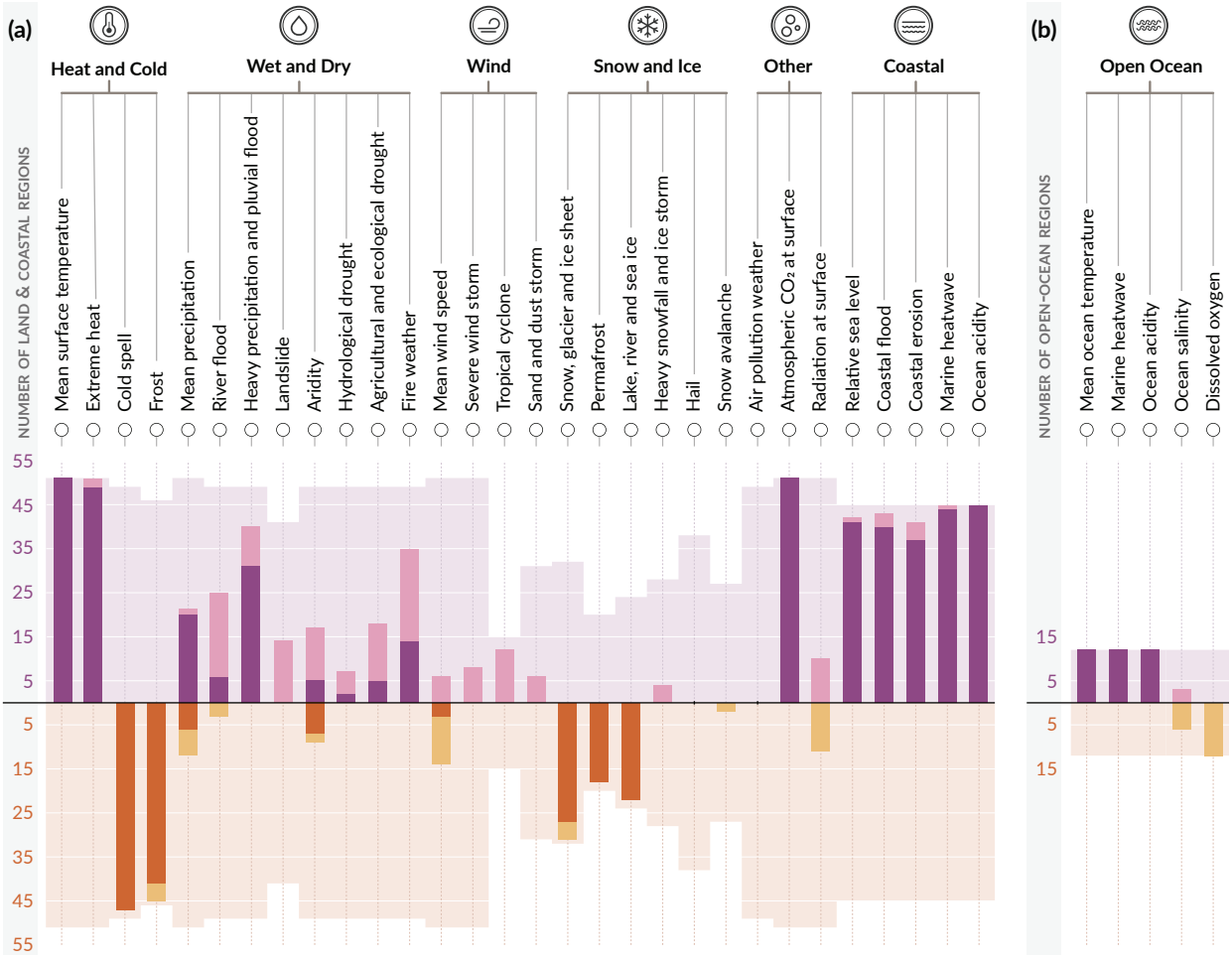
Multiple climatic impact-drivers are projected to change in all regions of the world

Climatic impact-drivers (CIDs) are physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems. Depending on system tolerance, CIDs and their changes can be detrimental, beneficial, neutral, or a mixture of each across interacting system elements and regions. The CIDs are grouped into seven types, which are summarized under the icons in the figure. All regions are projected to experience changes in at least 5 CIDs. Almost all (96%) are projected to experience changes in at least 10 CIDs and half in at least 15 CIDs. For many CID changes, there is wide geographical variation, and so each region is projected to experience a specific set of CID changes. Each bar in the chart represents a specific geographical set of changes that can be explored in the WGI Interactive Atlas.



interactive-atlas.ipcc.ch

Number of land & coastal regions (a) and **open-ocean regions** (b) where each **climatic impact-driver** (CID) is projected to increase or decrease with ***high*** *confidence* (dark shade) or ***medium*** *confidence* (light shade)



BAR CHART LEGEND

- Regions with ***high*** *confidence* increase
- Regions with ***medium*** *confidence* increase
- Regions with ***high*** *confidence* decrease
- Regions with ***medium*** *confidence* decrease

LIGHTER-SHADED 'ENVELOPE' LEGEND

The height of the lighter shaded 'envelope' behind each bar represents the maximum number of regions for which each CID is relevant. The envelope is symmetrical about the x-axis showing the maximum possible number of relevant regions for CID increase (upper part) or decrease (lower part).

ASSESSED FUTURE CHANGES

Changes refer to a 20–30 year period centred around 2050 and/or consistent with 2°C global warming compared to a similar period within 1960–2014 or 1850–1900.

Figure SPM.9 | Synthesis of the number of AR6 WGI reference regions where climatic impact-drivers are projected to change

A total of 35 climatic impact-drivers (CIDs) grouped into seven types are shown: heat and cold; wet and dry; wind; snow and ice; coastal; open ocean; and other. For each CID, the bar in the graph below displays the number of AR6 WGI reference regions where it is projected to change. The **colours** represent the direction of change and the level of confidence in the change: purple indicates an increase while brown indicates a decrease; darker and lighter shades refer to *high* and *medium confidence*, respectively. Lighter background colours represent the maximum number of regions for which each CID is broadly relevant.

Panel (a) shows the 30 CIDs relevant to the **land and coastal regions**, while **panel (b)** shows the five CIDs relevant to the **open-ocean regions**. Marine heatwaves and ocean acidity are assessed for coastal ocean regions in panel (a) and for open-ocean regions in panel (b). Changes refer to a 20–30-year period centred around 2050 and/or consistent with 2°C global warming compared to a similar period within 1960–2014, except for hydrological drought and agricultural and ecological drought, which is compared to 1850–1900. Definitions of the regions are provided in Sections 12.4 and Atlas.1 and the Interactive Atlas (see https://interactive-atlas.ipcc.ch/).

{11.9, 12.2, 12.4, Atlas.1, Table TS.5, Figures TS.22 and TS.25} (Table SPM.1)

C.3 Low-likelihood outcomes, such as ice-sheet collapse, abrupt ocean circulation changes, some compound extreme events, and warming substantially larger than the assessed *very likely* range of future warming, cannot be ruled out and are part of risk assessment.
{1.4, Cross-Chapter Box 1.3, 4.3, 4.4, 4.8, Cross-Chapter Box 4.1, 8.6, 9.2, Box 9.4, 11.8, Box 11.2, Cross-Chapter Box 12.1} (Table SPM.1)

C.3.1 If global warming exceeds the assessed *very likely* range for a given GHG emissions scenario, including low GHG emissions scenarios, global and regional changes in many aspects of the climate system, such as regional precipitation and other CIDs, would also exceed their assessed *very likely* ranges (*high confidence*). Such low-likelihood, high-warming outcomes are associated with potentially very large impacts, such as through more intense and more frequent heatwaves and heavy precipitation, and high risks for human and ecological systems, particularly for high GHG emissions scenarios.
{Cross-Chapter Box 1.3, 4.3, 4.4, 4.8, Box 9.4, Box 11.2, Cross-Chapter Box 12.1, TS.1.4, Box TS.3, Box TS.4} (Table SPM.1)

C.3.2 Low-likelihood, high-impact outcomes[34] could occur at global and regional scales even for global warming within the *very likely* range for a given GHG emissions scenario. The probability of low-likelihood, high-impact outcomes increases with higher global warming levels (*high confidence*). Abrupt responses and tipping points of the climate system, such as strongly increased Antarctic ice-sheet melt and forest dieback, cannot be ruled out (*high confidence*).
{1.4, 4.3, 4.4, 4.8, 5.4, 8.6, Box 9.4, Cross-Chapter Box 12.1, TS.1.4, TS.2.5, Box TS.3, Box TS.4, Box TS.9} (Table SPM.1)

C.3.3 If global warming increases, some compound extreme events[18] with low likelihood in past and current climate will become more frequent, and there will be a higher likelihood that events with increased intensities, durations and/or spatial extents unprecedented in the observational record will occur (*high confidence*).
{11.8, Box 11.2, Cross-Chapter Box 12.1, Box TS.3, Box TS.9}

C.3.4 The Atlantic Meridional Overturning Circulation is *very likely* to weaken over the 21st century for all emissions scenarios. While there is *high confidence* in the 21st century decline, there is only *low confidence* in the magnitude of the trend. There is *medium confidence* that there will not be an abrupt collapse before 2100. If such a collapse were to occur, it would *very likely* cause abrupt shifts in regional weather patterns and water cycle, such as a southward shift in the tropical rain belt, weakening of the African and Asian monsoons and strengthening of Southern Hemisphere monsoons, and drying in Europe.
{4.3, 8.6, 9.2, TS2.4, Box TS.3}

C.3.5 Unpredictable and rare natural events not related to human influence on climate may lead to low-likelihood, high-impact outcomes. For example, a sequence of large explosive volcanic eruptions within decades has occurred in the past, causing substantial global and regional climate perturbations over several decades. Such events cannot be ruled out in the future, but due to their inherent unpredictability they are not included in the illustrative set of scenarios referred to in this Report
{2.2, Cross-Chapter Box 4.1, Box TS.3} (Box SPM.1)

D. Limiting Future Climate Change

Since AR5, estimates of remaining carbon budgets have been improved by a new methodology first presented in SR1.5, updated evidence, and the integration of results from multiple lines of evidence. A comprehensive range of possible future air pollution controls in scenarios is used to consistently assess the effects of various assumptions on projections of climate and air pollution. A novel development is the ability to ascertain when climate responses to emissions reductions would become discernible above natural climate variability, including internal variability and responses to natural drivers.

D.1 From a physical science perspective, limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions. Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality.
{3.3, 4.6, 5.1, 5.2, 5.4, 5.5, 5.6, Box 5.2, Cross-Chapter Box 5.1, 6.7, 7.6, 9.6} (Figure SPM.10, Table SPM.2)

D.1.1 This Report reaffirms with *high confidence* the AR5 finding that there is a near-linear relationship between cumulative anthropogenic CO_2 emissions and the global warming they cause. Each 1000 $GtCO_2$ of cumulative CO_2 emissions is assessed to *likely* cause a 0.27°C to 0.63°C increase in global surface temperature with a best estimate of 0.45°C.[41] This is a narrower range compared to AR5 and SR1.5. This quantity is referred to as the transient climate response to cumulative CO_2 emissions (TCRE). This relationship implies that reaching net zero anthropogenic CO_2 emissions[42] is a requirement to stabilize human-induced global temperature increase at any level, but that limiting global temperature increase to a specific level would imply limiting cumulative CO_2 emissions to within a carbon budget.[43] {5.4, 5.5, TS.1.3, TS.3.3, Box TS.5} (Figure SPM.10)

Every tonne of CO_2 emissions adds to global warming

Global surface temperature increase since 1850–1900 (°C) as a function of cumulative CO_2 emissions ($GtCO_2$)

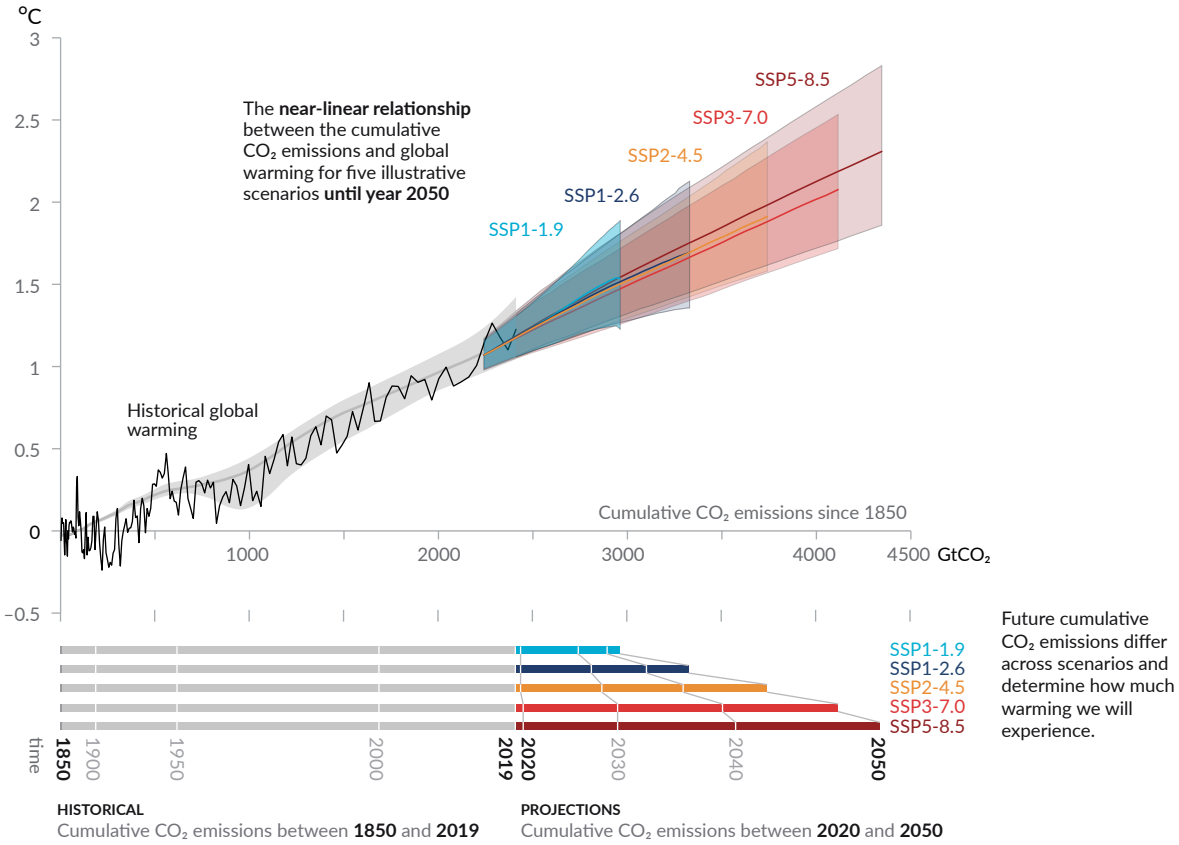


Figure SPM.10 | Near-linear relationship between cumulative CO_2 emissions and the increase in global surface temperature

Top panel: Historical data (thin black line) shows observed global surface temperature increase in °C since 1850–1900 as a function of historical cumulative carbon dioxide (CO_2) emissions in $GtCO_2$ from 1850 to 2019. The grey range with its central line shows a corresponding estimate of the historical human-caused surface warming (see Figure SPM.2). Coloured areas show the assessed *very likely* range of global surface temperature projections, and thick coloured central lines show the median estimate as a function of cumulative CO_2 emissions from 2020 until year 2050 for the set of illustrative scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5; see Figure SPM.4). Projections use the cumulative CO_2 emissions of each respective scenario, and the projected global warming includes the contribution from all anthropogenic forcers. The relationship is illustrated over the domain of cumulative CO_2 emissions for which there is *high confidence* that the transient climate response to cumulative CO_2 emissions (TCRE) remains constant, and for the time period from 1850 to 2050 over which global CO_2 emissions remain net positive under all illustrative scenarios, as there is *limited evidence* supporting the quantitative application of TCRE to estimate temperature evolution under net negative CO_2 emissions.

Bottom panel: Historical and projected cumulative CO_2 emissions in $GtCO_2$ for the respective scenarios.

{Section 5.5, Figure 5.31, Figure TS.18}

41 In the literature, units of °C per 1000 PgC (petagrams of carbon) are used, and the AR6 reports the TCRE *likely* range as 1.0°C to 2.3°C per 1000 PgC in the underlying report, with a best estimate of 1.65°C.

42 The condition in which anthropogenic carbon dioxide (CO_2) emissions are balanced by anthropogenic CO_2 removals over a specified period (Glossary).

43 The term 'carbon budget' refers to the maximum amount of cumulative net global anthropogenic CO_2 emissions that would result in limiting global warming to a given level with a given probability, taking into account the effect of other anthropogenic climate forcers. This is referred to as the total carbon budget when expressed starting from the pre-industrial period, and as the remaining carbon budget when expressed from a recent specified date (Glossary). Historical cumulative CO_2 emissions determine to a large degree warming to date, while future emissions cause future additional warming. The remaining carbon budget indicates how much CO_2 could still be emitted while keeping warming below a specific temperature level.

D.1.2 Over the period 1850–2019, a total of 2390 ± 240 (*likely* range) $GtCO_2$ of anthropogenic CO_2 was emitted. Remaining carbon budgets have been estimated for several global temperature limits and various levels of probability, based on the estimated value of TCRE and its uncertainty, estimates of historical warming, variations in projected warming from non-CO_2 emissions, climate system feedbacks such as emissions from thawing permafrost, and the global surface temperature change after global anthropogenic CO_2 emissions reach net zero.
{5.1, 5.5, Box 5.2, TS.3.3} (Table SPM.2)

Table SPM.2 | Estimates of historical carbon dioxide (CO_2) emissions and remaining carbon budgets. Estimated remaining carbon budgets are calculated from the beginning of 2020 and extend until global net zero CO_2 emissions are reached. They refer to CO_2 emissions, while accounting for the global warming effect of non-CO_2 emissions. Global warming in this table refers to human-induced global surface temperature increase, which excludes the impact of natural variability on global temperatures in individual years.
{Table 3.1, 5.5.1, 5.5.2, Box 5.2, Table 5.1, Table 5.7, Table 5.8, Table TS.3}

Global Warming Between 1850–1900 and 2010–2019 (°C)		Historical Cumulative CO_2 Emissions from 1850 to 2019 ($GtCO_2$)					
1.07 (0.8–1.3; likely range)		2390 (± 240; likely range)					
Approximate global warming relative to 1850–1900 until temperature limit (°C)[a]	Additional global warming relative to 2010–2019 until temperature limit (°C)	Estimated remaining carbon budgets from the beginning of 2020 ($GtCO_2$) *Likelihood of limiting global warming to temperature limit*[b]					Variations in reductions in non-CO_2 emissions[c]
		17%	*33%*	*50%*	*67%*	*83%*	
1.5	0.43	900	650	500	400	300	Higher or lower reductions in accompanying non-CO_2 emissions can increase or decrease the values on the left by 220 $GtCO_2$ or more
1.7	0.63	1450	1050	850	700	550	
2.0	0.93	2300	1700	1350	1150	900	

[a] Values at each 0.1°C increment of warming are available in Tables TS.3 and 5.8.

[b] This likelihood is based on the uncertainty in transient climate response to cumulative CO_2 emissions (TCRE) and additional Earth system feedbacks and provides the probability that global warming will not exceed the temperature levels provided in the two left columns. Uncertainties related to historical warming (±550 $GtCO_2$) and non-CO_2 forcing and response (±220 $GtCO_2$) are partially addressed by the assessed uncertainty in TCRE, but uncertainties in recent emissions since 2015 (±20 $GtCO_2$) and the climate response after net zero CO_2 emissions are reached (±420 $GtCO_2$) are separate.

[c] Remaining carbon budget estimates consider the warming from non-CO_2 drivers as implied by the scenarios assessed in SR1.5. The Working Group III Contribution to AR6 will assess mitigation of non-CO_2 emissions.

D.1.3 Several factors that determine estimates of the remaining carbon budget have been re-assessed, and updates to these factors since SR1.5 are small. When adjusted for emissions since previous reports, estimates of remaining carbon budgets are therefore of similar magnitude compared to SR1.5 but larger compared to AR5 due to methodological improvements.[44]
{5.5, Box 5.2, TS.3.3} (Table SPM.2)

D.1.4 Anthropogenic CO_2 removal (CDR) has the potential to remove CO_2 from the atmosphere and durably store it in reservoirs (*high confidence*). CDR aims to compensate for residual emissions to reach net zero CO_2 or net zero GHG emissions or, if implemented at a scale where anthropogenic removals exceed anthropogenic emissions, to lower surface temperature. CDR methods can have potentially wide-ranging effects on biogeochemical cycles and climate, which can either weaken or strengthen the potential of these methods to remove CO_2 and reduce warming, and can also influence water availability and quality, food production and biodiversity[45] (*high confidence*).
{5.6, Cross-Chapter Box 5.1, TS.3.3}

D.1.5 Anthropogenic CO_2 removal (CDR) leading to global net negative emissions would lower the atmospheric CO_2 concentration and reverse surface ocean acidification (*high confidence*). Anthropogenic CO_2 removals and emissions are partially

44 Compared to AR5, and when taking into account emissions since AR5, estimates in AR6 are about 300–350 $GtCO_2$ larger for the remaining carbon budget consistent with limiting warming to 1.5°C; for 2°C, the difference is about 400–500 $GtCO_2$.

45 Potential negative and positive effects of CDR for biodiversity, water and food production are methods-specific and are often highly dependent on local context, management, prior land use, and scale. IPCC Working Groups II and III assess the CDR potential and ecological and socio-economic effects of CDR methods in their AR6 contributions.

compensated by CO_2 release and uptake respectively, from or to land and ocean carbon pools (*very high confidence*). CDR would lower atmospheric CO_2 by an amount approximately equal to the increase from an anthropogenic emission of the same magnitude (*high confidence*). The atmospheric CO_2 decrease from anthropogenic CO_2 removals could be up to 10% less than the atmospheric CO_2 increase from an equal amount of CO_2 emissions, depending on the total amount of CDR (*medium confidence*).
{5.3, 5.6, TS.3.3}

D.1.6 If global net negative CO_2 emissions were to be achieved and be sustained, the global CO_2-induced surface temperature increase would be gradually reversed but other climate changes would continue in their current direction for decades to millennia (*high confidence*). For instance, it would take several centuries to millennia for global mean sea level to reverse course even under large net negative CO_2 emissions (*high confidence*).
{4.6, 9.6, TS.3.3}

D.1.7 In the five illustrative scenarios, simultaneous changes in CH_4, aerosol and ozone precursor emissions, which also contribute to air pollution, lead to a net global surface warming in the near and long term (*high confidence*). In the long term, this net warming is lower in scenarios assuming air pollution controls combined with strong and sustained CH_4 emissions reductions (*high confidence*). In the low and very low GHG emissions scenarios, assumed reductions in anthropogenic aerosol emissions lead to a net warming, while reductions in CH_4 and other ozone precursor emissions lead to a net cooling. Because of the short lifetime of both CH_4 and aerosols, these climate effects partially counterbalance each other, and reductions in CH_4 emissions also contribute to improved air quality by reducing global surface ozone (*high confidence*).
{6.7, Box TS.7} (Figure SPM.2, Box SPM.1)

D.1.8 Achieving global net zero CO_2 emissions, with anthropogenic CO_2 emissions balanced by anthropogenic removals of CO_2, is a requirement for stabilizing CO_2-induced global surface temperature increase. This is different from achieving net zero GHG emissions, where metric-weighted anthropogenic GHG emissions equal metric-weighted anthropogenic GHG removals. For a given GHG emissions pathway, the pathways of individual GHGs determine the resulting climate response,[46] whereas the choice of emissions metric[47] used to calculate aggregated emissions and removals of different GHGs affects what point in time the aggregated GHGs are calculated to be net zero. Emissions pathways that reach and sustain net zero GHG emissions defined by the 100-year global warming potential are projected to result in a decline in surface temperature after an earlier peak (*high confidence*).
{4.6, 7.6, Box 7.3, TS.3.3}

D.2 Scenarios with very low or low GHG emissions (SSP1-1.9 and SSP1-2.6) lead within years to discernible effects on greenhouse gas and aerosol concentrations and air quality, relative to high and very high GHG emissions scenarios (SSP3-7.0 or SSP5-8.5). Under these contrasting scenarios, discernible differences in trends of global surface temperature would begin to emerge from natural variability within around 20 years, and over longer time periods for many other climatic impact-drivers (*high confidence*).
{4.6, 6.6, 6.7, Cross-Chapter Box 6.1, 9.6, 11.2, 11.4, 11.5, 11.6, Cross-Chapter Box 11.1, 12.4, 12.5} (Figure SPM.8, Figure SPM.10)

D.2.1 Emissions reductions in 2020 associated with measures to reduce the spread of COVID-19 led to temporary but detectable effects on air pollution (*high confidence*) and an associated small, temporary increase in total radiative forcing, primarily due to reductions in cooling caused by aerosols arising from human activities (*medium confidence*). Global and regional climate responses to this temporary forcing are, however, undetectable above natural variability (*high confidence*). Atmospheric CO_2 concentrations continued to rise in 2020, with no detectable decrease in the observed CO_2 growth rate (*medium confidence*).[48]
{Cross-Chapter Box 6.1, TS.3.3}

D.2.2 Reductions in GHG emissions also lead to air quality improvements. However, in the near term,[49] even in scenarios with strong reduction of GHGs, as in the low and very low GHG emissions scenarios (SSP1-2.6 and SSP1-1.9), these improvements

46 A general term for how the climate system responds to a radiative forcing (Glossary).

47 The choice of emissions metric depends on the purposes for which gases or forcing agents are being compared. This Report contains updated emissions metric values and assesses new approaches to aggregating gases.

48 For other GHGs, there was insufficient literature available at the time of the assessment to assess detectable changes in their atmospheric growth rate during 2020.

49 Near term: 2021–2040.

are not sufficient in many polluted regions to achieve air quality guidelines specified by the World Health Organization (*high confidence*). Scenarios with targeted reductions of air pollutant emissions lead to more rapid improvements in air quality within years compared to reductions in GHG emissions only, but from 2040, further improvements are projected in scenarios that combine efforts to reduce air pollutants as well as GHG emissions, with the magnitude of the benefit varying between regions (*high confidence*).
{6.6, 6.7, Box TS.7}.

D.2.3 Scenarios with very low or low GHG emissions (SSP1-1.9 and SSP1-2.6) would have rapid and sustained effects to limit human-caused climate change, compared with scenarios with high or very high GHG emissions (SSP3-7.0 or SSP5-8.5), but early responses of the climate system can be masked by natural variability. For global surface temperature, differences in 20-year trends would *likely* emerge during the near term under a very low GHG emissions scenario (SSP1-1.9), relative to a high or very high GHG emissions scenario (SSP3-7.0 or SSP5-8.5). The response of many other climate variables would emerge from natural variability at different times later in the 21st century (*high confidence*).
{4.6, Cross-Section Box TS.1} (Figure SPM.8, Figure SPM.10)

D.2.4 Scenarios with very low and low GHG emissions (SSP1-1.9 and SSP1-2.6) would lead to substantially smaller changes in a range of CIDs[36] beyond 2040 than under high and very high GHG emissions scenarios (SSP3-7.0 and SSP5-8.5). By the end of the century, scenarios with very low and low GHG emissions would strongly limit the change of several CIDs, such as the increases in the frequency of extreme sea level events, heavy precipitation and pluvial flooding, and exceedance of dangerous heat thresholds, while limiting the number of regions where such exceedances occur, relative to higher GHG emissions scenarios (*high confidence*). Changes would also be smaller in very low compared to low GHG emissions scenarios, as well as for intermediate (SSP2-4.5) compared to high or very high GHG emissions scenarios (*high confidence*).
{9.6, 11.2, 11.3, 11.4, 11.5, 11.6, 11.9, Cross-Chapter Box 11.1, 12.4, 12.5, TS.4.3}

Summary for Policymakers

SPM

Summary for Policymakers

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A: Introduction

This Summary for Policymakers (SPM) presents key findings of the Working Group II (WGII) contribution to the Sixth Assessment Report (AR6) of the IPCC[1]. The report builds on the WGII contribution to the Fifth Assessment Report (AR5) of the IPCC, three Special Reports[2], and the Working Group I (WGI) contribution to the AR6 cycle.

This report recognizes the interdependence of climate, ecosystems and biodiversity[3], and human societies (Figure SPM.1) and integrates knowledge more strongly across the natural, ecological, social and economic sciences than earlier IPCC assessments. The assessment of climate change impacts and risks as well as adaptation is set against concurrently unfolding non-climatic global trends e.g., biodiversity loss, overall unsustainable consumption of natural resources, land and ecosystem degradation, rapid urbanisation, human demographic shifts, social and economic inequalities and a pandemic.

The scientific evidence for each key finding is found in the 18 chapters of the underlying report and in the 7 cross-chapter papers as well as the integrated synthesis presented in the Technical Summary (hereafter TS) and referred to in curly brackets {}. Based on scientific understanding, key findings can be formulated as statements of fact or associated with an assessed level of confidence using the IPCC calibrated language[4]. The WGII Global to Regional Atlas (Annex I) facilitates exploration of key synthesis findings across the WGII regions.

The concept of risk is central to all three AR6 Working Groups. A risk framing and the concepts of adaptation, vulnerability, exposure, resilience, equity and justice, and transformation provide alternative, overlapping, complementary, and widely used entry points to the literature assessed in this WGII report.

Across all three AR6 working groups, **risk**[5] provides a framework for understanding the increasingly severe, interconnected and often irreversible impacts of climate change on ecosystems, biodiversity, and human systems; differing impacts across regions, sectors and communities; and how to best reduce adverse consequences for current and future generations. In the context of climate change, risk can arise from the dynamic interactions among climate-related **hazards**[6] (see Working Group I), the **exposure**[7] and **vulnerability**[8] of affected human and ecological systems. The risk that can be introduced by human responses to climate change is a new aspect considered in the risk concept. This report identifies 127 key risks[9]. {1.3, 16.5}

The vulnerability of exposed human and natural systems is a component of risk, but also, independently, an important focus in the literature. Approaches to analysing and assessing vulnerability have evolved since previous IPCC assessments. Vulnerability is widely understood to differ within communities and across societies, regions and countries, also changing through time.

Adaptation[10] plays a key role in reducing exposure and vulnerability to climate change. Adaptation in ecological systems includes autonomous adjustments through ecological and evolutionary processes. In human systems, adaptation can be anticipatory or reactive, as well as incremental

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1 Decision IPCC/XLVI-3, The assessment covers scientific literature accepted for publication by 1 September 2021.

2 The three Special Reports are: 'Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (SR1.5)'; 'Climate Change and Land. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL)'; 'IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC)'.

3 Biodiversity: Biodiversity or biological diversity means the variability among living organisms from all sources including, among other things, terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems.

4 Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, e.g., *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Assessed likelihood is typeset in italics, e.g., *very likely*. This is consistent with AR5 and the other AR6 Reports.

5 Risk is defined as the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems.

6 Hazard is defined as the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. Physical climate conditions that may be associated with hazards are assessed in Working Group I as climatic impact-drivers.

7 Exposure is defined as the presence of people; livelihoods; species or ecosystems; environmental functions, services and resources; infrastructure; or economic, social or cultural assets in places and settings that could be adversely affected.

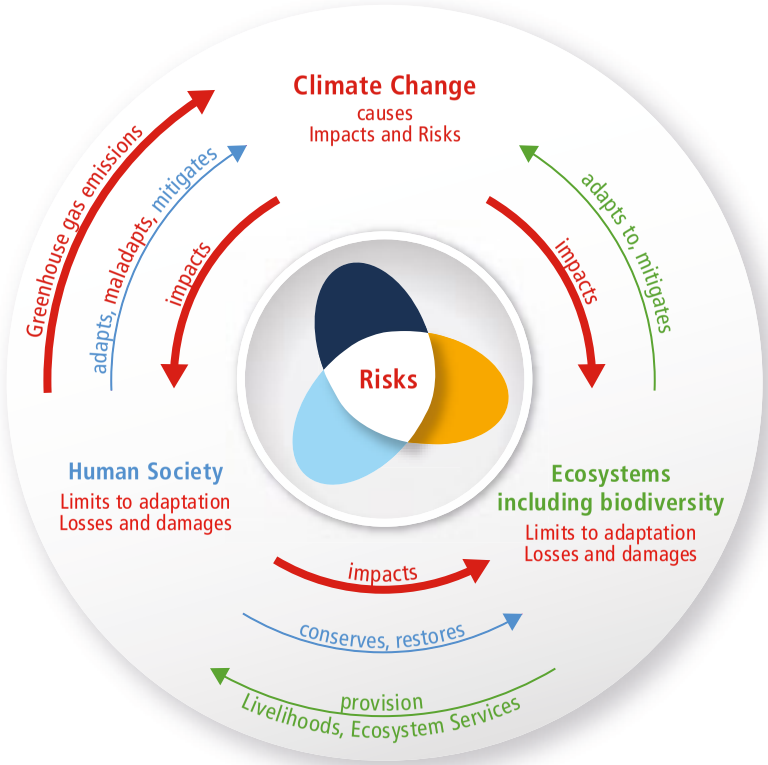
8 Vulnerability in this report is defined as the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

9 Key risks have potentially severe adverse consequences for humans and social-ecological systems resulting from the interaction of climate related hazards with vulnerabilities of societies and systems exposed.

10 Adaptation is defined, in human systems, as the process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities. In natural systems, adaptation is the process of adjustment to actual climate and its effects; human intervention may facilitate this.

From climate risk to climate resilient development: climate, ecosystems (including biodiversity) and human society as coupled systems

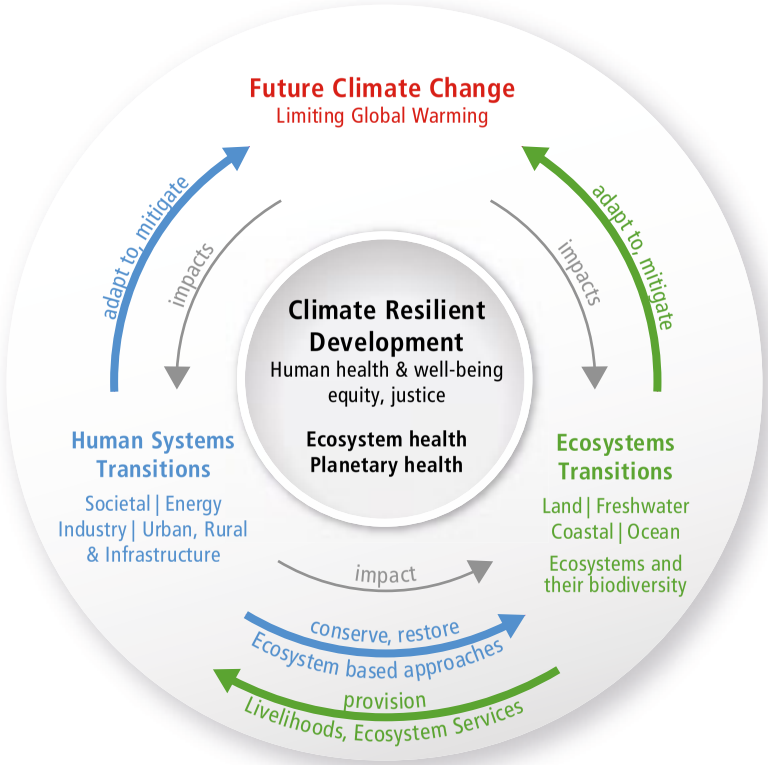
(a) Main interactions and trends



From urgent to timely action

Governance
Finance
Knowledge and capacity
Catalysing conditions
Technologies

(b) Options to reduce climate risks and establish resilience



The risk propeller shows that risk emerges from the overlap of:

Climate hazard(s)

Vulnerability

Exposure

...of human systems, ecosystems and their biodiversity

Figure SPM.1 | This report has a strong focus on the interactions among the coupled systems climate, ecosystems (including their biodiversity) and human society. These interactions are the basis of emerging risks from climate change, ecosystem degradation and biodiversity loss and, at the same time, offer opportunities for the future.

(a) Human society causes climate change. Climate change, through hazards, exposure and vulnerability generates impacts and risks that can surpass limits to adaptation and result in losses and damages. Human society can adapt to, maladapt and mitigate climate change, ecosystems can adapt and mitigate within limits. Ecosystems and their biodiversity provision livelihoods and ecosystem services. Human society impacts ecosystems and can restore and conserve them.

(b) Meeting the objectives of climate resilient development thereby supporting human, ecosystem and planetary health, as well as human well-being, requires society and ecosystems to move over (transition) to a more resilient state. The recognition of climate risks can strengthen adaptation and mitigation actions and transitions that reduce risks. Taking action is enabled by governance, finance, knowledge and capacity building, technology and catalysing conditions. Transformation entails system transitions strengthening the resilience of ecosystems and society (Section D). In a) arrow colours represent principle human society interactions **(blue)**, ecosystem (including biodiversity) interactions **(green)** and the impacts of climate change and human activities, including losses and damages, under continued climate change **(red)**. In b) arrow colours represent human system interactions **(blue)**, ecosystem (including biodiversity) interactions **(green)** and reduced impacts from climate change and human activities **(grey)**. {1.2, Figure 1.2, Figure TS. 2}

and/ or transformational. The latter changes the fundamental attributes of a social-ecological system in anticipation of climate change and its impacts. Adaptation is subject to hard and soft limits[11].

Resilience[12] in the literature has a wide range of meanings. Adaptation is often organized around resilience as bouncing back and returning to a previous state after a disturbance. More broadly the term describes not just the ability to maintain essential function, identity and structure, but also the capacity for transformation.

This report recognises the value of diverse forms of knowledge such as scientific, as well as Indigenous knowledge and local knowledge in understanding and evaluating climate adaptation processes and actions to reduce risks from human-induced climate change. AR6 highlights adaptation solutions which are effective, feasible[13], and conform to principles of justice[14]. The term climate justice, while used in different ways in different contexts by different communities, generally includes three principles: *distributive justice* which refers to the allocation of burdens and benefits among individuals, nations and generations; *procedural justice* which refers to who decides and participates in decision-making; and *recognition* which entails basic respect and robust engagement with and fair consideration of diverse cultures and perspectives.

Effectiveness refers to the extent to which an action reduces vulnerability and climate-related risk, increases resilience, and avoids maladaptation[15].

This report has a particular focus on transformation[16] and system transitions in energy; land, ocean, coastal and freshwater ecosystems; urban, rural and infrastructure; and industry and society. These transitions make possible the adaptation required for high levels of human health and well-being, economic and social resilience, ecosystem health[17], and planetary health[18] (Figure SPM.1). These system transitions are also important for achieving the low global warming levels (Working Group III) that would avoid many limits to adaptation[11]. The report also assesses economic and non-economic losses and damages[19]. This report labels the process of implementing mitigation and adaptation together in support of sustainable development for all as climate resilient development[20].

Box SPM.1 | AR6 Common Climate Dimensions, Global Warming Levels and Reference Periods

Assessments of climate risks consider possible future climate change, societal development and responses. This report assesses literature including that based on climate model simulations that are part of the fifth and sixth Coupled Model Intercomparison Project Phase (CMIP5, CMIP6) of the World Climate Research Programme. Future projections are driven by emissions and/or concentrations from illustrative Representative Concentration Pathways (RCPs)[21] and Shared Socioeconomic Pathways (SSPs)[22] scenarios, respectively[23]. Climate impacts literature is based primarily on climate projections assessed in AR5 or earlier, or assumed global warming levels, though some recent impacts literature uses newer projections based on the CMIP6 exercise. Given differences in the impacts literature regarding

11 Adaptation limits: The point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions.
Hard adaptation limit—No adaptive actions are possible to avoid intolerable risks.
Soft adaptation limit—Options may exist but are currently not available to avoid intolerable risks through adaptive action.

12 Resilience in this report is defined as the capacity of social, economic and ecosystems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure as well as biodiversity in case of ecosystems while also maintaining the capacity for adaptation, learning and transformation. Resilience is a positive attribute when it maintains such a capacity for adaptation, learning, and/or transformation.

13 Feasibility refers to the potential for an adaptation option to be implemented.

14 Justice is concerned with setting out the moral or legal principles of fairness and equity in the way people are treated, often based on the ethics and values of society. *Social justice* comprises just or fair relations within society that seek to address the distribution of wealth, access to resources, opportunity and support according to principles of justice and fairness. *Climate justice* comprises justice that links development and human rights to achieve a rights-based approach to addressing climate change.

15 Maladaptation refers to actions that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence.

16 Transformation refers to a change in the fundamental attributes of natural and human systems.

17 Ecosystem health: a metaphor used to describe the condition of an ecosystem, by analogy with human health. Note that there is no universally accepted benchmark for a healthy ecosystem. Rather, the apparent health status of an ecosystem is judged on the ecosystem's resilience to change, with details depending upon which metrics (such as species richness and abundance) are employed in judging it and which societal aspirations are driving the assessment.

18 Planetary health: a concept based on the understanding that human health and human civilisation depend on ecosystem health and the wise stewardship of ecosystems.

19 In this report, the term 'losses and damages' refers to adverse observed impacts and/or projected risks and can be economic and/or non-economic.

20 In the WGII report, climate resilient development refers to the process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development for all.

21 RCP-based scenarios are referred to as RCPy, where 'y' refers to the level of radiative forcing (in watts per square meter, or W m^{-2}) resulting from the scenario in the year 2100.

22 SSP-based scenarios are referred to as SSPx-y, where 'SSPx' refers to the Shared Socioeconomic Pathway describing the socioeconomic trends underlying the scenarios, and 'y' refers to the level of radiative forcing (in watts per square meter, or W m^{-2}) resulting from the scenario in the year 2100.

23 IPCC is neutral with regard to the assumptions underlying the SSPs, which do not cover all possible scenarios. Alternative scenarios may be considered or developed.

Box SPM.1 (continued)

socioeconomic details and assumptions, WGII chapters contextualize impacts with respect to exposure, vulnerability and adaptation as appropriate for their literature, this includes assessments regarding sustainable development and climate resilient development. There are many emissions and socioeconomic pathways that are consistent with a given global warming outcome. These represent a broad range of possibilities as available in the literature assessed that affect future climate change exposure and vulnerability. Where available, WGII also assesses literature that is based on an integrative SSP-RCP framework where climate projections obtained under the RCP scenarios are analysed against the backdrop of various illustrative SSPs[22]. The WGII assessment combines multiple lines of evidence including impacts modelling driven by climate projections, observations, and process understanding. {1.2, 16.5, 18.2, CCB CLIMATE, WGI AR6 SPM.C, WGI AR6 Box SPM.1, WGI AR6 1.6, WGI AR6 12, AR5 WGI}

A common set of reference years and time periods are adopted for assessing climate change and its impacts and risks: the reference period 1850–1900 approximates pre-industrial global surface temperature, and three future reference periods cover the near-term (2021–2040), mid-term (2041–2060) and long-term (2081–2100). {CCB CLIMATE}

Common levels of global warming relative to 1850–1900 are used to contextualize and facilitate analysis, synthesis and communication of assessed past, present and future climate change impacts and risks considering multiple lines of evidence. Robust geographical patterns of many variables can be identified at a given level of global warming, common to all scenarios considered and independent of timing when the global warming level is reached. {16.5, CCB CLIMATE, WGI AR6 Box SPM.1, WGI AR6 4.2, WGI AR6 CCB11.1}

WGI assessed the increase in global surface temperature is 1.09 [0.95 to 1.20][24] °C in 2011–2020 above 1850–1900. The estimated increase in global surface temperature since AR5 is principally due to further warming since 2003–2012 (+0.19 [0.16 to 0.22] °C).[25] Considering all five illustrative scenarios assessed by WGI, there is at least a greater than 50% likelihood that global warming will reach or exceed 1.5°C in the near-term, even for the very low greenhouse gas emissions scenario[26]. { WGI AR6 SPM A1.2, WGI AR6 SPM B1.3, WGI AR6 Table SPM.1, WGI AR6 CCB 2.3}

B: Observed and Projected Impacts and Risks

Since AR5, the knowledge base on observed and projected impacts and risks generated by climate hazards, exposure and vulnerability has increased with impacts attributed to climate change and key risks identified across the report. Impacts and risks are expressed in terms of their damages, harms, economic, and non-economic losses. Risks from observed vulnerabilities and responses to climate change are highlighted. Risks are projected for the near-term (2021–2040), the mid (2041–2060) and long term (2081–2100), at different global warming levels and for pathways that overshoot 1.5°C global warming level for multiple decades[27]. Complex risks result from multiple climate hazards occurring concurrently, and from multiple risks interacting, compounding overall risk and resulting in risks transmitting through interconnected systems and across regions.

24 In the WGI report, square brackets [x to y] are used to provide the assessed *very likely* range, or 90% interval.

25 Since AR5, methodological advances and new datasets have provided a more complete spatial representation of changes in surface temperature, including in the Arctic. These and other improvements have also increased the estimate of global surface temperature change by approximately 0.1°C, but this increase does not represent additional physical warming since AR5.

26 Global warming of 1.5°C relative to 1850–1900 would be exceeded during the 21st century under the intermediate, high and very high greenhouse gas emissions scenarios considered in this report (SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively). Under the five illustrative scenarios, in the near term (2021–2040), the 1.5°C global warming level is *very likely* to be exceeded under the very high greenhouse gas emissions scenario (SSP5-8.5), *likely* to be exceeded under the intermediate and high greenhouse gas emissions scenarios (SSP2-4.5 and SSP3-7.0), *more likely than not* to be exceeded under the low greenhouse gas emissions scenario (SSP1-2.6) and *more likely than not* to be reached under the very low greenhouse gas emissions scenario (SSP1-1.9). Furthermore, for the very low greenhouse gas emissions scenario (SSP1-1.9), it is *more likely than not* that global surface temperature would decline back to below 1.5°C toward the end of the 21st century, with a temporary overshoot of no more than 0.1°C above 1.5°C global warming.

27 Overshoot: In this report, pathways that first exceed a specified global warming level (usually 1.5°C, by more than 0.1°C), and then return to or below that level again before the end of a specified period of time (e.g., before 2100). Sometimes the magnitude and likelihood of the overshoot is also characterized. The overshoot duration can vary from at least one decade up to several decades.

Observed Impacts from Climate Change

B.1 Human-induced climate change, including more frequent and intense extreme events, has caused widespread adverse impacts and related losses and damages to nature and people, beyond natural climate variability. Some development and adaptation efforts have reduced vulnerability. Across sectors and regions the most vulnerable people and systems are observed to be disproportionately affected. The rise in weather and climate extremes has led to some irreversible impacts as natural and human systems are pushed beyond their ability to adapt. (*high confidence*) (Figure SPM.2) {TS B.1, Figure TS.5, 1.3, 2.3, 2.4, 2.6, 3.3, 3.4, 3.5, 4.2, 4.3, 5.2, 5.12, 6.2, 7.2, 8.2, 9.6, 9.8, 9.10, 9.11, 10.4, 11.3, 12.3, 12.4, 13.10, 14.4, 14.5, 15.3, 16.2, CCP1.2, CCP3.2, CCP4.1, CCP5.2, CCP6.2, CCP7.2, CCP7.3, CCB DISASTER, CCB EXTREMES, CCB ILLNESS, CCB MIGRATE, CCB NATURAL, CCB SLR}

B.1.1 Widespread, pervasive impacts to ecosystems, people, settlements, and infrastructure have resulted from observed increases in the frequency and intensity of climate and weather extremes, including hot extremes on land and in the ocean, heavy precipitation events, drought and fire weather (*high confidence*). Increasingly since AR5, these observed impacts have been attributed[28] to human-induced climate change particularly through increased frequency and severity of extreme events. These include increased heat-related human mortality (*medium confidence*), warm-water coral bleaching and mortality (*high confidence*), and increased drought-related tree mortality (*high confidence*). Observed increases in areas burned by wildfires have been attributed to human-induced climate change in some regions (*medium* to *high confidence*). Adverse impacts from tropical cyclones, with related losses and damages[19], have increased due to sea level rise and the increase in heavy precipitation (*medium confidence*). Impacts in natural and human systems from slow-onset processes[29] such as ocean acidification, sea level rise or regional decreases in precipitation have also been attributed to human induced climate change (*high confidence*). {1.3, 2.3, 2.4, 2.5, 3.2, 3.4, 3.5, 3.6, 4.2, 5.2, 5.4, 5.6, 5.12, 7.2, 9.6, 9.7, 9.8, 9.11, 11.3, Box 11.1, Box 11.2, Table 11.9, 12.3, 12.4, 13.3, 13.5, 13.10, 14.2, 14.5, 15.7, 15.8, 16.2, CCP1.2, CCP2.2, Box CCP5.1, CCP7.3, CCB DISASTER, CCB EXTREME, CCB ILLNESS, WGI AR6 SPM.3, WGI AR6 9, WGI AR6 11.3–11.8, SROCC Chapter 4}

B.1.2 Climate change has caused substantial damages, and increasingly irreversible losses, in terrestrial, freshwater and coastal and open ocean marine ecosystems (*high confidence*). The extent and magnitude of climate change impacts are larger than estimated in previous assessments (*high confidence*). Widespread deterioration of ecosystem structure and function, resilience and natural adaptive capacity, as well as shifts in seasonal timing have occurred due to climate change (*high confidence*), with adverse socioeconomic consequences (*high confidence*). Approximately half of the species assessed globally have shifted polewards or, on land, also to higher elevations (*very high confidence*). Hundreds of local losses of species have been driven by increases in the magnitude of heat extremes (*high confidence*), as well as mass mortality events on land and in the ocean (*very high confidence*) and loss of kelp forests (*high confidence*). Some losses are already irreversible, such as the first species extinctions driven by climate change (*medium confidence*). Other impacts are approaching irreversibility such as the impacts of hydrological changes resulting from the retreat of glaciers, or the changes in some mountain (*medium confidence*) and Arctic ecosystems driven by permafrost thaw (*high confidence*). (Figure SPM.2a). { TS B.1, Figure TS.5, 2.3, 2.4, 3.4, 3.5, 4.2, 4.3, 4.5, 9.6, 10.4, 11.3, 12.3, 12.8, 13.3, 13.4, 13.10, 14.4, 14.5, 14.6, 15.3, 16.2, CCP1.2, CCP3.2, CCP4.1, CCP5.2, Figure CCP5.4, CCP6.1, CCP6.2, CCP7.2, CCP7.3, CCB EXTREMES, CCB ILLNESS, CCB MOVING PLATE, CCB NATURAL, CCB PALEO, CCB SLR, SROCC 2.3}

B.1.3 Climate change including increases in frequency and intensity of extremes have reduced food and water security, hindering efforts to meet Sustainable Development Goals (*high confidence*). Although overall agricultural productivity has increased, climate change has slowed this growth over the past 50 years globally (*medium confidence*), related negative impacts were mainly in mid- and low latitude regions but positive impacts occurred in some high latitude regions (*high confidence*). Ocean warming and ocean acidification have adversely affected food production from shellfish aquaculture and fisheries in some oceanic regions (*high confidence*). Increasing weather and climate extreme events have exposed millions of people to acute food insecurity[30] and reduced water security, with the largest impacts observed in many locations and/or communities in Africa, Asia, Central and South America, Small Islands and the Arctic (*high confidence*). Jointly, sudden losses of food production and access to food compounded by decreased diet diversity have increased malnutrition in many communities (*high confidence*), especially for Indigenous Peoples, small-scale food producers and low-income households (*high confidence*), with children, elderly people and pregnant women particularly impacted (*high confidence*). Roughly half of the world's population currently experience severe water scarcity for at least some part of the year due to climatic and non-climatic drivers (*medium confidence*). (Figure SPM.2b) {3.5, 4.3, 4.4, Box 4.1, 5.2, 5.4, 5.8, 5.9, 5.12, 7.1, 7.2, 9.8, 10.4, 11.3, 12.3, 13.5, 14.4, 14.5, 15.3, 16.2, CCP5.2, CCP6.2}

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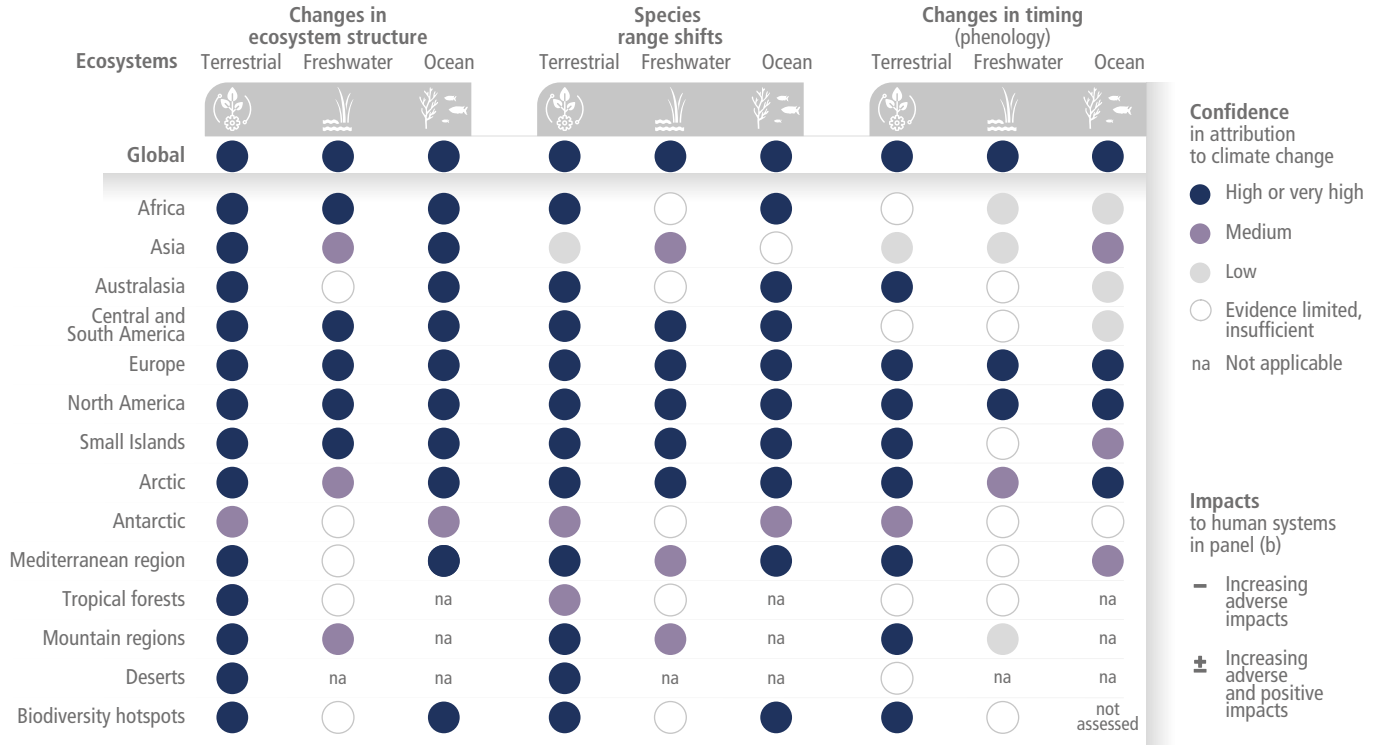
28 Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assessment of confidence. {Annex II Glossary, CWGB ATTRIB}

29 Impacts of climate change are caused by slow onset and extreme events. Slow onset events are described among the climatic-impact drivers of the WGI AR6 and refer to the risks and impacts associated with e.g., increasing temperature means, desertification, decreasing precipitation, loss of biodiversity, land and forest degradation, glacial retreat and related impacts, ocean acidification, sea level rise and salinization (https://interactive-atlas.ipcc.ch).

30 Acute food insecurity can occur at any time with a severity that threatens lives, livelihoods or both, regardless of the causes, context or duration, as a result of shocks risking determinants of food security and nutrition, and used to assess the need for humanitarian action.

Impacts of climate change are observed in many ecosystems and human systems worldwide

(a) Observed impacts of climate change on ecosystems



(b) Observed impacts of climate change on human systems

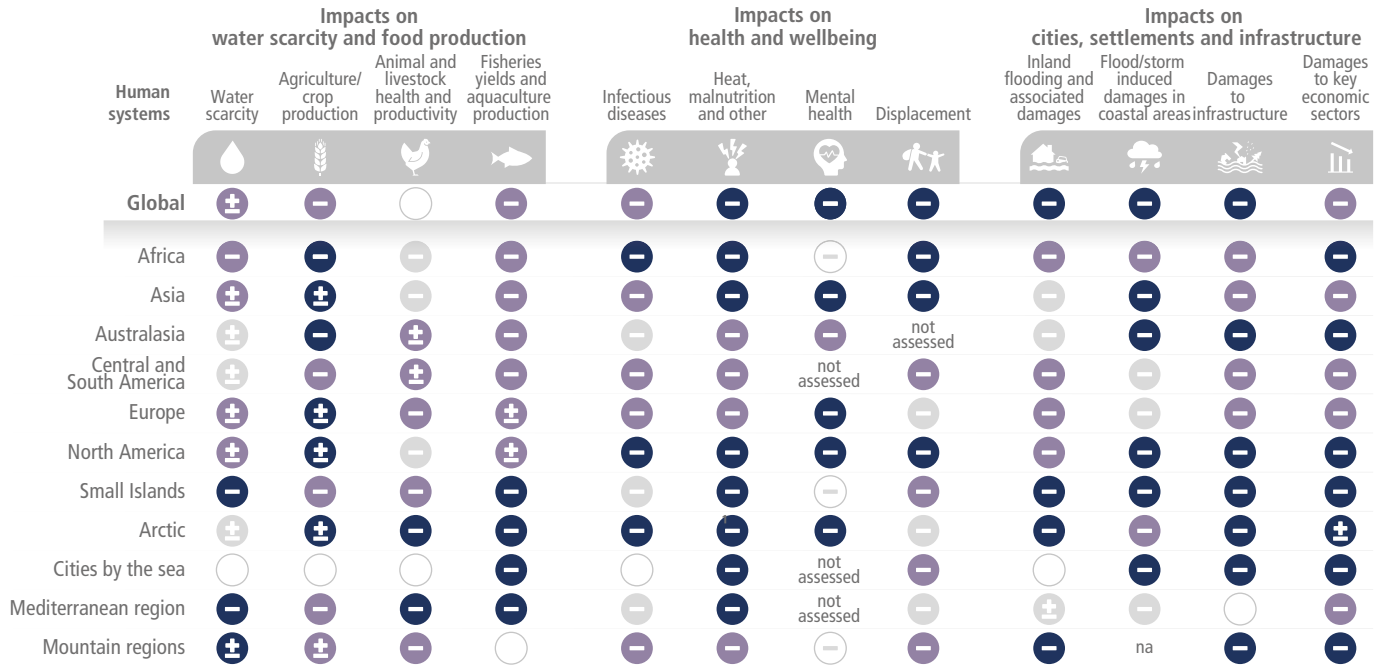


Figure SPM.2 | Observed global and regional impacts on ecosystems and human systems attributed to climate change. Confidence levels reflect uncertainty in attribution of the observed impact to climate change. Global assessments focus on large studies, multi-species, meta-analyses and large reviews. For that reason they can be assessed with higher confidence than regional studies, which may often rely on smaller studies that have more limited data. Regional assessments consider evidence on impacts across an entire region and do not focus on any country in particular.

(a) Climate change has already altered terrestrial, freshwater and ocean ecosystems at global scale, with multiple impacts evident at regional and local scales where there is sufficient literature to make an assessment. Impacts are evident on ecosystem structure, species geographic ranges and timing of seasonal life cycles (phenology) (for methodology and detailed references to chapters and cross-chapter papers see SMTS.1 and SMTS.1.1).

(b) Climate change has already had diverse adverse impacts on human systems, including on water security and food production, health and well-being, and cities, settlements and infrastructure. The + and – symbols indicate the direction of observed impacts, with a – denoting an increasing adverse impact and a ± denoting that, within a region or globally, both adverse and positive impacts have been observed (e.g., adverse impacts in one area or food item may occur with positive impacts in another area or food item). Globally, '–' denotes an overall adverse impact; 'Water scarcity' considers, e.g., water availability in general, groundwater, water quality, demand for water, drought in cities. Impacts on food production were assessed by excluding non-climatic drivers of production increases; Global assessment for agricultural production is based on the impacts on global aggregated production; 'Reduced animal and livestock health and productivity' considers, e.g., heat stress, diseases, productivity, mortality; 'Reduced fisheries yields and aquaculture production' includes marine and freshwater fisheries/production; 'Infectious diseases' include, e.g., water-borne and vector-borne diseases; 'Heat, malnutrition and other' considers, e.g., human heat-related morbidity and mortality, labour productivity, harm from wildfire, nutritional deficiencies; 'Mental health' includes impacts from extreme weather events, cumulative events, and vicarious or anticipatory events; 'Displacement' assessments refer to evidence of displacement attributable to climate and weather extremes; 'Inland flooding and associated damages' considers, e.g., river overflows, heavy rain, glacier outbursts, urban flooding; 'Flood/storm induced damages in coastal areas' include damages due to, e.g., cyclones, sea level rise, storm surges. Damages by key economic sectors are observed impacts related to an attributable mean or extreme climate hazard or directly attributed. Key economic sectors include standard classifications and sectors of importance to regions (for methodology and detailed references to chapters and cross-chapter papers see SMTS.1 and SMTS.1.2).

B.1.4 Climate change has adversely affected physical health of people globally (*very high confidence)* and mental health of people in the assessed regions (*very high confidence*). Climate change impacts on health are mediated through natural and human systems, including economic and social conditions and disruptions (*high confidence*). In all regions extreme heat events have resulted in human mortality and morbidity (*very high confidence*). The occurrence of climate-related food-borne and water-borne diseases has increased (*very high confidence*). The incidence of vector-borne diseases has increased from range expansion and/or increased reproduction of disease vectors (*high confidence*). Animal and human diseases, including zoonoses, are emerging in new areas (*high confidence*). Water and food-borne disease risks have increased regionally from climate-sensitive aquatic pathogens, including *Vibrio* spp. (*high confidence*), and from toxic substances from harmful freshwater cyanobacteria (*medium confidence*). Although diarrheal diseases have decreased globally, higher temperatures, increased rain and flooding have increased the occurrence of diarrheal diseases, including cholera (*very high confidence*) and other gastrointestinal infections (*high confidence*). In assessed regions, some mental health challenges are associated with increasing temperatures (*high confidence*), trauma from weather and climate extreme events (*very high confidence*), and loss of livelihoods and culture (*high confidence*). Increased exposure to wildfire smoke, atmospheric dust, and aeroallergens have been associated with climate-sensitive cardiovascular and respiratory distress (*high confidence*). Health services have been disrupted by extreme events such as floods (*high confidence*). {4.3, 5.12, 7.2, Box 7.3, 8.2, 8.3, Box 8.6, Figure 8.10, 9.10, Figure 9.33, Figure 9.34, 10.4, 11.3, 12.3, 13.7, 14.4, 14.5, Figure 14.8, 15.3, 16.2, CCP5.2, Table CCP5.1, CCP6.2, Figure CCP6.3, Table CCB ILLNESS.1}

B.1.5 In urban settings, observed climate change has caused impacts on human health, livelihoods and key infrastructure (*high confidence*). Multiple climate and non-climate hazards impact cities, settlements and infrastructure and sometimes coincide, magnifying damage (*high confidence*). Hot extremes including heatwaves have intensified in cities (*high confidence*), where they have also aggravated air pollution events (*medium confidence*) and limited functioning of key infrastructure (*high confidence*). Observed impacts are concentrated amongst the economically and socially marginalized urban residents, e.g., in informal settlements (*high confidence*). Infrastructure, including transportation, water, sanitation and energy systems have been compromised by extreme and slow-onset events, with resulting economic losses, disruptions of services and impacts to well-being (*high confidence*). {4.3, 6.2, 7.1, 7.2, 9.9, 10.4, 11.3, 12.3, 13.6, 14.5, 15.3, CCP2.2, CCP4.2, CCP5.2}

B.1.6 Overall adverse economic impacts attributable to climate change, including slow-onset and extreme weather events, have been increasingly identified (*medium confidence*). Some positive economic effects have been identified in regions that have benefited from lower energy demand as well as comparative advantages in agricultural markets and tourism (*high confidence*). Economic damages from climate change have been detected in climate-exposed sectors, with regional effects to agriculture, forestry, fishery, energy, and tourism (*high confidence*), and through outdoor labour productivity (*high confidence*). Some extreme weather events, such as tropical cyclones, have reduced economic growth in the short-term (*high confidence*). Non-climatic factors including some patterns of settlement, and siting of infrastructure have contributed to the exposure of more assets to extreme climate hazards increasing the magnitude of the losses (*high confidence*). Individual livelihoods have been affected through changes in agricultural productivity, impacts on human health and food security, destruction of homes and infrastructure, and loss of property and income, with adverse effects on gender and social equity (*high confidence*). {3.5, 4.2, 5.12, 6.2, 7.2, 8.2, 9.6, 10.4, 13.10, 14.5, Box 14.6, 16.2, Table 16.5, 18.3, CCP6.2, CCB GENDER, CWGB ECONOMICS}

B.1.7 Climate change is contributing to humanitarian crises where climate hazards interact with high vulnerability (*high confidence*). Climate and weather extremes are increasingly driving displacement in all regions (*high confidence*), with Small Island States disproportionately affected (*high confidence*). Flood and drought-related acute food insecurity and malnutrition have increased in Africa (*high confidence*) and Central and South America (*high confidence*). While non-climatic factors are the dominant drivers of existing intrastate violent conflicts, in some assessed regions extreme weather and climate events have had a small, adverse impact on their length, severity or frequency, but the statistical association is weak (*medium confidence*). Through displacement and involuntary migration from extreme weather and climate events, climate change has generated and perpetuated vulnerability (*medium confidence*). {4.2, 4.3, 5.4, 7.2, 9.8, Box 9.9, Box 10.4, 12.3, 12.5, 16.2, CCB DISASTER, CCB MIGRATE}

Vulnerability and Exposure of Ecosystems and People

B.2 Vulnerability of ecosystems and people to climate change differs substantially among and within regions (*very high confidence*), driven by patterns of intersecting socioeconomic development, unsustainable ocean and land use, inequity, marginalization, historical and ongoing patterns of inequity such as colonialism, and governance[31] (*high confidence*). Approximately 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change (*high confidence*). A high proportion of species is vulnerable to climate change (*high confidence*). Human and ecosystem vulnerability are interdependent (*high confidence*). Current unsustainable development patterns are increasing exposure of ecosystems and people to climate hazards (*high confidence*). {2.3, 2.4, 3.5, 4.3, 6.2, 8.2, 8.3, 9.4, 9.7, 10.4, 12.3, 14.5, 15.3, CCP5.2, CCP6.2, CCP7.3, CCP7.4, CCB GENDER}

B.2.1 Since AR5 there is increasing evidence that degradation and destruction of ecosystems by humans increases the vulnerability of people (*high confidence*). Unsustainable land-use and land cover change, unsustainable use of natural resources, deforestation, loss of biodiversity, pollution, and their interactions, adversely affect the capacities of ecosystems, societies, communities and individuals to adapt to climate change (*high confidence*). Loss of ecosystems and their services has cascading and long-term impacts on people globally, especially for Indigenous Peoples and local communities who are directly dependent on ecosystems, to meet basic needs (*high confidence*). {2.3, 2.5, 2.6, 3.5, 3.6, 4.2, 4.3, 4.6, 5.1, 5.4, 5.5, 5.7, 5.8, 7.2, 8.1, 8.2, 8.3, 8.4, 8.5, 9.6, 10.4, 11.3, 12.2, 12.5, 13.8, 14.4, 14.5, 15.3, CCP1.2, CCP1.3, CCP2.2, CCP3, CCP4.3, CCP5.2, CCP6.2, CCP7.2, CCP7.3, CCP7.4, CCB ILLNESS, CCB MOVING PLATE, CCB SLR}

B.2.2 Non-climatic human-induced factors exacerbate current ecosystem vulnerability to climate change (*very high confidence*). Globally, and even within protected areas, unsustainable use of natural resources, habitat fragmentation, and ecosystem damage by pollutants increase ecosystem vulnerability to climate change (*high confidence*). Globally, less than 15% of the land, 21% of the freshwater and 8% of the ocean are protected areas. In most protected areas, there is insufficient stewardship to contribute to reducing damage from, or increasing resilience to, climate change (*high confidence*). {2.4, 2.5, 2.6, 3.4, 3.6, 4.2, 4.3, 5.8, 9.6, 11.3, 12.3, 13.3, 13.4, 14.5, 15.3, CCP1.2, Figure CCP1.15, CCP2.1, CCP2.2, CCP4.2, CCP5.2, CCP6.2, CCP7.2, CCP7.3, CCB NATURAL}

B.2.3 Future vulnerability of ecosystems to climate change will be strongly influenced by the past, present and future development of human society, including from overall unsustainable consumption and production, and increasing demographic pressures, as well as persistent unsustainable use and management of land, ocean, and water (*high confidence*). Projected climate change, combined with non-climatic drivers, will cause loss and degradation of much of the world's forests (*high confidence*), coral reefs and low-lying coastal wetlands (*very high confidence*). While agricultural development contributes to food security, unsustainable agricultural expansion, driven in part by unbalanced diets[32], increases ecosystem and human vulnerability and leads to competition for land and/or water resources (*high confidence*). {2.2, 2.3, 2.4, 2.6, 3.4, 3.5, 3.6, 4.3, 4.5, 5.6, 5.12, 5.13, 7.2, 12.3, 13.3, 13.4, 13.10, 14.5, CCP1.2, CCP2.2, CCP5.2, CCP6.2, CCP7.2, CCP7.3, CCB HEALTH, CCB NATURAL}

B.2.4 Regions and people with considerable development constraints have high vulnerability to climatic hazards (*high confidence*). Global hotspots of high human vulnerability are found particularly in West-, Central- and East Africa, South Asia, Central and South America, Small Island Developing States and the Arctic (*high confidence*). Vulnerability is higher in locations with poverty, governance challenges and limited access to basic services and resources, violent conflict and high levels of climate-sensitive livelihoods (e.g., smallholder farmers, pastoralists, fishing communities) (*high confidence*). Between 2010–2020, human mortality from floods, droughts and storms was 15 times higher in highly vulnerable regions, compared to regions with very low vulnerability (*high confidence*). Vulnerability at different spatial levels is exacerbated by inequity and marginalization linked to gender, ethnicity, low income or combinations thereof (*high confidence*), especially for many Indigenous Peoples and local communities (*high confidence*). Present development challenges causing high vulnerability are influenced by historical and ongoing patterns of inequity such as colonialism, especially for many Indigenous Peoples and local communities (*high confidence*). {4.2, 5.12, 6.2, 6.4, 7.1, 7.2, Box 7.1, 8.2, 8.3, Box 8.4, Figure 8.6, Box 9.1, 9.4, 9.7, 9.9, 10.3, 10.4, 10.6, 12.3, 12.5, Box 13.2, 14.4, 15.3, 15.6, 16.2, CCP6.2, CCP7.4}

B.2.5 Future human vulnerability will continue to concentrate where the capacities of local, municipal and national governments, communities and the private sector are least able to provide infrastructures and basic services (*high confidence*). Under the global trend of urbanization, human vulnerability will also concentrate in informal settlements and rapidly growing smaller settlements (*high*

31 Governance: The structures, processes and actions through which private and public actors interact to address societal goals. This includes formal and informal institutions and the associated norms, rules, laws and procedures for deciding, managing, implementing and monitoring policies and measures at any geographic or political scale, from global to local.

32 Balanced diets feature plant-based foods, such as those based on coarse grains, legumes fruits and vegetables, nuts and seeds, and animal-source foods produced in resilient, sustainable and low-greenhouse gas emissions systems, as described in SRCCL.

confidence). In rural areas vulnerability will be heightened by compounding processes including high emigration, reduced habitability and high reliance on climate-sensitive livelihoods (*high confidence*). Key infrastructure systems including sanitation, water, health, transport, communications and energy will be increasingly vulnerable if design standards do not account for changing climate conditions (*high confidence*). Vulnerability will also rapidly rise in low-lying Small Island Developing States and atolls in the context of sea level rise and in some mountain regions, already characterised by high vulnerability due to high dependence on climate-sensitive livelihoods, rising population displacement, the accelerating loss of ecosystem services and limited adaptive capacities (*high confidence*). Future exposure to climatic hazards is also increasing globally due to socioeconomic development trends including migration, growing inequality and urbanization *(high confidence*). {4.5, 5.5, 6.2, 7.2, 8.3, 9.9, 9.11, 10.3, 10.4, 12.3, 12.5, 13.6, 14.5, 15.3, 15.4, 16.5, CCP2.3, CCP4.3, CCP5.2, CCP5.3, CCP5.4, CCP6.2, CCB MIGRATE}

Risks in the near term (2021–2040)

B.3 Global warming, reaching 1.5°C in the near-term, would cause unavoidable increases in multiple climate hazards and present multiple risks to ecosystems and humans (*very high confidence*). The level of risk will depend on concurrent near-term trends in vulnerability, exposure, level of socioeconomic development and adaptation (*high confidence*). Near-term actions that limit global warming to close to 1.5°C would substantially reduce projected losses and damages related to climate change in human systems and ecosystems, compared to higher warming levels, but cannot eliminate them all (*very high confidence*). (Figure SPM.3, Box SPM.1) {16.4, 16.5, 16.6, CCP1.2, CCP5.3, CCB SLR, WGI AR6 SPM B1.3, WGI AR6 Table SPM.1}

B.3.1 Near-term warming and increased frequency, severity and duration of extreme events will place many terrestrial, freshwater, coastal and marine ecosystems at high or very high risks of biodiversity loss (*medium to very high confidence*, depending on ecosystem). Near-term risks for biodiversity loss are moderate to high in forest ecosystems (*medium confidence*), kelp and seagrass ecosystems (*high* to *very high confidence*), and high to very high in Arctic sea-ice and terrestrial ecosystems (*high confidence*) and warm-water coral reefs (*very high confidence*). Continued and accelerating sea level rise will encroach on coastal settlements and infrastructure (*high confidence*) and commit low-lying coastal ecosystems to submergence and loss (*medium confidence*). If trends in urbanisation in exposed areas continue, this will exacerbate the impacts, with more challenges where energy, water and other services are constrained (*medium confidence*). The number of people at risk from climate change and associated loss of biodiversity will progressively increase (*medium confidence*). Violent conflict and, separately, migration patterns, in the near-term will be driven by socioeconomic conditions and governance more than by climate change (*medium confidence*). (Figure SPM.3) {2.5, 3.4, 4.6, 6.2, 7.3, 8.7, 9.2, 9.9, 11.6, 12.5, 13.6, 13.10, 14.6, 15.3, 16.5, 16.6, CCP1.2, CCP2.1, CCP2.2, CCP5.3, CCP6.2, CCP6.3, CCB MIGRATE, CCB SLR}

B.3.2 In the near term, climate-associated risks to natural and human systems depend more strongly on changes in their vulnerability and exposure than on differences in climate hazards between emissions scenarios (*high confidence*). Regional differences exist, and risks are highest where species and people exist close to their upper thermal limits, along coastlines, in close association with ice or seasonal rivers (*high confidence*). Risks are also high where multiple non-climate drivers persist or where vulnerability is otherwise elevated (*high confidence*). Many of these risks are unavoidable in the near-term, irrespective of emissions scenario (*high confidence*). Several risks can be moderated with adaptation (*high confidence*). (Figure SPM.3, Section C) {2.5, 3.3, 3.4, 4.5, 6.2, 7.1, 7.3, 8.2, 11.6, 12.4, 13.6, 13.7, 13.10, 14.5, 16.4, 16.5, CCP2.2, CCP4.3, CCP5.3, CCB SLR, WGI AR6 Table SPM.1}

B.3.3 Levels of risk for all Reasons for Concern (RFC) are assessed to become high to very high at lower global warming levels than in AR5 (*high confidence*). Between 1.2°C and 4.5°C global warming level very high risks emerge in all five RFCs compared to just two RFCs in AR5 (*high confidence*). Two of these transitions from high to very high risk are associated with near-term warming: risks to unique and threatened systems at a median value of 1.5 [1.2 to 2.0] °C (*high confidence*) and risks associated with extreme weather events at a median value of 2.0 [1.8 to 2.5] °C (*medium confidence*). Some key risks contributing to the RFCs are projected to lead to widespread, pervasive, and potentially irreversible impacts at global warming levels of 1.5–2°C if exposure and vulnerability are high and adaptation is low (*medium confidence*). Near-term actions that limit global warming to close to 1.5°C would substantially reduce projected losses and damages related to climate change in human systems and ecosystems, compared to higher warming levels, but cannot eliminate them all (*very high confidence*). (Figure SPM.3b) {16.5, 16.6, CCB SLR}

Mid to Long-term Risks (2041–2100)

B.4 Beyond 2040 and depending on the level of global warming, climate change will lead to numerous risks to natural and human systems (*high confidence*). For 127 identified key risks, assessed mid- and long-term impacts are up to multiple times higher than currently observed (*high confidence*). The magnitude and rate of climate change and associated risks depend strongly on near-term mitigation and adaptation actions, and projected adverse impacts and related losses and damages escalate with every increment of global warming (*very high confidence*). (Figure SPM.3) {2.5, 3.4, 4.4, 5.2, 6.2, 7.3, 8.4, 9.2, 10.2, 11.6, 12.4, 13.2, 13.3, 13.4, 13.5, 13.6, 13.7, 13.8, 14.6, 15.3, 16.5, 16.6, CCP1.2, CCP2.2, CCP3.3, CCP4.3, CCP5.3, CCP6.3, CCP7.3}

B.4.1 Biodiversity loss and degradation, damages to and transformation of ecosystems are already key risks for every region due to past global warming and will continue to escalate with every increment of global warming (*very high confidence*). In terrestrial ecosystems, 3 to 14% of species assessed[33] will *likely* face very high risk of extinction[34] at global warming levels of 1.5°C, increasing up to 3 to 18% at 2°C, 3 to 29% at 3°C, 3 to 39% at 4°C, and 3 to 48% at 5°C. In ocean and coastal ecosystems, risk of biodiversity loss ranges between moderate and very high by 1.5°C global warming level and is moderate to very high by 2°C but with more ecosystems at high and very high risk (*high confidence*), and increases to high to very high across most ocean and coastal ecosystems by 3°C (*medium* to *high confidence*, depending on ecosystem). Very high extinction risk for endemic species in biodiversity hotspots is projected to at least double from 2% between 1.5°C and 2°C global warming levels and to increase at least tenfold if warming rises from 1.5°C to 3°C (*medium confidence*). (Figure SPM.3c, d, f) {2.4, 2.5, 3.4, 3.5,12.3, 12.5, Table 12.6, 13.4, 13.10, 16.4, 16.6, CCP1.2, Figure CCP1.6, Figure CCP1.7, CCP5.3, CCP6.3, CCB PALEO}

B.4.2 Risks in physical water availability and water-related hazards will continue to increase by the mid- to long-term in all assessed regions, with greater risk at higher global warming levels (*high confidence*). At approximately 2°C global warming, snowmelt water availability for irrigation is projected to decline in some snowmelt dependent river basins by up to 20%, and global glacier mass loss of 18 ± 13% is projected to diminish water availability for agriculture, hydropower, and human settlements in the mid- to long-term, with these changes projected to double with 4°C global warming (*medium confidence*). In Small Islands, groundwater availability is threatened by climate change (*high confidence*). Changes to streamflow magnitude, timing and associated extremes are projected to adversely impact freshwater ecosystems in many watersheds by the mid- to long-term across all assessed scenarios (*medium confidence*). Projected increases in direct flood damages are higher by 1.4 to 2 times at 2°C and 2.5 to 3.9 times at 3°C compared to 1.5°C global warming without adaptation (*medium confidence*). At global warming of 4°C, approximately 10% of the global land area is projected to face increases in both extreme high and low river flows in the same location, with implications for planning for all water use sectors (*medium confidence*). Challenges for water management will be exacerbated in the near, mid and long term, depending on the magnitude, rate and regional details of future climate change and will be particularly challenging for regions with constrained resources for water management (*high confidence*). {2.3, 4.4, 4.5, Box 4.2, Figure 4.20, 15.3, CCP5.3, CCB DISASTER, SROCC 2.3}

B.4.3 Climate change will increasingly put pressure on food production and access, especially in vulnerable regions, undermining food security and nutrition (*high confidence*). Increases in frequency, intensity and severity of droughts, floods and heatwaves, and continued sea level rise will increase risks to food security (*high confidence*) in vulnerable regions from moderate to high between 1.5°C and 2°C global warming level, with no or low levels of adaptation (*medium confidence*). At 2°C or higher global warming level in the mid-term, food security risks due to climate change will be more severe, leading to malnutrition and micro-nutrient deficiencies, concentrated in Sub-Saharan Africa, South Asia, Central and South America and Small Islands (*high confidence).* Global warming will progressively weaken soil health and ecosystem services such as pollination, increase pressure from pests and diseases, and reduce marine animal biomass, undermining food productivity in many regions on land and in the ocean (*medium confidence*). At 3°C or higher global warming level in the long term, areas exposed to climate-related hazards will expand substantially compared with 2°C or lower global warming level (*high confidence*), exacerbating regional disparity in food security risks (*high confidence*). (Figure SPM.3) {1.1, 3.3, 4.5, 5.2, 5.4, 5.5, 5.8, 5.9, 5.12, 7.3, 8.3, 9.11, 13.5, 15.3, 16.5, 16.6, CCB MOVING PLATE, CCB SLR}

33 Numbers of species assessed are in the tens of thousands globally.

34 The term 'very high risks of extinction' is used here consistently with the IUCN categories and criteria and equates with 'critically endangered'.

B.4.4 Climate change and related extreme events will significantly increase ill health and premature deaths from the near- to long-term (*high confidence*). Globally, population exposure to heatwaves will continue to increase with additional warming, with strong geographical differences in heat-related mortality without additional adaptation (*very high confidence*). Climate-sensitive food-borne, water-borne, and vector-borne disease risks are projected to increase under all levels of warming without additional adaptation (*high confidence*). In particular, dengue risk will increase with longer seasons and a wider geographic distribution in Asia, Europe, Central and South America and sub-Saharan Africa, potentially putting additional billions of people at risk by the end of the century (*high confidence*). Mental health challenges, including anxiety and stress, are expected to increase under further global warming in all assessed regions, particularly for children, adolescents, elderly, and those with underlying health conditions (*very high confidence*). {4.5, 5.12, Box 5.10, 7.3, Figure 7.9, 8.4, 9.10, Figure 9.32, Figure 9.35, 10.4, Figure 10.11, 11.3, 12.3, Figure 12.5, Figure 12.6, 13.7, Figure 13.23, Figure 13.24, 14.5, 15.3, CCP6.2}

B.4.5 Climate change risks to cities, settlements and key infrastructure will rise rapidly in the mid- and long-term with further global warming, especially in places already exposed to high temperatures, along coastlines, or with high vulnerabilities (*high confidence*). Globally, population change in low-lying cities and settlements will lead to approximately a billion people projected to be at risk from coastal-specific climate hazards in the mid-term under all scenarios, including in Small Islands (*high confidence*). The population potentially exposed to a 100-year coastal flood is projected to increase by about 20% if global mean sea level rises by 0.15 m relative to 2020 levels; this exposed population doubles at a 0.75 m rise in mean sea level and triples at 1.4 m without population change and additional adaptation (*medium confidence*). Sea level rise poses an existential threat for some Small Islands and some low-lying coasts (*medium confidence*). By 2100 the value of global assets within the future 1-in-100 year coastal floodplains is projected to be between US$7.9 and US$12.7 trillion (2011 value) under RCP4.5, rising to between US$8.8 and US$14.2 trillion under RCP8.5 (*medium confidence*). Costs for maintenance and reconstruction of urban infrastructure, including building, transportation, and energy will increase with global warming level (*medium confidence*), the associated functional disruptions are projected to be substantial particularly for cities, settlements and infrastructure located on permafrost in cold regions and on coasts (*high confidence*). {6.2, 9.9, 10.4, 13.6, 13.10, 15.3, 16.5, CCP2.1, CCP2.2, CCP5.3, CCP6.2, CCB SLR, SROCC 2.3, SROCC CCB9}

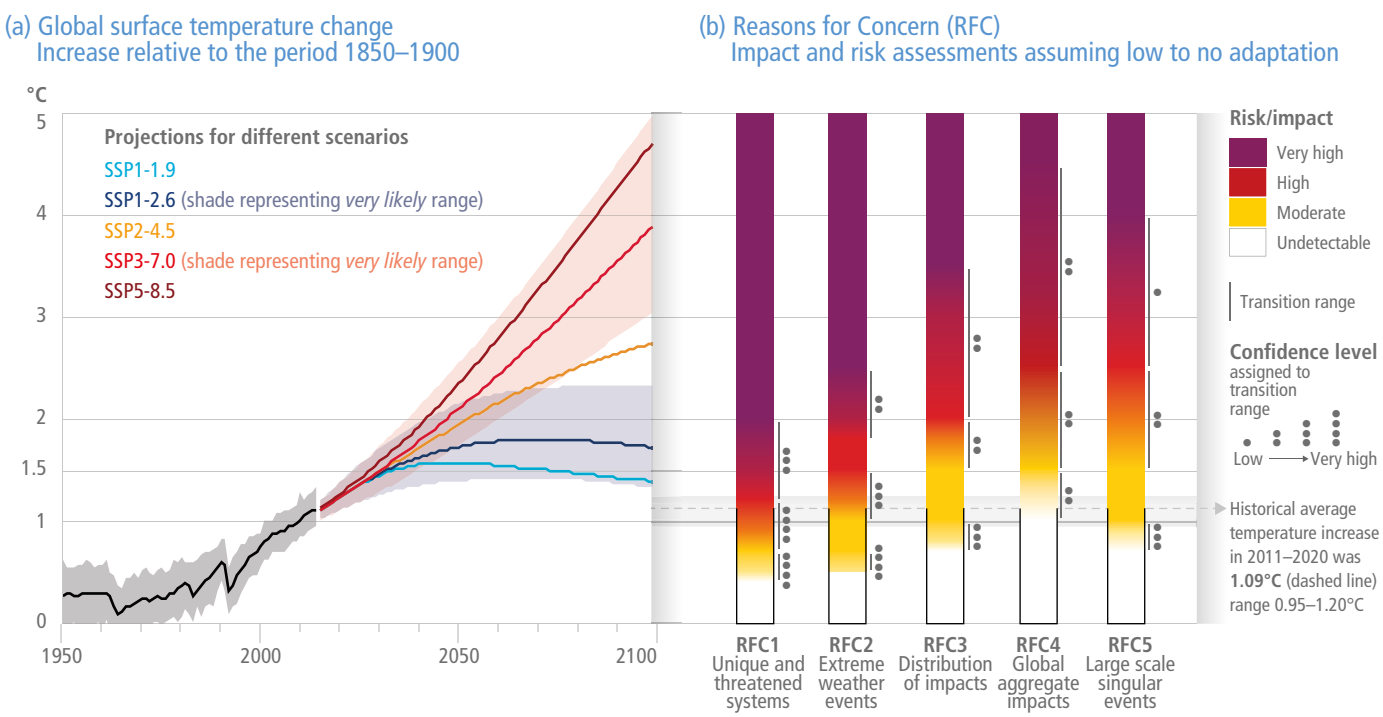
B.4.6 Projected estimates of global aggregate net economic damages generally increase non-linearly with global warming levels (*high confidence*).[35] The wide range of global estimates, and the lack of comparability between methodologies, does not allow for identification of a robust range of estimates (*high confidence*). The existence of higher estimates than assessed in AR5 indicates that global aggregate economic impacts could be higher than previous estimates (*low confidence*).[36] Significant regional variation in aggregate economic damages from climate change is projected (*high confidence*) with estimated economic damages per capita for developing countries often higher as a fraction of income (*high confidence*). Economic damages, including both those represented and those not represented in economic markets, are projected to be lower at 1.5°C than at 3°C or higher global warming levels (*high confidence*). {4.4, 9.11, 11.5, 13.10, Box 14.6, 16.5, CWGB ECONOMIC}

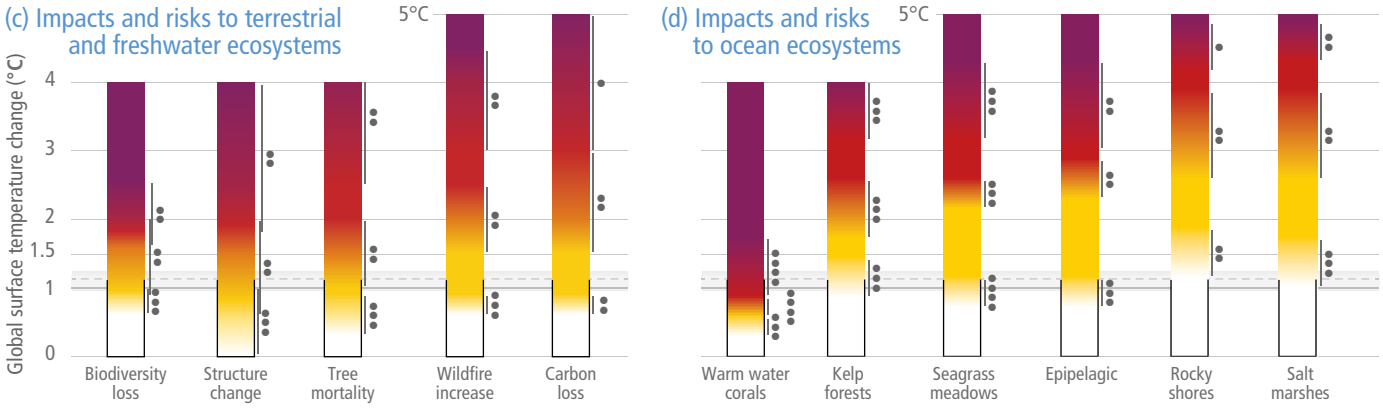
B.4.7 In the mid- to long-term, displacement will increase with intensification of heavy precipitation and associated flooding, tropical cyclones, drought and, increasingly, sea level rise (*high confidence*). At progressive levels of warming, involuntary migration from regions with high exposure and low adaptive capacity would occur (*medium confidence*). Compared to other socioeconomic factors the influence of climate on conflict is assessed as relatively weak (*high confidence*). Along long-term socioeconomic pathways that reduce non-climatic drivers, risk of violent conflict would decline (*medium confidence*). At higher global warming levels, impacts of weather and climate extremes, particularly drought, by increasing vulnerability will increasingly affect violent intrastate conflict (*medium confidence*). {TS B.7.4, 7.3, 16.5, CCB MIGRATE }

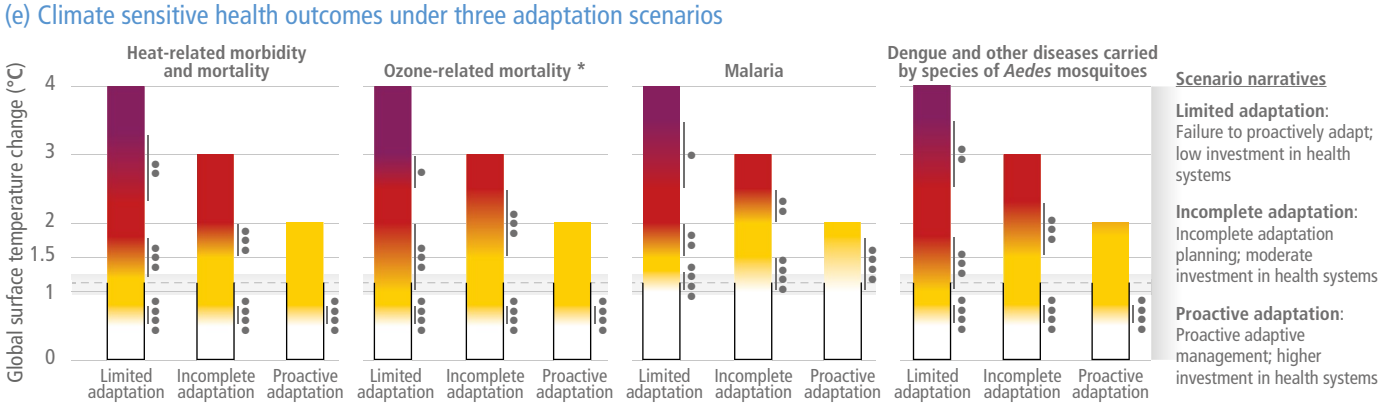
35 The assessment found estimated rates of increase in projected global economic damages that were both greater than linear and less than linear as global warming level increases. There is evidence that some regions could benefit from low levels of warming (*high confidence*). {CWGB ECONOMIC}

36 *Low confidence* assigned due to the assessed lack of comparability and robustness of global aggregate economic damage estimates. {CWGB ECONOMIC}

Global and regional risks for increasing levels of global warming







* Mortality projections include demographic trends but do not include future efforts to improve air quality that reduce ozone concentrations.

(f) Examples of regional key risks

Absence of risk diagrams does not imply absence of risks within a region. The development of synthetic diagrams for Small Islands, Asia and Central and South America was limited due to the paucity of adequately downscaled climate projections, with uncertainty in the direction of change, the diversity of climatologies and socioeconomic contexts across countries within a region, and the resulting few numbers of impact and risk projections for different warming levels.

The risks listed are of at least *medium confidence* level:

Small Islands
- Loss of terrestrial, marine and coastal biodiversity and ecosystem services
- Loss of lives and assets, risk to food security and economic disruption due to destruction of settlements and infrastructure
- Economic decline and livelihood failure of fisheries, agriculture, tourism and from biodiversity loss from traditional agroecosystems
- Reduced habitability of reef and non-reef islands leading to increased displacement
- Risk to water security in almost every small island

North America
- Climate-sensitive mental health outcomes, human mortality and morbidity due to increasing average temperature, weather and climate extremes, and compound climate hazards
- Risk of degradation of marine, coastal and terrestrial ecosystems, including loss of biodiversity, function, and protective services
- Risk to freshwater resources with consequences for ecosystems, reduced surface water availability for irrigated agriculture, other human uses, and degraded water quality
- Risk to food and nutritional security through changes in agriculture, livestock, hunting, fisheries, and aquaculture productivity and access
- Risks to well-being, livelihoods and economic activities from cascading and compounding climate hazards, including risks to coastal cities, settlements and infrastructure from sea level rise

Europe
- Risks to people, economies and infrastructures due to coastal and inland flooding
- Stress and mortality to people due to increasing temperatures and heat extremes
- Marine and terrestrial ecosystems disruptions
- Water scarcity to multiple interconnected sectors
- Losses in crop production, due to compound heat and dry conditions, and extreme weather

Central and South America
- Risk to water security
- Severe health effects due to increasing epidemics, in particular vector-borne diseases
- Coral reef ecosystems degradation due to coral bleaching
- Risk to food security due to frequent/extreme droughts
- Damages to life and infrastructure due to floods, landslides, sea level rise, storm surges and coastal erosion

Australasia
- Degradation of tropical shallow coral reefs and associated biodiversity and ecosystem service values
- Loss of human and natural systems in low-lying coastal areas due to sea level rise
- Impact on livelihoods and incomes due to decline in agricultural production
- Increase in heat-related mortality and morbidity for people and wildlife
- Loss of alpine biodiversity in Australia due to less snow

Asia
- Urban infrastructure damage and impacts on human well-being and health due to flooding, especially in coastal cities and settlements
- Biodiversity loss and habitat shifts as well as associated disruptions in dependent human systems across freshwater, land, and ocean ecosystems
- More frequent, extensive coral bleaching and subsequent coral mortality induced by ocean warming and acidification, sea level rise, marine heat waves and resource extraction
- Decline in coastal fishery resources due to sea level rise, decrease in precipitation in some parts and increase in temperature
- Risk to food and water security due to increased temperature extremes, rainfall variability and drought

Africa
- Species extinction and reduction or irreversible loss of ecosystems and their services, including freshwater, land and ocean ecosystems
- Risk to food security, risk of malnutrition (micronutrient deficiency), and loss of livelihood due to reduced food production from crops, livestock and fisheries
- Risks to marine ecosystem health and to livelihoods in coastal communities
- Increased human mortality and morbidity due to increased heat and infectious diseases (including vector-borne and diarrhoeal diseases)
- Reduced economic output and growth, and increased inequality and poverty rates
- Increased risk to water and energy security due to drought and heat

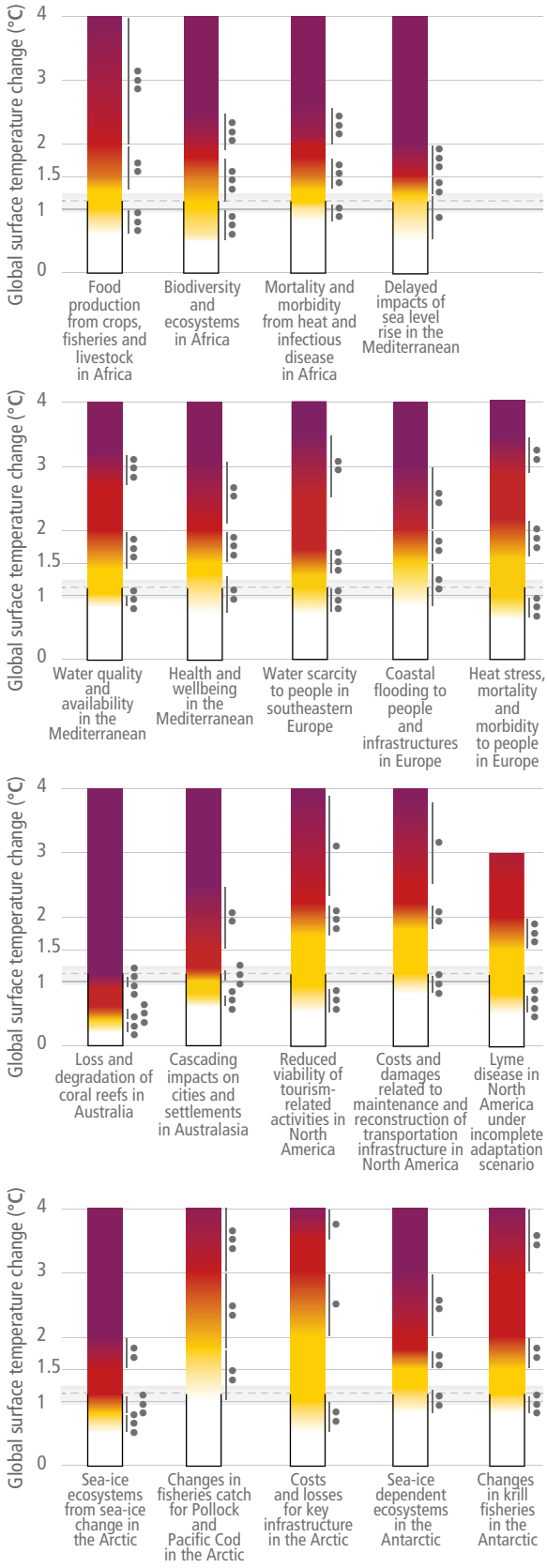


Figure SPM.3 | Synthetic diagrams of global and sectoral assessments and examples of regional key risks. Diagrams show the change in the levels of impacts and risks assessed for global warming of 0–5°C global surface temperature change relative to pre-industrial period (1850–1900) over the range.

(a) Global surface temperature changes in °C relative to 1850–1900. These changes were obtained by combining CMIP6 model simulations with observational constraints based on past simulated warming, as well as an updated assessment of equilibrium climate sensitivity (Box SPM.1). Changes relative to 1850–1900 based on 20-year averaging periods are calculated by adding 0.85°C (the observed global surface temperature increase from 1850–1900 to 1995–2014) to simulated changes relative to 1995–2014. *Very likely* ranges are shown for SSP1-2.6 and SSP3-7.0 (WGI AR6 Figure SPM.8). Assessments were carried out at the global scale for (b), (c), (d) and (e).

(b) The Reasons for Concern (RFC) framework communicates scientific understanding about accrual of risk for five broad categories. Diagrams are shown for each RFC, assuming low to no adaptation (i.e., adaptation is fragmented, localized and comprises incremental adjustments to existing practices). However, the transition to a very high risk level has an emphasis on irreversibility and adaptation limits. Undetectable risk level (white) indicates no associated impacts are detectable and attributable to climate change; moderate risk (yellow) indicates associated impacts are both detectable and attributable to climate change with at least *medium confidence*, also accounting for the other specific criteria for key risks; high risk (red) indicates severe and widespread impacts that are judged to be high on one or more criteria for assessing key risks; and very high risk level (purple) indicates very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks. The horizontal line denotes the present global warming of 1.09°C which is used to separate the observed, past impacts below the line from the future projected risks above it. RFC1: Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its Indigenous Peoples, mountain glaciers and biodiversity hotspots. RFC2: Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heatwaves, heavy rain, drought and associated wildfires, and coastal flooding. RFC3: Distribution of impacts: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. RFC4: Global aggregate impacts: impacts to socio-ecological systems that can be aggregated globally into a single metric, such as monetary damages, lives affected, species lost or ecosystem degradation at a global scale. RFC5: Large-scale singular events: relatively large, abrupt and sometimes irreversible changes in systems caused by global warming, such as ice sheet disintegration or thermohaline circulation slowing. Assessment methods are described in SM16.6 and are identical to AR5, but are enhanced by a structured approach to improve robustness and facilitate comparison between AR5 and AR6.

Risks for **(c)** terrestrial and freshwater ecosystems and **(d)** ocean ecosystems. For c) and d), diagrams shown for each risk assume low to no adaptation. The transition to a very high risk level has an emphasis on irreversibility and adaptation limits.

(e) Climate-sensitive human health outcomes under three scenarios of adaptation effectiveness. The assessed projections were based on a range of scenarios, including SRES, CMIP5, and ISIMIP, and, in some cases, demographic trends. The diagrams are truncated at the nearest whole ºC within the range of temperature change in 2100 under three SSP scenarios in panel (a).

(f) Examples of regional key risks. Risks identified are of at least *medium confidence* level. Key risks are identified based on the magnitude of adverse consequences (pervasiveness of the consequences, degree of change, irreversibility of consequences, potential for impact thresholds or tipping points, potential for cascading effects beyond system boundaries); likelihood of adverse consequences; temporal characteristics of the risk; and ability to respond to the risk, e.g., by adaptation. The full set of 127 assessed global and regional key risks is given in SM16.7. Diagrams are provided for some risks. The development of synthetic diagrams for Small Islands, Asia and Central and South America were limited by the availability of adequately downscaled climate projections, with uncertainty in the direction of change, the diversity of climatologies and socioeconomic contexts across countries within a region, and the resulting low number of impact and risk projections for different warming levels. Absence of risks diagrams does not imply absence of risks within a region. (Box SPM.1) {Figure TS.4, Figure 2.11, Figure SM3.1, Figure 7.9, Figure 9.6, Figure 11.6, Figure 13.28, 16.5, 16.6, Figure 16.15, SM16.3, SM16.4, SM16.5, SM16.6 (methodologies), SM16.7, Figure CCP4.8, Figure CCP4.10, Figure CCP6.5, WGI AR6 2, WGI AR6 SPM A.1.2, WGI AR6 Figure SPM.8}

Complex, Compound and Cascading Risks

B.5 Climate change impacts and risks are becoming increasingly complex and more difficult to manage. Multiple climate hazards will occur simultaneously, and multiple climatic and non-climatic risks will interact, resulting in compounding overall risk and risks cascading across sectors and regions. Some responses to climate change result in new impacts and risks. (*high confidence*) {1.3, 2.4, Box 2.2, Box 9.5, 11.5, 13.5, 14.6, Box 15.1, CCP1.2, CCP2.2, CCB COVID, CCB DISASTER, CCB INTEREG, CCB SRM, }

B.5.1 Concurrent and repeated climate hazards occur in all regions, increasing impacts and risks to health, ecosystems, infrastructure, livelihoods and food (*high confidence*). Multiple risks interact, generating new sources of vulnerability to climate hazards, and compounding overall risk (*high confidence*). Increasing concurrence of heat and drought events are causing crop production losses and tree mortality (*high confidence*). Above 1.5°C global warming increasing concurrent climate extremes will increase risk of simultaneous crop losses of maize in major food-producing regions, with this risk increasing further with higher global warming levels (*medium confidence*). Future sea level rise combined with storm surge and heavy rainfall will increase compound flood risks (*high confidence*). Risks to health and food production will be made more severe from the interaction of sudden food production losses from heat and drought, exacerbated by heat-induced labour productivity losses (*high confidence*). These interacting impacts will increase food prices, reduce household incomes, and lead to health risks of malnutrition and climate-related mortality with no or low levels of adaptation, especially in tropical regions (*high confidence*). Risks to food safety from climate change will further compound the risks to health by increasing food contamination of crops from mycotoxins and contamination of seafood from harmful algal blooms, mycotoxins, and chemical contaminants (*high confidence*). {Figure TS.10c, 5.2, 5.4, 5.8, 5.9, 5.11, 5.12, 7.2, 7.3, 9.8, 9.11, 10.4, 11.3, 11.5, 12.3, 13.5, 14.5, 15.3, Box 15.1, 16.6, CCP1.2, CCP6.2, , WGI AR6 SPM A.3.1, WGI AR6 SPM A.3.2, WGI AR6 SPM C.2.7}

B.5.2 Adverse impacts from climate hazards and resulting risks are cascading across sectors and regions (*high confidence*), propagating impacts along coasts and urban centres (*medium confidence*) and in mountain regions (*high confidence*). These hazards and cascading risks also trigger tipping points in sensitive ecosystems and in significantly and rapidly changing social-ecological systems impacted by ice melt, permafrost thaw and changing hydrology in polar regions (*high confidence*). Wildfires, in many regions, have affected ecosystems and species, people and their built assets, economic activity, and health (*medium to high confidence*). In cities and

settlements, climate impacts to key infrastructure are leading to losses and damages across water and food systems, and affect economic activity, with impacts extending beyond the area directly impacted by the climate hazard (*high confidence*). In Amazonia, and in some mountain regions, cascading impacts from climatic (e.g., heat) and non-climatic stressors (e.g., land use change) will result in irreversible and severe losses of ecosystem services and biodiversity at 2°C global warming level and beyond (*medium confidence*). Unavoidable sea level rise will bring cascading and compounding impacts resulting in losses of coastal ecosystems and ecosystem services, groundwater salinisation, flooding and damages to coastal infrastructure that cascade into risks to livelihoods, settlements, health, well-being, food and water security, and cultural values in the near to long-term (*high confidence*). (Figure SPM.3) {Figure TS.10, 2.5, 3.4, 3.5, Box 7.3, Box 8.7, Box 9.4, 11.5, Box 11.1, 12.3, 13.9, 14.6, 15.3, 16.5, 16.6, CCP1.2, CCP2.2, CCP5.2, CCP5.3, CCP6.2, CCP6.3, Box CCP6.1, Box CCP6.2, CCB EXTREMES, WGI AR6 Figure SPM.8d}

B.5.3 Weather and climate extremes are causing economic and societal impacts across national boundaries through supply-chains, markets, and natural resource flows, with increasing transboundary risks projected across the water, energy and food sectors (*high confidence*). Supply chains that rely on specialized commodities and key infrastructure can be disrupted by weather and climate extreme events. Climate change causes the redistribution of marine fish stocks, increasing risk of transboundary management conflicts among fisheries users, and negatively affecting equitable distribution of food provisioning services as fish stocks shift from lower to higher latitude regions, thereby increasing the need for climate-informed transboundary management and cooperation (*high confidence*). Precipitation and water availability changes increases the risk of planned infrastructure projects, such as hydropower in some regions, having reduced productivity for food and energy sectors including across countries that share river basins (*medium confidence*). {Figure TS.10e-f, 3.4, 3.5, 4.5, 5.8, 5.13, 6.2, 9.4, Box 9.5,14.5, Box 14.5, Box 14.6, CCP5.3, CCB DISASTER, CCB EXTREMES, CCB INTEREG, CCB MOVING PLATE}

B.5.4 Risks arise from some responses that are intended to reduce the risks of climate change, including risks from maladaptation and adverse side effects of some emissions reduction and carbon dioxide removal measures (*high confidence*). Deployment of afforestation of naturally unforested land, or poorly implemented bioenergy, with or without carbon capture and storage, can compound climate-related risks to biodiversity, water and food security, and livelihoods, especially if implemented at large scales, especially in regions with insecure land tenure (*high confidence*). {Box 2.2, 4.1, 4.7, 5.13, Table 5.18, Box 9.3, Box 13.2, CCB NATURAL, CWGB BIOECONOMY}

B.5.5 Solar radiation modification approaches, if they were to be implemented, introduce a widespread range of new risks to people and ecosystems, which are not well understood (*high confidence*). Solar radiation modification approaches have potential to offset warming and ameliorate some climate hazards, but substantial residual climate change or overcompensating change would occur at regional scales and seasonal timescales (*high confidence*). Large uncertainties and knowledge gaps are associated with the potential of solar radiation modification approaches to reduce climate change risks. Solar radiation modification would not stop atmospheric CO_2 concentrations from increasing or reduce resulting ocean acidification under continued anthropogenic emissions (*high confidence*). {CWGB SRM}

Impacts of Temporary Overshoot

B.6 If global warming transiently exceeds 1.5°C in the coming decades or later (overshoot)[37], then many human and natural systems will face additional severe risks, compared to remaining below 1.5°C (*high confidence*). Depending on the magnitude and duration of overshoot, some impacts will cause release of additional greenhouse gases (*medium confidence*) and some will be irreversible, even if global warming is reduced (*high confidence*). (Box SPM.1, Figure SPM.3) {2.5, 3.4, 12.3, 16.6, CCB DEEP, CCB SLR}

B.6.1 While model-based assessments of the impacts of overshoot pathways are limited, observations and current understanding of processes permit assessment of impacts from overshoot. Additional warming, e.g., above 1.5°C during an overshoot period this century, will result in irreversible impacts on certain ecosystems with low resilience, such as polar, mountain, and coastal ecosystems, impacted by ice-sheet, glacier melt, or by accelerating and higher committed sea level rise (*high confidence*).[38] Risks to human systems will increase, including those to infrastructure, low-lying coastal settlements, some ecosystem-based adaptation measures, and associated livelihoods (*high confidence*), cultural and spiritual values (*medium confidence*). Projected impacts are less severe with shorter duration and lower levels of overshoot (*medium confidence*). {2.5, 3.4, 12.3, 13.2, 16.5, 16.6, CCP1.2, CCP2.2, CCP5.3, CCP6.1, CCP6.2, CCB SLR, WGI AR6 SPM B.5, WGI AR6 SPM C.3, SROCC 2.3, SROCC 5.4}

37 In this report, overshoot pathways exceed 1.5°C global warming and then return to that level, or below, after several decades.

38 Despite limited evidence specifically on the impacts of a temporary overshoot of 1.5°C, a much broader evidence base from process understanding and the impacts of higher global warming levels allows a high confidence statement on the irreversibility of some impacts that would be incurred following such an overshoot.

B.6.2 Risk of severe impacts increase with every additional increment of global warming during overshoot (*high confidence*). In high-carbon ecosystems (currently storing 3,000 to 4,000 GtC)[39] such impacts are already observed and are projected to increase with every additional increment of global warming, such as increased wildfires, mass mortality of trees, drying of peatlands, and thawing of permafrost, weakening natural land carbon sinks and increasing releases of greenhouse gases (*medium confidence*). The resulting contribution to a potential amplification of global warming indicates that a return to a given global warming level or below would be more challenging (*medium confidence*). {2.4, 2.5, CCP4.2, WGI AR6 SPM B.4.3, SROCC 5.4}

C: Adaptation Measures and Enabling Conditions

Adaptation, in response to current climate change, is reducing climate risks and vulnerability mostly via adjustment of existing systems. Many adaptation options exist and are used to help manage projected climate change impacts, but their implementation depends upon the capacity and effectiveness of governance and decision-making processes. These and other enabling conditions can also support climate resilient development (Section D).

Current Adaptation and its Benefits

C.1 Progress in adaptation planning and implementation has been observed across all sectors and regions, generating multiple benefits (*very high confidence*). However, adaptation progress is unevenly distributed with observed adaptation gaps[40] (*high confidence*). Many initiatives prioritize immediate and near-term climate risk reduction which reduces the opportunity for transformational adaptation (*high confidence*). {2.6, 5.14, 7.4, 10.4, 12.5, 13.11, 14.7, 16.3, 17.3, CCP5.2, CCP5.4}

C.1.1 Adaptation planning and implementation have continued to increase across all regions (*very high confidence*). Growing public and political awareness of climate impacts and risks has resulted in at least 170 countries and many cities including adaptation in their climate policies and planning processes (*high confidence*). Decision support tools and climate services are increasingly being used (*very high confidence*). Pilot projects and local experiments are being implemented in different sectors (*high confidence*). Adaptation can generate multiple additional benefits such as improving agricultural productivity, innovation, health and well-being, food security, livelihood, and biodiversity conservation as well as reduction of risks and damages (*very high confidence*). {1.4, 2.6, 3.5, 3.6, 4.7, 4.8, 5.4, 5.6, 5.10, 6.4, 7.4, 8.5, 9.3, 9.6, 10.4, 12.5, 13.11, 15.5, 16.3, 17.2, 17.3, 17.5, CCP5.4, CCB ADAPT, CCB NATURAL}

C.1.2 Despite progress, adaptation gaps exist between current levels of adaptation and levels needed to respond to impacts and reduce climate risks (*high confidence*). Most observed adaptation is fragmented, small in scale, incremental, sector-specific, designed to respond to current impacts or near-term risks, and focused more on planning rather than implementation (*high confidence*). Observed adaptation is unequally distributed across regions *(high confidence)*, and gaps are partially driven by widening disparities between the estimated costs of adaptation and documented finance allocated to adaptation (*high confidence*). The largest adaptation gaps exist among lower income population groups (*high confidence*). At current rates of adaptation planning and implementation the adaptation gap will continue to grow (*high confidence*). As adaptation options often have long implementation times, long-term planning and accelerated implementation, particularly in the next decade, is important to close adaptation gaps, recognising that constraints remain for some regions (*high confidence*). {1.1, 1.4, 5.6, 6.3, Figure 6.4, 7.4, 8.3, 10.4, 11.3, 11.7, 13.11, Box 13.1, 15.2, 15.5, 16.3, 16.5, Box 16.1, Figure 16.4, Figure 16.5, 17.4, 18.2, CCP2.4, CCP5.4, CCB FINANCE, CCB SLR}

39 At the global scale, terrestrial ecosystems currently remove more carbon from the atmosphere (-3.4 ± 0.9 Gt yr^{-1}) than they emit (+1.6 ± 0.7 Gt yr^{-1}), a net sink of -1.9 ± 1.1 Gt yr^{-1}. However, recent climate change has shifted some systems in some regions from being net carbon sinks to net carbon sources.

40 Adaptation gaps are defined as the difference between actually implemented adaptation and a societally set goal, determined largely by preferences related to tolerated climate change impacts and reflecting resource limitations and competing priorities.

Future Adaptation Options and their Feasibility

C.2 There are feasible[41] and effective[42] adaptation options which can reduce risks to people and nature. The feasibility of implementing adaptation options in the near-term differs across sectors and regions (*very high confidence*). The effectiveness of adaptation to reduce climate risk is documented for specific contexts, sectors and regions (*high confidence*) and will decrease with increasing warming (*high confidence*). Integrated, multi-sectoral solutions that address social inequities, differentiate responses based on climate risk and cut across systems, increase the feasibility and effectiveness of adaptation in multiple sectors (*high confidence*). (Figure SPM.4) {Figure TS.6e, 1.4, 3.6, 4.7, 5.12, 6.3, 7.4, 11.3, 11.7, 13.2, 15.5, 17.6, CCP2.3, CCB FEASIB}

Land, Ocean and Ecosystems Transition

C.2.1 Adaptation to water-related risks and impacts make up the majority of all documented adaptation (*high confidence*). For inland flooding, combinations of non-structural measures like early warning systems and structural measures like levees have reduced loss of lives (*medium confidence*). Enhancing natural water retention such as by restoring wetlands and rivers, land use planning such as no build zones or upstream forest management, can further reduce flood risk (*medium confidence*). On-farm water management, water storage, soil moisture conservation and irrigation are some of the most common adaptation responses and provide economic, institutional or ecological benefits and reduce vulnerability (*high confidence*). Irrigation is effective in reducing drought risk and climate impacts in many regions and has several livelihood benefits, but needs appropriate management to avoid potential adverse outcomes, which can include accelerated depletion of groundwater and other water sources and increased soil salinization (*medium confidence*). Large scale irrigation can also alter local to regional temperature and precipitation patterns (*high confidence*), including both alleviating and exacerbating temperature extremes (*medium confidence*). The effectiveness of most water-related adaptation options to reduce projected risks declines with increasing warming (*high confidence*). {4.1, 4.6, 4.7, Box 4.3, Box 4.6, Box 4.7, Figure 4.22, Figure 4.28, Figure 4.29, Table 4.9, 9.3, 9.7, 11.3, 12.5, 13.1, 13.2, 16.3, CCP5.4}

C.2.2 Effective adaptation options, together with supportive public policies enhance food availability and stability and reduce climate risk for food systems while increasing their sustainability (*medium confidence*). Effective options include cultivar improvements, agroforestry, community-based adaptation, farm and landscape diversification, and urban agriculture (*high confidence*). Institutional feasibility, adaptation limits of crops and cost effectiveness also influence the effectiveness of the adaptation options (*limited evidence*, *medium agreement*). Agroecological principles and practices, ecosystem-based management in fisheries and aquaculture, and other approaches that work with natural processes support food security, nutrition, health and well-being, livelihoods and biodiversity, sustainability and ecosystem services (*high confidence*). These services include pest control, pollination, buffering of temperature extremes, and carbon sequestration and storage (*high confidence*). Trade-offs and barriers associated with such approaches include costs of establishment, access to inputs and viable markets, new knowledge and management (*high confidence*) and their potential effectiveness varies by socioeconomic context, ecosystem zone, species combinations and institutional support (*medium confidence*). Integrated, multi-sectoral solutions that address social inequities and differentiate responses based on climate risk and local situation will enhance food security and nutrition (*high confidence*). Adaptation strategies which reduce food loss and waste or support balanced diets[33] (as described in the IPCC Special Report on Climate Change and Land) contribute to nutrition, health, biodiversity and other environmental benefits (*high confidence*). {3.2, 4.7, 4.6, Box 4.3, 5.4, 5.5, 5.6, 5.8, 5.9, 5.10, 5.11, 5.12, 5.13, 5.14, Box 5.10, Box 5.13, 6.3, 7.4, 10.4, 12.5, 13.5, 13.10, 14.5, CCP5.4, CCB FEASIB, CCB HEALTH, CCB MOVING PLATE, CCB NATURAL, CWGB BIOECONOMY}

C.2.3 Adaptation for natural forests[43] includes conservation, protection and restoration measures. In managed forests[43], adaptation options include sustainable forest management, diversifying and adjusting tree species compositions to build resilience, and managing increased risks from pests and diseases and wildfires. Restoring natural forests and drained peatlands and improving sustainability of managed forests, generally enhances the resilience of carbon stocks and sinks. Cooperation, and inclusive decision making, with local communities and Indigenous Peoples, as well as recognition of inherent rights of Indigenous Peoples, is integral to successful forest adaptation in many areas. (*high confidence*) {2.6, Box 2.2, 5.6, 5.13, Table 5.23, 11.4, 12.5, 13.5, Box 14.1, Box 14.2, CCP7.5, Box CCP7.1, CCB FEASIB, CCB INDIG, CCB NATURAL}

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41 In this report, feasibility refers to the potential for a mitigation or adaptation option to be implemented. Factors influencing feasibility are context-dependent, temporally dynamic, and may vary between different groups and actors. Feasibility depends on geophysical, environmental-ecological, technological, economic, socio-cultural and institutional factors that enable or constrain the implementation of an option. The feasibility of options may change when different options are combined and increase when enabling conditions are strengthened.

42 Effectiveness refers to the extent to which an adaptation option is anticipated or observed to reduce climate-related risk.

43 In this report, the term natural forests describes those which are subject to little or no direct human intervention, whereas the term managed forests describes those where planting or other management activities take place, including those managed for commodity production.

(a) Diverse feasible climate responses and adaptation options exist to respond to Representative Key Risks of climate change, with varying synergies with mitigation

Multidimensional feasibility and synergies with mitigation of climate responses and adaptation options relevant in the near-term, at global scale and up to 1.5°C of global warming

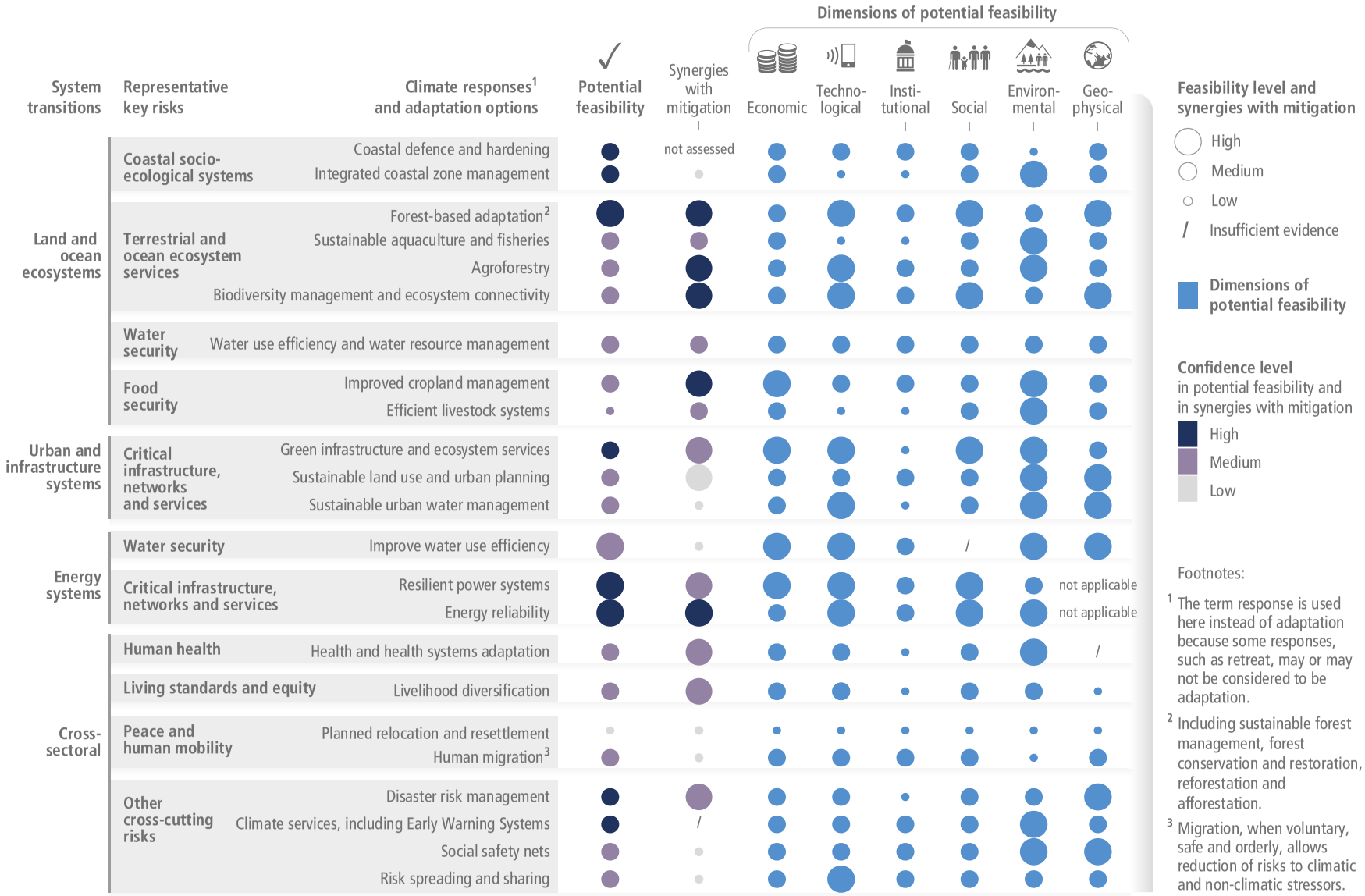

Figure SPM.4 | (a) Climate responses and adaptation options, organized by System Transitions and Representative Key Risks (RKRs), are assessed for their multidimensional feasibility at global scale, in the near term and up to 1.5°C global warming. As literature above 1.5°C is limited, feasibility at higher levels of warming may change, which is currently not possible to assess robustly. Climate responses and adaptation options at global scale are drawn from a set of options assessed in AR6 that have robust evidence across the feasibility dimensions. This figure shows the six feasibility dimensions (economic, technological, institutional, social, environmental and geophysical) that are used to calculate the potential feasibility of climate responses and adaptation options, along with their synergies with mitigation. For potential feasibility and feasibility dimensions, the figure shows high, medium, or low feasibility. Synergies with mitigation are identified as high, medium, and low. Insufficient evidence is denoted by a dash. {CCB FEASIB, Table SMCCB FEASIB.1.1, SR1.5 4.SM.4.3}

(b) Climate responses and adaptation options have benefits for ecosystems, ethnic groups, gender equity, low-income groups and the Sustainable Development Goals

Relations of sectors and groups at risk (as observed) and the SDGs (relevant in the near-term, at global scale and up to 1.5°C of global warming) with climate responses and adaptation options

Footnotes: [1] The term response is used here instead of adaptation because some responses, such as retreat, may or may not be considered to be adaptation. [2] Including sustainable forest management, forest conservation and restoration, reforestation and afforestation. [3] Migration, when voluntary, safe and orderly, allows reduction of risks to climatic and non-climatic stressors. [4] The Sustainable Development Goals (SDGs) are integrated and indivisible, and efforts to achieve any goal in isolation may trigger synergies or trade-offs with other SDGs. [5] Relevant in the near-term, at global scale and up to 1.5°C of global warming.

Figure SPM.4 | (b) Climate responses and adaptation options, organized by System Transitions and Representative Key Risks, are assessed at global scale for their likely ability to reduce risks for ecosystems and social groups at risk, as well as their relation with the 17 Sustainable Development Goals (SDGs). Climate responses and adaptation options are assessed for observed benefits (+) to ecosystems and their services, ethnic groups, gender equity, and low-income groups, or observed dis-benefits (-) for these systems and groups. Where there is highly diverging evidence of benefits/ dis-benefits across the scientific literature, e.g., based on differences between regions, it is shown as not clear or mixed (•). Insufficient evidence is shown by a dash. The relation with the SDGs is assessed as having benefits (+), dis-benefits (-) or not clear or mixed (•) based on the impacts of the climate response and adaptation option on each SDG. Areas not coloured indicate there is no evidence of a relation or no interaction with the respective SDG. The climate responses and adaptation options are drawn from two assessments. For comparability of climate responses and adaptation options see Table SM17.5. {17.2, 17.5, CCB FEASIB}

C.2.4 Conservation, protection and restoration of terrestrial, freshwater, coastal and ocean ecosystems, together with targeted management to adapt to unavoidable impacts of climate change, reduces the vulnerability of biodiversity to climate change (*high confidence*). The resilience of species, biological communities and ecosystem processes increases with size of natural area, by restoration of degraded areas and by reducing non-climatic stressors (*high confidence*). To be effective, conservation and restoration actions will increasingly need to be responsive, as appropriate, to ongoing changes at various scales, and plan for future changes in ecosystem structure, community composition and species' distributions, especially as 1.5°C global warming is approached and even more so if it is exceeded (*high confidence*). Adaptation options, where circumstances allow, include facilitating the movement of species to new ecologically appropriate locations, particularly through increasing connectivity between conserved or protected areas, targeted intensive management for vulnerable species and protecting refugial areas where species can survive locally (*medium confidence*). {2.3, 2,6, Figure 2.1, Table 2.6, 3.3, 3.6, Box 3.4, 4.6, Box 4.6, Box 11.2, 12.3, 12.5, 13.4, 14.7, CCP5.4, CCB FEASIB}

C.2.5 Effective Ecosystem-based Adaptation[44] reduces a range of climate change risks to people, biodiversity and ecosystem services with multiple co-benefits (*high confidence*). Ecosystem-based Adaptation is vulnerable to climate change impacts, with effectiveness declining with increasing global warming (*high confidence*). Urban greening using trees and other vegetation can provide local cooling (*very high confidence*). Natural river systems, wetlands and upstream forest ecosystems reduce flood risk by storing water and slowing water flow, in most circumstances (*high confidence*). Coastal wetlands protect against coastal erosion and flooding associated with storms and sea level rise where sufficient space and adequate habitats are available until rates of sea level rise exceeds natural adaptive capacity to build sediment (*very high confidence*). {2.4, 2.5, 2.6, Table 2.7, 3.4, 3.5, 3.6, Figure 3.26, 4.6, Box 4.6, Box 4.7, 5.5, 5.14, Box 5.11, 6.3, 6.4, Figure 6.6, 7.4, 8.5, 8.6, 9.6, 9.8, 9.9, 10.2, 11.3, 12.5, 13.3, 13.4, 13.5, 14.5, Box 14.7, 16.3, 18.3, CCP5.4, CCB FEASIB.3, CCB HEALTH, CCB MOVING PLATE, CCB NATURAL, CWGB BIOECONOMY}

Urban, Rural and Infrastructure Transition

C.2.6 Considering climate change impacts and risks in the design and planning of urban and rural settlements and infrastructure is critical for resilience and enhancing human well-being (*high confidence*). The urgent provision of basic services, infrastructure, livelihood diversification and employment, strengthening of local and regional food systems and community-based adaptation enhance lives and livelihoods, particularly of low-income and marginalised groups (*high confidence*). Inclusive, integrated and long-term planning at local, municipal, sub-national and national scales, together with effective regulation and monitoring systems and financial and technological resources and capabilities foster urban and rural system transition (*high confidence*). Effective partnerships between governments, civil society, and private sector organizations, across scales provide infrastructure and services in ways that enhance the adaptive capacity of vulnerable people (*medium* to *high confidence*). {5.12, 5.13, 5.14, 6.3, 6.4, Box 6.3, Box 6.6, Table 6.6, 7.4, 12.5, 13.6, 14.5, Box 14.4, Box 17.4, CCP2.3, CCP2.4, CCP5.4, CCB FEASIB}

C.2.7 An increasing number of adaptation responses exist for urban systems, but their feasibility and effectiveness is constrained by institutional, financial, and technological access and capacity, and depends on coordinated and contextually appropriate responses across physical, natural and social infrastructure (*high confidence*). Globally, more financing is directed at physical infrastructure than natural and social infrastructure (*medium confidence*) and there is *limited evidence* of investment in the informal settlements hosting the most vulnerable urban residents (*medium* to *high confidence*). Ecosystem-based adaptation (e.g., urban agriculture and forestry, river restoration) has increasingly been applied in urban areas (*high confidence*). Combined ecosystem-based and structural adaptation responses are being developed, and there is growing evidence of their potential to reduce adaptation costs and contribute to flood control, sanitation, water resources management, landslide prevention and coastal protection (*medium confidence*). {3.6, Box 4.6, 5.12, 6.3, 6.4, Table 6.8, 7.4, 9.7, 9.9, 10.4, Table 10.3, 11.3, 11.7, Box 11.6, 12.5, 13.2, 13.3, 13.6, 14.5, 15.5, 17.2, Box 17.4, CCP2.3, CCP 3.2, CCP5.4, CCB FEASIB, CCB SLR, SROCC SPM}

44 Ecosystem based Adaptation (EbA) is recognised internationally under the Convention on Biological Diversity (CBD14/5). A related concept is Nature-based Solutions (NbS), which includes a broader range of approaches with safeguards, including those that contribute to adaptation and mitigation. The term 'Nature-based Solutions' is widely but not universally used in the scientific literature. The term is the subject of ongoing debate, with concerns that it may lead to the misunderstanding that NbS on its own can provide a global solution to climate change.

C.2.8 Sea level rise poses a distinctive and severe adaptation challenge as it implies dealing with slow onset changes and increased frequency and magnitude of extreme sea level events which will escalate in the coming decades (*high confidence*). Such adaptation challenges would occur much earlier under high rates of sea level rise, in particular if low-likelihood, high impact outcomes associated with collapsing ice sheets occur (*high confidence*). Responses to ongoing sea level rise and land subsidence in low-lying coastal cities and settlements and small islands include protection, accommodation, advance and planned relocation (*high confidence*)[45]. These responses are more effective if combined and/or sequenced, planned well ahead, aligned with sociocultural values and development priorities, and underpinned by inclusive community engagement processes (*high confidence*). { 6.2, 10.4, 11.7, Box 11.6, 13.2, 14.5, 15.5, CCP2.3, CCB SLR, WGI AR6 SPM B.5, WGI AR6 SPM C.3, SROCC SPM C3.2}

C.2.9 Approximately 3.4 billion people globally live in rural areas around the world, and many are highly vulnerable to climate change. Integrating climate adaptation into social protection programs, including cash transfers and public works programmes, is highly feasible and increases resilience to climate change, especially when supported by basic services and infrastructure. Social safety nets are increasingly being reconfigured to build adaptive capacities of the most vulnerable in rural and also urban communities. Social safety nets that support climate change adaptation have strong co-benefits with development goals such as education, poverty alleviation, gender inclusion and food security. (*high confidence*) {5.14, 9.4, 9.10, 9.11, 12.5, 14.5, CCP5.4, CCB FEASIB, CCB GENDER}

Energy System Transition

C.2.10 Within energy system transitions, the most feasible adaptation options support infrastructure resilience, reliable power systems and efficient water use for existing and new energy generation systems (*very high confidence*). Energy generation diversification, including with renewable energy resources and generation that can be decentralised depending on context (e.g., wind, solar, small scale hydroelectric) and demand side management (e.g., storage, and energy efficiency improvements) can reduce vulnerabilities to climate change, especially in rural populations (*high confidence*). Adaptations for hydropower and thermo-electric power generation are effective in most regions up to 1.5°C to 2°C, with decreasing effectiveness at higher levels of warming (*medium confidence*). Climate responsive energy markets, updated design standards on energy assets according to current and projected climate change, smart-grid technologies, robust transmission systems and improved capacity to respond to supply deficits have high feasibility in the medium- to long-term, with mitigation co-benefits (*very high confidence*). {4.6, 4.7, Figure 4.28, Figure 4.29, 10.4, Table 11.8, 13.6, Figure 13.16, Figure 13.19, 18.3,CCP5.2, CCP5.4, CCB FEASIB, CWGB BIOECONOMY}

Cross-cutting Options

C.2.11 Strengthening the climate resiliency of health systems will protect and promote human health and well-being (*high confidence*). There are multiple opportunities for targeted investments and finance to protect against exposure to climate hazards, particularly for those at highest risk. Heat Health Action Plans that include early warning and response systems are effective adaptation options for extreme heat (*high confidence*). Effective adaptation options for water-borne and food-borne diseases include improving access to potable water, reducing exposure of water and sanitation systems to flooding and extreme weather events, and improved early warning systems (*very high confidence*). For vector-borne diseases, effective adaptation options include surveillance, early warning systems, and vaccine development (*very high confidence*). Effective adaptation options for reducing mental health risks under climate change include improving surveillance, access to mental health care, and monitoring of psychosocial impacts from extreme weather events (*high confidence*). Health and well-being would benefit from integrated adaptation approaches that mainstream health into food, livelihoods, social protection, infrastructure, water and sanitation policies requiring collaboration and coordination at all scales of governance (*very high confidence*). {5.12, 6.3, 7.4, 9.10, Box 9.7, 11.3, 12.5, 13.7, 14.5, CCB COVID, CCB FEASIB, CCB ILLNESS }

C.2.12 Increasing adaptive capacities minimises the negative impacts of climate-related displacement and involuntary migration for migrants and sending and receiving areas (*high confidence*). This improves the degree of choice under which migration decisions are made, ensuring safe and orderly movements of people within and between countries (*high confidence*). Some development reduces underlying vulnerabilities associated with conflict, and adaptation contributes by reducing the impacts of climate change on climate sensitive drivers of conflict (*high confidence*). Risks to peace are reduced, for example, by supporting people in climate-sensitive economic activities (*medium confidence*) and advancing women's empowerment (*high confidence*). {7.4, Box 9.8, Box 10.2, 12.5, CCB FEASIB, CCB MIGRATE}

45 The term 'response' is used here instead of adaptation because some responses, such as retreat, may or may not be considered to be adaptation.

C.2.13 There are a range of adaptation options, such as disaster risk management, early warning systems, climate services and risk spreading and sharing that have broad applicability across sectors and provide greater benefits to other adaptation options when combined (*high confidence*). For example, climate services that are inclusive of different users and providers can improve agricultural practices, inform better water use and efficiency, and enable resilient infrastructure planning (*high confidence*). {2.6, 3.6, 4.7, 5.4, 5.5, 5.6, 5.8, 5.9, 5.12, 5.14, 9.4, 9.8, 10.4, 12.5, 13.11, CCP5.4, CCB FEASIB, CCB MOVING PLATE}

Limits to Adaptation

C.3 Soft limits to some human adaptation have been reached, but can be overcome by addressing a range of constraints, primarily financial, governance, institutional and policy constraints (*high confidence*). Hard limits to adaptation have been reached in some ecosystems (*high confidence*). With increasing global warming, losses and damages will increase and additional human and natural systems will reach adaptation limits (*high confidence*). {Figure TS.7, 1.4, 2.4, 2.5, 2.6, 3.4, 3.6, 4.7, Figure 4.30, 5.5, Table 8.6, Box 10.7, 11.7, Table 11.16, 12.5, 13.2, 13.5, 13.6, 13.10, 13.11, Figure 13.21, 14.5, 15.6, 16.4, Figure 16.8, Table 16.3, Table 16.4, CCP1.2, CCP1.3, CCP2.3, CCP3.3, CCP5.2, CCP5.4, CCP6.3, CCP7.3, CCB SLR}

C.3.1 Soft limits to some human adaptation have been reached, but can be overcome by addressing a range of constraints, which primarily consist of financial, governance, institutional and policy constraints (*high confidence*). For example, individuals and households in low-lying coastal areas in Australasia and Small Islands and smallholder farmers in Central and South America, Africa, Europe and Asia have reached soft limits (*medium confidence*). Inequity and poverty also constrain adaptation, leading to soft limits and resulting in disproportionate exposure and impacts for most vulnerable groups (*high confidence*). Lack of climate literacy[46] at all levels and limited availability of information and data pose further constraints to adaptation planning and implementation (*medium confidence*). {1.4, 4.7, 5.4, 8.4, Table 8.6, 9.1, 9.4, 9.5, 9.8, 11.7, 12.5 13.5, 15.3, 15.5, 15.6, 16.4, Box 16.1, Figure 16.8, CCP5.2, CCP5.4, CCP6.3}

C.3.2 Financial constraints are important determinants of soft limits to adaptation across sectors and all regions (*high confidence*). Although global tracked climate finance has shown an upward trend since AR5, current global financial flows for adaptation, including from public and private finance sources, are insufficient for and constrain implementation of adaptation options especially in developing countries (*high confidence*). The overwhelming majority of global tracked climate finance was targeted to mitigation while a small proportion was targeted to adaptation (*very high confidence*). Adaptation finance has come predominantly from public sources (*very high confidence*). Adverse climate impacts can reduce the availability of financial resources by incurring losses and damages and through impeding national economic growth, thereby further increasing financial constraints for adaptation, particularly for developing and least developed countries (*medium confidence*). {Figure TS.7, 1.4, 2.6, 3.6, 4.7, Figure 4.30, 5.14, 7.4, 8.4, Table 8.6, 9.4, 9.9, 9.11, 10.5, 12.5, 13.3, 13.11, Box 14.4, 15.6, 16.2, 16.4, Figure 16.8, Table 16.4, 17.4, 18.1, CCP2.4, CCP5.4, CCP6.3, CCB FINANCE}

C.3.3 Many natural systems are near the hard limits of their natural adaptation capacity and additional systems will reach limits with increasing global warming (*high confidence*). Ecosystems already reaching or surpassing hard adaptation limits include some warm-water coral reefs, some coastal wetlands, some rainforests, and some polar and mountain ecosystems (*high confidence*). Above 1.5°C global warming level, some Ecosystem-based Adaptation measures will lose their effectiveness in providing benefits to people as these ecosystems will reach hard adaptation limits (*high confidence*). (Figure SPM.4) {1.4, 2.4, 2.6, 3.4, 3.6, 9.6, Box 11.2, 13.4, 14.5, 15.5, 16.4, 16.6, 17.2, CCP1.2, CCP5.2, CCP6.3, CCP7.3, CCB SLR}

C.3.4 In human systems, some coastal settlements face soft adaptation limits due to technical and financial difficulties of implementing coastal protection (*high confidence*). Above 1.5°C global warming level, limited freshwater resources pose potential hard limits for Small Islands and for regions dependent on glacier and snow-melt (*medium confidence*). By 2°C global warming level, soft limits are projected for multiple staple crops in many growing areas, particularly in tropical regions (*high confidence*). By 3°C global warming level, soft limits are projected for some water management measures for many regions, with hard limits projected for parts of Europe (*medium confidence*). Transitioning from incremental to transformational adaptation can help overcome soft adaptation limits (*high confidence*). {1.4, 4.7, 5.4, 5.8, 7.2, 7.3, 8.4, Table 8.6, 9.8, 10.4, 12.5, 13.2, 13.6, 16.4, 17.2, CCP1.3. Box CCP1.1, CCP2.3, CCP3.3, CCP4.4, CCP5.3, CCB SLR}

C.3.5 Adaptation does not prevent all losses and damages, even with effective adaptation and before reaching soft and hard limits. Losses and damages are unequally distributed across systems, regions and sectors and are not comprehensively addressed by current financial, governance and institutional arrangements, particularly in vulnerable developing countries. With increasing global warming, losses and damages increase and become increasingly difficult to avoid, while strongly concentrated among the poorest vulnerable populations. (*high confidence*) {1.4, 2.6, 3.4, 3.6, 6.3, Figure 6.4, 8.4, 13.2, 13.7, 13.10, 17.2, CCP2.3, CCP4.4, CCB LOSS, CCB SLR, CWGB ECONOMIC}

46 Climate literacy encompasses being aware of climate change, its anthropogenic causes and implications.

Avoiding Maladaptation

C.4 There is increased evidence of maladaptation[15] across many sectors and regions since the AR5. Maladaptive responses to climate change can create lock-ins of vulnerability, exposure and risks that are difficult and expensive to change and exacerbate existing inequalities. Maladaptation can be avoided by flexible, multi-sectoral, inclusive and long-term planning and implementation of adaptation actions with benefits to many sectors and systems. (*high confidence*) {1.3, 1.4, 2.6, Box 2.2, 3.2, 3.6, 4.6, 4.7, Box 4.3, Box 4.5, Figure 4.29, 5.6, 5.13, 8.2, 8.3, 8.4, 8.6, 9.6, 9.7, 9.8, 9.9, 9.10, 9.11, Box 9.5, Box 9.8, Box 9.9, Box 11.6, 13.11, 13.3, 13.4, 13.5, 14.5, 15.5, 15.6, 16.3, 17.2, 17.3, 17.4, 17.5, 17.6, CCP2.3, CCP2.3, CCP5.4, CCB DEEP, CCB NATURAL, CCB SLR, CWGB BIOECONOMY}

C.4.1 Actions that focus on sectors and risks in isolation and on short-term gains often lead to maladaptation if long-term impacts of the adaptation option and long-term adaptation commitment are not taken into account (*high confidence*). The implementation of these maladaptive actions can result in infrastructure and institutions that are inflexible and/or expensive to change (*high confidence*). For example, seawalls effectively reduce impacts to people and assets in the short-term but can also result in lock-ins and increase exposure to climate risks in the long-term unless they are integrated into a long-term adaptive plan (*high confidence*). Adaptation integrated with development reduces lock-ins and creates opportunities (e.g., infrastructure upgrading) (*medium confidence*). {1.4, 3.4, 3.6, 10.4, 11.7, Box 11.6, 13.2, 17.2, 17.5, 17.6, CCP 2.3, CCB DEEP, CCB SLR}

C.4.2 Biodiversity and ecosystem resilience to climate change are decreased by maladaptive actions, which also constrain ecosystem services. Examples of these maladaptive actions for ecosystems include fire suppression in naturally fire-adapted ecosystems or hard defences against flooding. These actions reduce space for natural processes and represent a severe form of maladaptation for the ecosystems they degrade, replace or fragment, thereby reducing their resilience to climate change and the ability to provide ecosystem services for adaptation. Considering biodiversity and autonomous adaptation in long-term planning processes reduces the risk of maladaptation. (*high confidence*) {2.4, 2.6, Table 2.7, 3.4, 3.6, 4.7, 5.6, 5.13, Table 5.21, Table 5.23, Box 11.2, 13.2, Box 13.2, 17.2, 17.5, CCP5.4}

C.4.3 Maladaptation especially affects marginalised and vulnerable groups adversely (e.g., Indigenous Peoples, ethnic minorities, low-income households, informal settlements), reinforcing and entrenching existing inequities. Adaptation planning and implementation that do not consider adverse outcomes for different groups can lead to maladaptation, increasing exposure to risks, marginalising people from certain socioeconomic or livelihood groups, and exacerbating inequity. Inclusive planning initiatives informed by cultural values, Indigenous knowledge, local knowledge, and scientific knowledge can help prevent maladaptation. (*high confidence*) (Figure SPM.4) {2.6, 3.6, 4.3, 4.6, 4.8, 5.12, 5.13, 5.14, 6.1, Box 7.1, 8.4, 11.4, 12.5, Box 13.2, 14.4, Box 14.1, 17.2, 17.5, 18.2, 17.2, CCP2.4}

C.4.4 To minimize maladaptation, multi-sectoral, multi-actor and inclusive planning with flexible pathways encourages low-regret[47] and timely actions that keep options open, ensure benefits in multiple sectors and systems and indicate the available solution space for adapting to long-term climate change (*very high confidence*). Maladaptation is also minimized by planning that accounts for the time it takes to adapt (*high confidence*), the uncertainty about the rate and magnitude of climate risk (*medium confidence*) and a wide range of potentially adverse consequences of adaptation actions (*high confidence*). {1.4, 3.6, 5.12, 5.13, 5.14, 11.6, 11.7, 17.3, 17.6, CCP2.3, CCP2.4, CCP5.4, CCB DEEP, CCB SLR}

Enabling Conditions

C.5 Enabling conditions are key for implementing, accelerating and sustaining adaptation in human systems and ecosystems. These include political commitment and follow-through, institutional frameworks, policies and instruments with clear goals and priorities, enhanced knowledge on impacts and solutions, mobilization of and access to adequate financial resources, monitoring and evaluation, and inclusive governance processes. (*high confidence*) {1.4, 2.6, 3.6, 4.8, 6.4, 7.4, 8.5, 9.4, 10.5, 11.4, 11.7, 12.5, 13.11, 14.7, 15.6, 17.4, 18.4, CCP2.4, CCP5.4, CCB FINANCE, CCB INDIG}

C.5.1 Political commitment and follow-through across all levels of government accelerate the implementation of adaptation actions (*high confidence*). Implementing actions can require large upfront investments of human, financial and technological resources (*high confidence*), whilst some benefits could only become visible in the next decade or beyond (*medium confidence*). Accelerating commitment and follow-through is promoted by rising public awareness, building business cases for adaptation, accountability and transparency mechanisms, monitoring and evaluation of adaptation progress, social movements, and climate-related litigation in some regions (*medium confidence*). {3.6, 4.8, 5.8, 6.4, 8.5, 9.4, 11.7, 12.5, 13.11, 17.4, 17.5, 18.4, CCP2.4, CCB COVID}

47 From AR5, an option *that would generate net social and/or economic benefits under current climate change and a range of future climate change scenarios*, and represent one example of robust strategies.

C.5.2 Institutional frameworks, policies and instruments that set clear adaptation goals and define responsibilities and commitments and that are coordinated amongst actors and governance levels, strengthen and sustain adaptation actions (*very high confidence*). Sustained adaptation actions are strengthened by mainstreaming adaptation into institutional budget and policy planning cycles, statutory planning, monitoring and evaluation frameworks and into recovery efforts from disaster events (*high confidence*). Instruments that incorporate adaptation such as policy and legal frameworks, behavioural incentives, and economic instruments that address market failures, such as climate risk disclosure, inclusive and deliberative processes strengthen adaptation actions by public and private actors (*medium confidence*). {1.4, 3.6, 4.8, 5.14, 6.3, 6.4, 7.4, 9.4, 10.4, 11.7, Box 11.6, Table 11.17, 13.10, 13.11, 14.7, 15.6, 17.3, 17.4, 17.5, 17.6, 18.4, CCP2.4, CCP5.4, CCP6.3, CCB DEEP}

C.5.3 Enhancing knowledge on risks, impacts, and their consequences, and available adaptation options promotes societal and policy responses (*high confidence*). A wide range of top-down, bottom-up and co-produced processes and sources can deepen climate knowledge and sharing, including capacity building at all scales, educational and information programmes, using the arts, participatory modelling and climate services, Indigenous knowledge and local knowledge and citizen science (*high confidence*). These measures can facilitate awareness, heighten risk perception and influence behaviours (*high confidence*). {1.3, 3.6, 4.8, 5.9, 5.14, 6.4, Table 6.8, 7.4, 9.4, 10.5, 11.1, 11.7, 12.5, 13.9, 13.11, 14.3, 15.6, 15.6, 17.4, 18.4, CCP2.4.1, CCB INDIG}

C.5.4 With adaptation finance needs estimated to be higher than those presented in AR5, enhanced mobilization of and access to financial resources are essential for implementation of adaptation and to reduce adaptation gaps (*high confidence*). Building capacity and removing some barriers to accessing finance is fundamental to accelerate adaptation, especially for vulnerable groups, regions and sectors (*high confidence*). Public and private finance instruments include inter alia grants, guarantee, equity, concessional debt, market debt, and internal budget allocation as well as savings in households and insurance. Public finance is an important enabler of adaptation (*high confidence*). Public mechanisms and finance can leverage private sector finance for adaptation by addressing real and perceived regulatory, cost and market barriers, for example via public-private partnerships (*high confidence*). Financial and technological resources enable effective and ongoing implementation of adaptation, especially when supported by institutions with a strong understanding of adaptation needs and capacity (*high confidence*). {4.8, 5.14, 6.4, Table 6.10, 7.4, 9.4, Table 11.17, 12.5, 13.11, 15.6, 17.4, 18.4, Box 18.9, CCP5.4, CCB FINANCE}

C.5.5 Monitoring and evaluation (M&E) of adaptation are critical for tracking progress and enabling effective adaptation (*high confidence*). M&E implementation is currently limited (*high confidence*) but has increased since AR5 at local and national levels. Although most of the monitoring of adaptation is focused towards planning and implementation, the monitoring of outcomes is critical for tracking the effectiveness and progress of adaptation *(high confidence).* M&E facilitates learning on successful and effective adaptation measures, and signals when and where additional action may be needed. M&E systems are most effective when supported by capacities and resources and embedded in enabling governance systems (*high confidence*). {1.4, 2.6, 6.4, 7.4, 11.7, 11.8, 13.2, 13.11, 17.5, 18.4, CCP2.4, CCB DEEP, CCB ILLNESS, CCB NATURAL, CCB PROGRESS}

C.5.6 Inclusive governance that prioritises equity and justice in adaptation planning and implementation leads to more effective and sustainable adaptation outcomes (*high confidence*). Vulnerabilities and climate risks are often reduced through carefully designed and implemented laws, policies, processes, and interventions that address context specific inequities such as based on gender, ethnicity, disability, age, location and income (*high confidence*). These approaches, which include multi-stakeholder co-learning platforms, transboundary collaborations, community-based adaptation and participatory scenario planning, focus on capacity-building, and meaningful participation of the most vulnerable and marginalised groups, and their access to key resources to adapt (*high confidence*). {1.4, 2.6, 3.6, 4.8, 5.4, 5.8, 5.9, 5.13, 6.4, 7.4, 8.5, 11.8, 12.5, 13.11, 14.7, 15.5, 15.7, 17.3, 17.5, 18.4, CCP2.4, CCP5.4, CCP6.4, CCB GENDER, CCB HEALTH, CCB INDIG}

D: Climate Resilient Development

Climate resilient development integrates adaptation measures and their enabling conditions (Section C) with mitigation to advance sustainable development for all. Climate resilient development involves questions of equity and system transitions in land, ocean and ecosystems; urban and infrastructure; energy; industry; and society and includes adaptations for human, ecosystem and planetary health. Pursuing climate resilient development focuses on both where people and ecosystems are co-located as well as the protection and maintenance of ecosystem function at the planetary scale. Pathways for advancing climate resilient development are development trajectories that successfully integrate mitigation and adaptation actions to advance sustainable development. Climate resilient development pathways may be temporarily coincident with any RCP and SSP scenario used throughout AR6, but do not follow any particular scenario in all places and over all time.

Conditions for Climate Resilient Development

D.1 Evidence of observed impacts, projected risks, levels and trends in vulnerability, and adaptation limits, demonstrate that worldwide climate resilient development action is more urgent than previously assessed in AR5. Comprehensive, effective, and innovative responses can harness synergies and reduce trade-offs between adaptation and mitigation to advance sustainable development. (*very high confidence*) {2.6, 3.4, 3.6, 4.2, 4.6, 7.2, 7.4, 8.3, 8.4, 9.3, 10.6, 13.3, 13.8, 13.10, 14.7, 17.2, 18.3, Box 18.1, Figure 18.1, Table 18.5}

D.1.1 There is a rapidly narrowing window of opportunity to enable climate resilient development. Multiple climate resilient development pathways are still possible by which communities, the private sector, governments, nations and the world can pursue climate resilient development – each involving and resulting from different societal choices influenced by different contexts and opportunities and constraints on system transitions. Climate resilient development pathways are progressively constrained by every increment of warming, in particular beyond 1.5°C, social and economic inequalities, the balance between adaptation and mitigation varying by national, regional and local circumstances and geographies, according to capabilities including resources, vulnerability, culture and values, past development choices leading to past emissions and future warming scenarios, bounding the climate resilient development pathways remaining, and the ways in which development trajectories are shaped by equity, and social and climate justice. (*very high confidence*) {Figure TS.14d, 2.6, 4.7, 4.8, 5.14, 6.4, 7.4, 8.3, 9.4, 9.3, 9.4, 9.5, 10.6, 11.8, 12.5, 13.10, 14.7, 15.3, 18.5, CCP2.3, CCP3.4, CCP4.4, CCP5.3, CCP5.4, Table CCP5.2, CCP6.3, CCP7.5}

D.1.2 Opportunities for climate resilient development are not equitably distributed around the world (*very high confidence*). Climate impacts and risks exacerbate vulnerability and social and economic inequities and consequently increase persistent and acute development challenges, especially in developing regions and sub-regions, and in particularly exposed sites, including coasts, small islands, deserts, mountains and polar regions. This in turn undermines efforts to achieve sustainable development, particularly for vulnerable and marginalized communities (*very high confidence*). {2.5, 4.4, 4.7, 6.3, Box 6.4, Figure 6.5, 9.4, Table 18.5, CCP2.2, CCP3.2, CCP3.3, CCP5.4, CCP6.2, CCB HEALTH, CWGB URBAN}

D.1.3 Embedding effective and equitable adaptation and mitigation in development planning can reduce vulnerability, conserve and restore ecosystems, and enable climate resilient development. This is especially challenging in localities with persistent development gaps and limited resources (*high confidence*). Dynamic trade-offs and competing priorities exist between mitigation, adaptation, and development. Integrated and inclusive system-oriented solutions based on equity and social and climate justice reduce risks and enable climate resilient development (*high confidence*). {1.4, 2.6, Box 2.2, 3.6, 4.7, 4.8, Box 4.5, Box 4.8, 5.13, 7.4, 8.5, 9.4, Box 9.3, 10.6, 12.5, 12.6, 13.3, 13.4, 13.10, 13.11, 14.7, 18.4, CCB DEEP, CCP2, CCP5.4, CCB HEALTH, SRCCL}

Enabling Climate Resilient Development

D.2 Climate resilient development is enabled when governments, civil society and the private sector make inclusive development choices that prioritise risk reduction, equity and justice, and when decision-making processes, finance and actions are integrated across governance levels, sectors and timeframes (*very high confidence*). Climate resilient development is facilitated by international cooperation and by governments at all levels working with communities, civil society, educational bodies, scientific and other institutions, media, investors and businesses; and by developing partnerships with traditionally marginalised groups, including women, youth, Indigenous Peoples, local communities and ethnic minorities (*high confidence*). These partnerships are most effective when supported by enabling political leadership, institutions, resources, including finance, as well as climate services, information and decision support tools (*high confidence*). (Figure SPM.5) {1.3, 1.4, 1.5, 2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.4, 17.6, 18.4, 18.5, CCP2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB DEEP, CCB GENDER, CCB HEALTH, CCB INDIG, CCB NATURAL, CCB SLR}

D.2.1 Climate resilient development is advanced when actors work in equitable, just and enabling ways to reconcile divergent interests, values and worldviews, toward equitable and just outcomes (*high confidence*). These practices build on diverse knowledges about climate risk and chosen development pathways account for local, regional and global climate impacts, risks, barriers and opportunities (*high confidence*). Structural vulnerabilities to climate change can be reduced through carefully designed and implemented legal, policy, and process interventions from the local to global that address inequities based on gender, ethnicity, disability, age, location and income (*very high confidence*). This includes rights-based approaches that focus on capacity-building, meaningful participation of the most vulnerable groups, and their access to key resources, including financing, to reduce risk and adapt (*high confidence*). Evidence shows that climate resilient development processes link scientific, Indigenous, local, practitioner and other forms of knowledge, and are more effective and sustainable because they are locally appropriate and lead to more legitimate, relevant and effective actions (*high confidence*).

There is a rapidly narrowing window of opportunity to enable climate resilient development

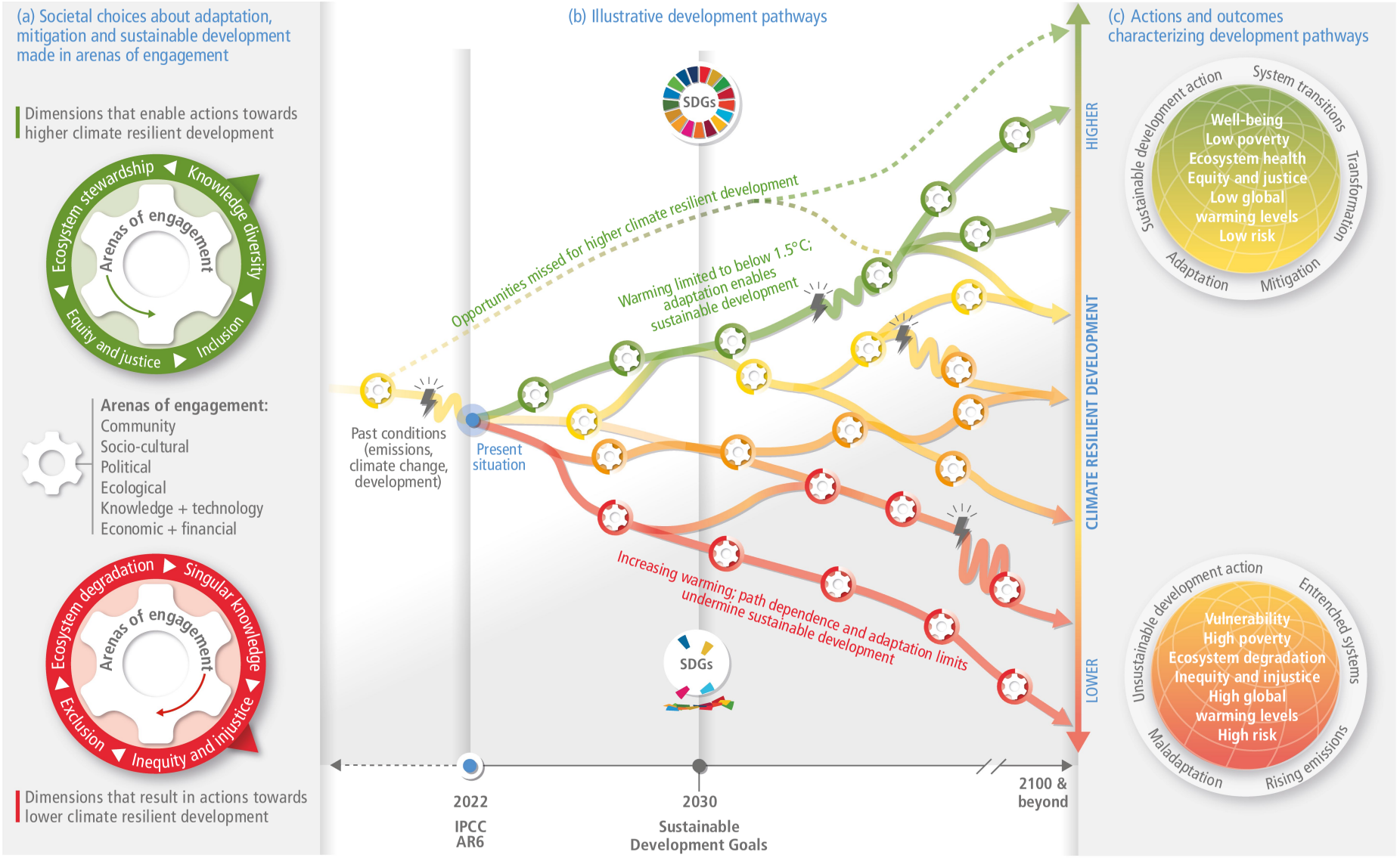

Figure SPM.5 | Climate resilient development (CRD) is the process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development. This figure builds on Figure SPM.9 in AR5 WGII (depicting climate resilient pathways) by describing how CRD pathways are the result of cumulative societal choices and actions within multiple arenas.

Panel (a) Societal choices towards higher CRD **(green cog)** or lower CRD **(red cog)** result from interacting decisions and actions by diverse government, private sector and civil society actors, in the context of climate risks, adaptation limits and development gaps. These actors engage with adaptation, mitigation and development actions in political, economic and financial, ecological, socio-cultural, knowledge and technology, and community arenas from local to international levels. Opportunities for climate resilient development are not equitably distributed around the world.

Panel (b) Cumulatively, societal choices, which are made continuously, shift global development pathways towards higher **(green)** or lower **(red)** climate resilient development. Past conditions (past emissions, climate change and development) have already eliminated some development pathways towards higher CRD **(dashed green line)**.

Panel (c) Higher CRD is characterised by outcomes that advance sustainable development for all. Climate resilient development is progressively harder to achieve with global warming levels beyond 1.5°C. Inadequate progress towards the Sustainable Development Goals (SDGs) by 2030 reduces climate resilient development prospects. There is a narrowing window of opportunity to shift pathways towards more climate resilient development futures as reflected by the adaptation limits and increasing climate risks, considering the remaining carbon budgets. (Figure SPM.2, Figure SPM.3) {Figure TS.14b, 2.6, 3.6, 7.2, 7.3, 7.4, 8.3, 8.4, 8.5, 16.4, 16.5, 17.3, 17.4, 17.5, 18.1, 18.2, 18.3, 18.4, Box 18.1, Figure 18.1, Figure 18.2, Figure 18.3, CCB COVID, CCB GENDER, CCB HEALTH, CCB INDIG, CCB SLR, WGI AR6 Table SPM.1, WGI AR6 Table SPM.2, SR1.5 Figure SPM.1}

Pathways towards climate resilient development overcome jurisdictional and organizational barriers, and are founded on societal choices that accelerate and deepen key system transitions (*very high confidence*). Planning processes and decision analysis tools can help identify 'low regrets' options[47] that enable mitigation and adaptation in the face of change, complexity, deep uncertainty and divergent views (*medium confidence*). {1.3, 1.4, 1.5, 2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, Box 8.7, 9.4, Box 9.2, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2–17.6, 18.2–18.4, CCP2.3–2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB DEEP, CCB HEALTH, CCB INDIG, CCB NATURAL, CCB SLR}

D.2.2 Inclusive governance contributes to more effective and enduring adaptation outcomes and enables climate resilient development (*high confidence*). Inclusive processes strengthen the ability of governments and other stakeholders to jointly consider factors such as the rate and magnitude of change and uncertainties, associated impacts, and timescales of different climate resilient development pathways given past development choices leading to past emissions and scenarios of future global warming (*high confidence*). Associated societal choices are made continuously through interactions in arenas of engagement from local to international levels. The quality and outcome of these interactions helps determine whether development pathways shift towards or away from climate resilient development (*medium confidence*). (Figure SPM.5) {2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2–17.6, 18.2, 18.4, CCP2.3–2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB GENDER, CCB HEALTH, CCB INDIG}

D.2.3 Governance for climate resilient development is most effective when supported by formal and informal institutions and practices that are well-aligned across scales, sectors, policy domains and timeframes. Governance efforts that advance climate resilient development account for the dynamic, uncertain and context-specific nature of climate-related risk, and its interconnections with non-climate risks. Institutions[48] that enable climate resilient development are flexible and responsive to emergent risks and facilitate sustained and timely action. Governance for climate resilient development is enabled by adequate and appropriate human and technological resources, information, capacities and finance. (*high confidence*) {2.7, 3.6, 4.8, 5.14, 6.3, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2-17.6, 18.2, 18.4, CCP2.3–2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB DEEP, CCB GENDER, CCB HEALTH, CCB INDIG, CCB NATURAL, CCB SLR}

Climate Resilient Development for Natural and Human Systems

D.3 Interactions between changing urban form, exposure and vulnerability can create climate change-induced risks and losses for cities and settlements. However, the global trend of urbanisation also offers a critical opportunity in the near-term, to advance climate resilient development (*high confidence*). Integrated, inclusive planning and investment in everyday decision-making about urban infrastructure, including social, ecological and grey/physical infrastructures, can significantly increase the adaptive capacity of urban and rural settlements. Equitable outcomes contributes to multiple benefits for health and well-being and ecosystem services, including for Indigenous Peoples, marginalised and vulnerable communities (*high confidence*). Climate resilient development in urban areas also supports adaptive capacity in more rural places through maintaining peri-urban supply chains of goods and services and financial flows (*medium confidence*). Coastal cities and settlements play an especially important role in advancing climate resilient development (*high confidence*). {6.2, 6.3, Table 6.6, 7.4, 8.6, Box 9.8, 18.3, CCP2.1. CCP2.2, CCP6.2, CWGB URBAN}

48 Institutions: Rules, norms and conventions that guide, constrain or enable human behaviours and practices. Institutions can be formally established, for instance through laws and regulations, or informally established, for instance by traditions or customs. Institutions may spur, hinder, strengthen, weaken or distort the emergence, adoption and implementation of climate action and climate governance.

D.3.1 Taking integrated action for climate resilience to avoid climate risk requires urgent decision making for the new built environment and retrofitting existing urban design, infrastructure and land use. Based on socioeconomic circumstances, adaptation and sustainable development actions will provide multiple benefits including for health and well-being, particularly when supported by national governments, non-governmental organisations and international agencies that work across sectors in partnerships with local communities. Equitable partnerships between local and municipal governments, the private sector, Indigenous Peoples, local communities, and civil society can, including through international cooperation, advance climate resilient development by addressing structural inequalities, insufficient financial resources, cross-city risks and the integration of Indigenous knowledge and local knowledge. (*high confidence*) {6.2, 6.3, 6.4, Table 6.6, 7.4, 8.5, 9.4, 10.5. 12.5, 17.4, Table 17.8, 18.2, Box 18.1, CCP2.4, CCB FINANCE, CCB GENDER, CCB INDIG, CWGB URBAN}

D.3.2 Rapid global urbanisation offers opportunities for climate resilient development in diverse contexts from rural and informal settlements to large metropolitan areas (*high confidence*). Dominant models of energy intensive and market-led urbanisation, insufficient and misaligned finance and a predominant focus on grey infrastructure in the absence of integration with ecological and social approaches, risks missing opportunities for adaptation and locking in maladaptation (*high confidence*). Poor land use planning and siloed approaches to health, ecological and social planning also exacerbates, vulnerability in already marginalised communities (*medium confidence*). Urban climate resilient development is observed to be more effective if it is responsive to regional and local land use development and adaptation gaps, and addresses the underlying drivers of vulnerability (*high confidence*). The greatest gains in well-being can be achieved by prioritizing finance to reduce climate risk for low-income and marginalized residents including people living in informal settlements (*high confidence*). {5.14, 6.1, 6.2, 6.3, 6.4, 6.5, Figure 6.5, Table 6.6, 7.4, 8.5, 8.6, 9.8, 9.9, 10.4, Table 17.8, 18.2, CCP2.2, CCP5.4, CCB HEALTH, CWGB URBAN}

D.3.3 Urban systems are critical, interconnected sites for enabling climate resilient development, especially at the coast. Coastal cities and settlements play a key role in moving toward higher climate resilient development given firstly, almost 11% of the global population – 896 million people – lived within the Low Elevation Coastal Zone[49] in 2020, potentially increasing to beyond 1 billion people by 2050, and these people, and associated development and coastal ecosystems, face escalating climate compounded risks, including sea level rise. Secondly, these coastal cities and settlements make key contributions to climate resilient development through their vital role in national economies and inland communities, global trade supply chains, cultural exchange, and centres of innovation. (*high confidence*) {6.1, 6.2, 6.4, Table 6.6, Box 15.2, SMCCP Table 2.1, CCP2.2, CCP2.4, CCB SLR, XWGB URBAN, SROCC Chapter 4}

D.4 Safeguarding biodiversity and ecosystems is fundamental to climate resilient development, in light of the threats climate change poses to them and their roles in adaptation and mitigation (*very high confidence*). Recent analyses, drawing on a range of lines of evidence, suggest that maintaining the resilience of biodiversity and ecosystem services at a global scale depends on effective and equitable conservation of approximately 30% to 50% of Earth's land, freshwater and ocean areas, including currently near-natural ecosystems (*high confidence*). {2.4, 2.5, 2.6, 3.4, 3.5, 3.6, Box 3.4, 12.5, 13.3, 13.4, 13.5, 13.10, CCB INDIG, CCB NATURAL}

D.4.1 Building the resilience of biodiversity and supporting ecosystem integrity[50] can maintain benefits for people, including livelihoods, human health and well-being and the provision of food, fibre and water, as well as contributing to disaster risk reduction and climate change adaptation and mitigation. {2.2, 2.5, 2.6, Table 2.6, Table 2.7, 3.5, 3.6, 5.8, 5.13, 5.14, Box 5.11, 12.5, CCP5.4, CCB COVID, CCB GENDER, CCB ILLNESS, CCB INDIG, CCB MIGRATE, CCB NATURAL}

D.4.2 Protecting and restoring ecosystems is essential for maintaining and enhancing the resilience of the biosphere (*very high confidence*). Degradation and loss of ecosystems is also a cause of greenhouse gas emissions and is at increasing risk of being exacerbated by climate change impacts, including droughts and wildfire *(high confidence).* Climate resilient development avoids adaptation and mitigation measures that damage ecosystems (*high confidence*). Documented examples of adverse impacts of land-based measures intended as mitigation, when poorly implemented, include afforestation of grasslands, savannas and peatlands, and risks from bioenergy crops at large scale to water supply, food security and biodiversity (*high confidence*). {2.4, 2.5, Box 2.2, 3.4, 3.5, Box 3.4, Box 9.3, CCP7.3, CCB NATURAL, CWGB BIOECONOMY}

49 LECZ, coastal areas below 10 m of elevation above sea level that are hydrologically connected to the sea.

50 Ecosystem integrity refers to the ability of ecosystems to maintain key ecological processes, recover from disturbance, and adapt to new conditions.

D.4.3 Biodiversity and ecosystem services have limited capacity to adapt to increasing global warming levels, which will make climate resilient development progressively harder to achieve beyond 1.5°C warming (*very high confidence*). Consequences of current and future global warming for climate resilient development include reduced effectiveness of Ecosystem-based Adaptation and approaches to climate change mitigation based on ecosystems and amplifying feedbacks to the climate system (*high confidence*). {Figure TS.14d, 2.4, 2.5, 2.6, 3.4, Box 3.4, 3.5, 3.6, Table 5.2, 12.5, 13.2, 13.3, 13.10, 14.5, 14.5, Box 14.3, 15.3, 17.3, 17.6, CCP5.3, CCP5.4, CCB EXTREMES, CCB ILLNESS, CCB NATURAL, CCB SLR, SR1.5, SRCCL, SROCC}

Achieving Climate Resilient Development

D.5 It is unequivocal that climate change has already disrupted human and natural systems. Past and current development trends (past emissions, development and climate change) have not advanced global climate resilient development (*very high confidence*). Societal choices and actions implemented in the next decade determine the extent to which medium- and long-term pathways will deliver higher or lower climate resilient development (*high confidence*). Importantly climate resilient development prospects are increasingly limited if current greenhouse gas emissions do not rapidly decline, especially if 1.5°C global warming is exceeded in the near-term (*high confidence*). These prospects are constrained by past development, emissions and climate change, and enabled by inclusive governance, adequate and appropriate human and technological resources, information, capacities and finance (*high confidence*). {Figure TS.14d, 1.2, 1.4, 1.5, 2.6, 2.7, 3.6, 4.7, 4.8, 5.14, 6.4, 7.4, 8.3, 8.5, 8.6, 9.3, 9.4, 9.5, 10.6, 11.8, 12.5, 13.10, 13.11, 14.7, 15.3, 15.6, 15.7, 16.2, 16.4, 16.5, 16.6, 17.2–17.6, 18.2–18.5, CCP2.3–2.4, CCP3.4, CCP4.4, CCP5.3, CCP5.4, Table CCP5.2, CCP6.3, CCP6.4, CCP7.5, CCP7.6, CCB DEEP, CCB HEALTH, CCB INDIG, CCB NATURAL, CCB SLR}

D.5.1 Climate resilient development is already challenging at current global warming levels (*high confidence*). The prospects for climate resilient development will be further limited if global warming levels exceeds 1.5°C (*high confidence*) and not be possible in some regions and sub-regions if the global warming level exceeds 2°C (*medium confidence*). Climate resilient development is most constrained in regions/subregions in which climate impacts and risks are already advanced, including low-lying coastal cities and settlements, small islands, deserts, mountains and polar regions (*high confidence*). Regions and subregions with high levels of poverty, water, food and energy insecurity, vulnerable urban environments, degraded ecosystems and rural environments, and/or few enabling conditions, face many non-climate challenges that inhibit climate resilient development which are further exacerbated by climate change (*high confidence*). {Figure TS.14d, 1.2, Box 6.6, 9.3, 9.4, 9.5, 10.6, 11.8, 12.5, 13.10, 14.7, 15.3, CCP2.3, CCP3.4, CCP4.4, CCP5.3, Table CCP5.2, CCP6.3, CCP7.5}

D.5.2 Inclusive governance, investment aligned with climate resilient development, access to appropriate technology and rapidly scaled-up finance, and capacity building of governments at all levels, the private sector and civil society enable climate resilient development. Experience shows that climate resilient development processes are timely, anticipatory, integrative, flexible and action focused. Common goals and social learning build adaptive capacity for climate resilient development. When implementing adaptation and mitigation together, and taking trade-offs into account, multiple benefits and synergies for human well-being as well as ecosystem and planetary health can be realised. Prospects for climate resilient development are increased by inclusive processes involving local knowledge and Indigenous Knowledge as well as processes that coordinate across risks and institutions. Climate resilient development is enabled by increased international cooperation including mobilising and enhancing access to finance, particularly for vulnerable regions, sectors and groups. (*high confidence*) (Figure SPM.5) {2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2–17.6, 18.2–18.5, CCP2.3–2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB DEEP, CCB HEALTH, CCB INDIG, CCB NATURAL, CCB SLR}

D.5.3 The cumulative scientific evidence is unequivocal: Climate change is a threat to human well-being and planetary health. Any further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all. (*very high confidence*) {1.2, 1.4, 1.5, 16.2, Table SM16.24, 16.4, 16.5, 16.6, 17.4, 17.5, 17.6, 18.3, 18.4, 18.5, CCB DEEP, CWGB URBAN, WGI AR6 SPM, SROCC SPM, SRCCL SPM}

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INTERGOVERNMENTAL PANEL ON climate change

Climate Change 2022

Mitigation of Climate Change

Summary for Policymakers

WGIII

Working Group III contribution to the
Sixth Assessment Report of the
Intergovernmental Panel on Climate Change

WMO UNEP

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Summary for Policymakers

SPM

Summary for Policymakers

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A. Introduction and Framing

The Working Group III (WGIII) contribution to the IPCC's Sixth Assessment Report (AR6) assesses literature on the scientific, technological, environmental, economic and social aspects of mitigation of climate change.[1] Levels of confidence[2] are given in () brackets. Numerical ranges are presented in square [] brackets. References to Chapters, Sections, Figures and Boxes in the underlying report and Technical Summary (TS) are given in {} brackets.

The report reflects new findings in the relevant literature and builds on previous IPCC reports, including the WGIII contribution to the IPCC's Fifth Assessment Report (AR5), the WGI and WGII contributions to AR6 and the three Special Reports in the Sixth Assessment cycle,[3] as well as other UN assessments. Some of the main developments relevant for this report include {TS.1, TS.2}:

- **An evolving international landscape.** The literature reflects, among other factors: developments in the UN Framework Convention on Climate Change (UNFCCC) process, including the outcomes of the Kyoto Protocol and the adoption of the Paris Agreement {13, 14, 15, 16}; the UN 2030 Agenda for Sustainable Development including the Sustainable Development Goals (SDGs) {1, 3, 4, 17}; and the evolving roles of international cooperation {14}, finance {15} and innovation {16}.

- **Increasing diversity of actors and approaches to mitigation.** Recent literature highlights the growing role of non-state and sub-national actors including cities, businesses, Indigenous Peoples, citizens including local communities and youth, transnational initiatives, and public-private entities in the global effort to address climate change {5, 13, 14, 15, 16, 17}. Literature documents the global spread of climate policies and cost declines of existing and emerging low emission technologies, along with varied types and levels of mitigation efforts, and sustained reductions in greenhouse gas (GHG) emissions in some countries {2, 5, 6, 8, 12, 13, 16}, and the impacts of, and some lessons from, the COVID-19 pandemic. {1, 2, 3, 5, 13, 15, Box TS.1, Cross-Chapter Box 1 in Chapter 1}

- **Close linkages between climate change mitigation, adaptation and development pathways.** The development pathways taken by countries at all stages of economic development impact GHG emissions and hence shape mitigation challenges and opportunities, which vary across countries and regions. Literature explores how development choices and the establishment of enabling conditions for action and support influence the feasibility and the cost of limiting emissions {1, 3, 4, 5, 13, 15, 16}. Literature highlights that climate change mitigation action designed and conducted in the context of sustainable development, equity, and poverty eradication, and rooted in the development aspirations of the societies within which they take place, will be more acceptable, durable and effective {1, 3, 4, 5}. This report covers mitigation from both targeted measures, and from policies and governance with other primary objectives.

- **New approaches in the assessment.** In addition to the sectoral and systems chapters {3, 6, 7, 8, 9, 10, 11, 12}, the report includes, for the first time in a WGIII report, chapters dedicated to demand for services, and social aspects of mitigation {5, Box TS.11}, and to innovation, technology development and transfer {16}. The assessment of future pathways in this report covers near term (to 2030), medium term (up to 2050), and long term (to 2100) time scales, combining assessment of existing pledges and actions {4, 5}, with an assessment of emissions reductions, and their implications, associated with long-term temperature outcomes up to the year 2100 {3}.[4] The assessment of modelled global pathways addresses ways of shifting development pathways towards sustainability. Strengthened collaboration between IPCC Working Groups is reflected in Cross-Working Group Boxes that integrate physical science, climate risks and adaptation, and the mitigation of climate change.[5]

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1 The Report covers literature accepted for publication by 11 October 2021.

2 Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers, typeset in italics: *very low*, *low*, *medium*, *high* and *very high*. The assessed likelihood of an outcome or a result is described as: *virtually certain* 99–100% probability; *very likely* 90–100%; *likely* 66–100%; *more likely than not* 50–100%; *about as likely as not* 33–66%; *unlikely* 0–33%; *very unlikely* 0–10%; *exceptionally unlikely* 0–1%. Additional terms may also be used when appropriate, consistent with the IPCC uncertainty guidance: https://www.ipcc.ch/site/assets/uploads/2018/05/uncertainty-guidance-note.pdf.

3 The three Special Reports are: Global Warming of 1.5°C: an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (2018); Climate Change and Land: an IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (2019); IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (2019).

4 The term 'temperature' is used in reference to 'global surface temperatures' throughout this SPM as defined in footnote 8 of the AR6 WGI SPM (see note 14 of Table SPM.2). Emission pathways and associated temperature changes are calculated using various forms of models, as summarised in Box SPM.1 and Chapter 3, and discussed in Annex III.

5 Namely: Economic Benefits from Avoided Climate Impacts along Long-Term Mitigation Pathways {Cross-Working Group Box 1 in Chapter 3}; Urban: Cities and Climate Change {Cross-Working Group Box 2 in Chapter 8}; and Mitigation and Adaptation via the Bioeconomy {Cross-Working Group Box 3 in Chapter 12}.

- **Increasing diversity of analytic frameworks from multiple disciplines including social sciences.** This report identifies multiple analytic frameworks to assess the drivers of, barriers to and options for, mitigation action. These include: economic efficiency, including the benefits of avoided impacts; ethics and equity; interlinked technological and social transition processes; and socio-political frameworks, including institutions and governance {1, 3, 13, Cross-Chapter Box 12 in Chapter 16}. These help to identify risks and opportunities for action, including co-benefits and just and equitable transitions at local, national and global scales. {1, 3, 4, 5, 13, 14, 16, 17}

Section B of this Summary for Policymakers (SPM) assesses *Recent developments and current trends*, including data uncertainties and gaps. Section C, *System transformations to limit global warming*, identifies emission pathways and alternative mitigation portfolios consistent with limiting global warming to different levels, and assesses specific mitigation options at the sectoral and system level. Section D addresses *Linkages between mitigation, adaptation, and sustainable development*. Section E, *Strengthening the response*, assesses knowledge of how enabling conditions of institutional design, policy, finance, innovation and governance arrangements can contribute to climate change mitigation in the context of sustainable development.

B. Recent Developments and Current Trends

B.1 Total net anthropogenic GHG emissions[6] have continued to rise during the period 2010–2019, as have cumulative net CO_2 emissions since 1850. Average annual GHG emissions during 2010–2019 were higher than in any previous decade, but the rate of growth between 2010 and 2019 was lower than that between 2000 and 2009. (*high confidence*) (Figure SPM.1) {Figure 2.2, Figure 2.5, Table 2.1, 2.2, Figure TS.2}

B.1.1 Global net anthropogenic GHG emissions were 59 ± 6.6 $GtCO_2$-eq[7,8] in 2019, about 12% (6.5 $GtCO_2$-eq) higher than in 2010 and 54% (21 $GtCO_2$-eq) higher than in 1990. The annual average during the decade 2010–2019 was 56 ± 6.0 $GtCO_2$-eq, 9.1 $GtCO_2$-eq yr^{-1} higher than in 2000–2009. This is the highest increase in average decadal emissions on record. The average annual rate of growth slowed from 2.1% yr^{-1} between 2000 and 2009 to 1.3% yr^{-1} between 2010 and 2019. (*high confidence*) (Figure SPM.1) {Figure 2.2, Figure 2.5, Table 2.1, 2.2, Figure TS.2}

B.1.2 Growth in anthropogenic emissions has persisted across all major groups of GHGs since 1990, albeit at different rates. By 2019, the largest growth in absolute emissions occurred in CO_2 from fossil fuels and industry followed by CH_4, whereas the highest relative growth occurred in fluorinated gases, starting from low levels in 1990 (*high confidence*). Net anthropogenic CO_2 emissions from land use, land-use change and forestry (CO_2-LULUCF) are subject to large uncertainties and high annual variability, with *low confidence* even in the direction of the long-term trend.[9] (Figure SPM.1) {Figure 2.2, Figure 2.5, 2.2, Figure TS.2}

B.1.3 Historical cumulative net CO_2 emissions from 1850 to 2019 were 2400 ± 240 $GtCO_2$ (*high confidence*). Of these, more than half (58%) occurred between 1850 and 1989 [1400 ± 195 $GtCO_2$], and about 42% between 1990 and 2019 [1000 ± 90 $GtCO_2$]. About 17% of historical cumulative net CO_2 emissions since 1850 occurred between 2010 and 2019 [410 ± 30 $GtCO_2$].[10] By comparison, the current central estimate of the remaining carbon budget from 2020 onwards for limiting warming to 1.5°C with a probability of 50% has been assessed as 500 $GtCO_2$, and as 1150 $GtCO_2$ for a probability of 67% for limiting warming to 2°C. Remaining carbon budgets depend on the amount of non-CO_2 mitigation (±220 $GtCO_2$) and are further subject to geophysical uncertainties. Based on central estimates only, cumulative net CO_2 emissions between 2010 and 2019 compare to about four-fifths of the size of the remaining carbon budget from 2020 onwards for a 50% probability of limiting global warming to 1.5°C, and about one-third of the remaining carbon budget for a 67% probability to limit global warming to 2°C. Even when taking uncertainties into account, historical emissions between 1850 and 2019 constitute a large share of total carbon budgets for these global

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[6] Net GHG emissions in this report refer to releases of greenhouse gases from anthropogenic sources minus removals by anthropogenic sinks, for those species of gases that are reported under the common reporting format of the United Nations Framework Convention on Climate Change (UNFCCC): CO_2 from fossil fuel combustion and industrial processes (CO_2-FFI); net CO_2 emissions from land use, land-use change and forestry (CO_2-LULUCF); methane (CH_4); nitrous oxide (N_2O); and fluorinated gases (F-gases) comprising hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), as well as nitrogen trifluoride (NF_3). Different datasets for GHG emissions exist, with varying time horizons and coverage of sectors and gases, including some that go back to 1850. In this report, GHG emissions are assessed from 1990, and CO_2 sometimes also from 1850. Reasons for this include data availability and robustness, scope of the assessed literature, and the differing warming impacts of non-CO_2 gases over time.

[7] GHG emission metrics are used to express emissions of different greenhouse gases in a common unit. Aggregated GHG emissions in this report are stated in CO_2-equivalent (CO_2-eq) using the Global Warming Potential with a time horizon of 100 years (GWP100) with values based on the contribution of Working Group I to the AR6. The choice of metric depends on the purpose of the analysis, and all GHG emission metrics have limitations and uncertainties, given that they simplify the complexity of the physical climate system and its response to past and future GHG emissions. {Cross-Chapter Box 2 in Chapter 2, Supplementary Material 2.SM.3, Box TS.2; AR6 WGI Chapter 7 Supplementary Material}

[8] In this SPM, uncertainty in historic GHG emissions is reported using 90% uncertainty intervals unless stated otherwise. GHG emission levels are rounded to two significant digits; as a consequence, small differences in sums due to rounding may occur.

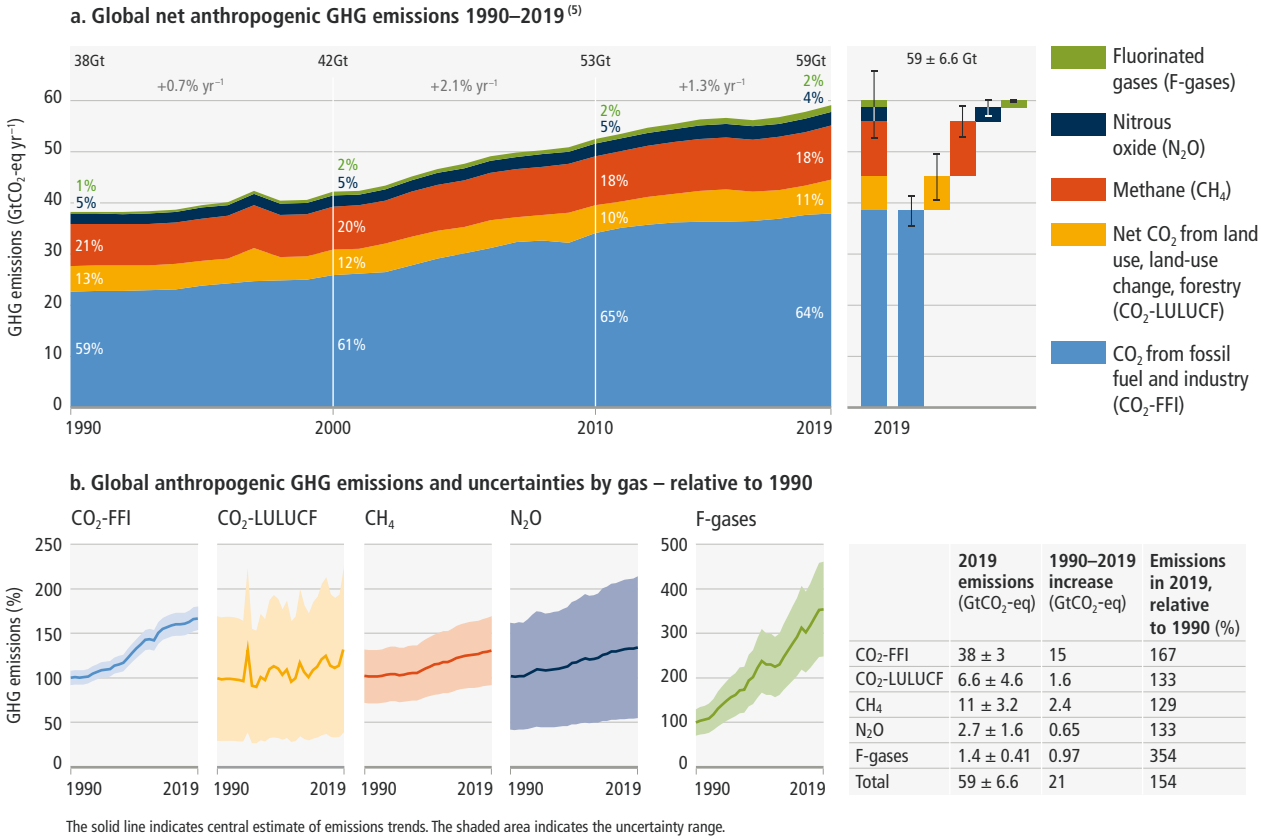
[9] Global databases make different choices about which emissions and removals occurring on land are considered anthropogenic. Currently, net CO_2 fluxes from land reported by global bookkeeping models used here are estimated to be about 5.5 $GtCO_2$ yr^{-1} higher than the aggregate global net emissions based on national GHG inventories. This difference, which has been considered in the literature, mainly reflects differences in how anthropogenic forest sinks and areas of managed land are defined. Other reasons for this difference, which are more difficult to quantify, can arise from the limited representation of land management in global models and varying levels of accuracy and completeness of estimated LULUCF fluxes in national GHG inventories. Neither method is inherently preferable. Even when the same methodological approach is applied, the large uncertainty of CO_2-LULUCF emissions can lead to substantial revisions to estimated emissions. {Cross-Chapter Box 3 in Chapter 3, 7.2, SRCCL SPM A.3.3}

[10] For consistency with WGI, historical cumulative CO_2 emissions from 1850 to 2019 are reported using 68% confidence intervals.

warming levels.[11,12] Based on central estimates only, historical cumulative net CO_2 emissions between 1850 and 2019 amount to about four-fifths[12] of the total carbon budget for a 50% probability of limiting global warming to 1.5°C (central estimate about 2900 $GtCO_2$), and to about two thirds[12] of the total carbon budget for a 67% probability to limit global warming to 2°C (central estimate about 3550 $GtCO_2$). {Figure 2.7, 2.2, Figure TS.3, WGI Table SPM.2}

B.1.4 Emissions of CO_2-FFI dropped temporarily in the first half of 2020 due to responses to the COVID-19 pandemic (*high confidence*), but rebounded by the end of the year (*medium confidence*). The annual average CO_2-FFI emissions reduction in 2020 relative to 2019 was about 5.8% [5.1–6.3%], or 2.2 [1.9–2.4] $GtCO_2$ (*high confidence*). The full GHG emissions impact of the COVID-19 pandemic could not be assessed due to a lack of data regarding non-CO_2 GHG emissions in 2020. {Cross-Chapter Box 1 in Chapter 1, Figure 2.6, 2.2, Box TS.1, Box TS.1 Figure 1}

Global net anthropogenic emissions have continued to rise across all major groups of greenhouse gases.



	2019 emissions ($GtCO_2$-eq)	1990–2019 increase ($GtCO_2$-eq)	Emissions in 2019, relative to 1990 (%)
CO_2-FFI	38 ± 3	15	167
CO_2-LULUCF	6.6 ± 4.6	1.6	133
CH_4	11 ± 3.2	2.4	129
N_2O	2.7 ± 1.6	0.65	133
F-gases	1.4 ± 0.41	0.97	354
Total	59 ± 6.6	21	154

Figure SPM.1 | Global net anthropogenic GHG emissions ($GtCO_2$-eq yr^{-1}) 1990–2019. Global net anthropogenic GHG emissions include CO_2 from fossil fuel combustion and industrial processes (CO_2-FFI); net CO_2 from land use, land-use change and forestry (CO_2-LULUCF)[9]; methane (CH_4); nitrous oxide (N_2O); and fluorinated gases (HFCs, PFCs, SF_6, NF_3).[6] **Panel a** shows aggregate annual global net anthropogenic GHG emissions by groups of gases from 1990 to 2019 reported in $GtCO_2$-eq converted based on global warming potentials with a 100-year time horizon (GWP100-AR6) from the IPCC Sixth Assessment Report Working Group I (Chapter 7). The fraction of global emissions for each gas is shown for 1990, 2000, 2010 and 2019; as well as the aggregate average annual growth rate between these decades. At the right side of Panel a, GHG emissions in 2019 are broken down into individual components with the associated uncertainties (90% confidence interval) indicated by the error bars: CO_2-FFI ±8%; CO_2-LULUCF ±70%; CH_4 ±30%; N_2O ±60%; F-gases ±30%; GHG ±11%. Uncertainties in GHG emissions are assessed in Supplementary Material 2.2. The single-year peak of emissions in 1997 was due to higher CO_2-LULUCF emissions from a forest and peat fire event in South East Asia. **Panel b** shows global anthropogenic CO_2-FFI, net CO_2-LULUCF, CH_4, N_2O and F-gas emissions individually for the period 1990–2019, normalised relative to 100 in 1990. Note the different scale for the included F-gas emissions compared to other gases, highlighting its rapid growth from a low base. Shaded areas indicate the uncertainty range. Uncertainty ranges as shown here are specific for individual groups of greenhouse gases and cannot be compared. The table shows the central estimate for: absolute emissions in 2019; the absolute change in emissions between 1990 and 2019; and emissions in 2019 expressed as a percentage of 1990 emissions. {2.2, Figure 2.5, Supplementary Material 2.2, Figure TS.2}

[11] The carbon budget is the maximum amount of cumulative net global anthropogenic CO_2 emissions that would result in limiting global warming to a given level with a given likelihood, taking into account the effect of other anthropogenic climate forcers. This is referred to as the 'total carbon budget' when expressed starting from the pre-industrial period, and as the 'remaining carbon budget' when expressed from a recent specified date. The total carbon budgets reported here are the sum of historical emissions from 1850 to 2019 and the remaining carbon budgets from 2020 onwards, which extend until global net zero CO_2 emissions are reached. {Annex I: Glossary; WGI SPM}

[12] Uncertainties for total carbon budgets have not been assessed and could affect the specific calculated fractions.

B.2 Net anthropogenic GHG emissions have increased since 2010 across all major sectors globally. An increasing share of emissions can be attributed to urban areas. Emissions reductions in CO_2 from fossil fuels and industrial processes (CO_2-FFI), due to improvements in energy intensity of GDP and carbon intensity of energy, have been less than emissions increases from rising global activity levels in industry, energy supply, transport, agriculture and buildings. (*high confidence*) {2.2, 2.4, 6.3, 7.2, 8.3, 9.3, 10.1, 11.2}

B.2.1 In 2019, approximately 34% (20 $GtCO_2$-eq) of total net anthropogenic GHG emissions came from the energy supply sector, 24% (14 $GtCO_2$-eq) from industry, 22% (13 $GtCO_2$-eq) from agriculture, forestry and other land use (AFOLU), 15% (8.7 $GtCO_2$-eq) from transport and 6% (3.3 $GtCO_2$-eq) from buildings.[13] If emissions from electricity and heat production are attributed to the sectors that use the final energy, 90% of these indirect emissions are allocated to the industry and buildings sectors, increasing their relative GHG emissions shares from 24% to 34%, and from 6% to 16%, respectively. After reallocating emissions from electricity and heat production, the energy supply sector accounts for 12% of global net anthropogenic GHG emissions. (*high confidence*) {Figure 2.12, 2.2, 6.3, 7.2, 9.3, 10.1, 11.2, Figure TS.6}

B.2.2 Average annual GHG emissions growth between 2010 and 2019 slowed compared to the previous decade in energy supply (from 2.3% to 1.0%) and industry (from 3.4% to 1.4%), but remained roughly constant at about 2% yr^{-1} in the transport sector (*high confidence*). Emissions growth in AFOLU, comprising emissions from agriculture (mainly CH_4 and N_2O) and forestry and other land use (mainly CO_2) is more uncertain than in other sectors due to the high share and uncertainty of CO_2-LULUCF emissions (*medium confidence*). About half of total net AFOLU emissions are from CO_2-LULUCF, predominantly from deforestation[14] (*medium confidence*). {Figure 2.13, 2.2, 6.3, 7.2, Figure 7.3, 9.3, 10.1, 11.2, TS.3}

B.2.3 The global share of emissions that can be attributed to urban areas is increasing. In 2015, urban emissions were estimated to be 25 $GtCO_2$-eq (about 62% of the global share) and in 2020, 29 $GtCO_2$-eq (67–72% of the global share).[15] The drivers of urban GHG emission are complex and include population size, income, state of urbanisation and urban form. (*high confidence*) {8.1, 8.3}

B.2.4 Global energy intensity (total primary energy per unit GDP) decreased by 2% yr^{-1} between 2010 and 2019. Carbon intensity (CO_2 from fossil fuel combustion and industrial processes (CO_2-FFI) per unit primary energy) decreased by 0.3% yr^{-1}, with large regional variations, over the same period mainly due to fuel switching from coal to gas, reduced expansion of coal capacity, and increased use of renewables. This reversed the trend observed for 2000–2009. For comparison, the carbon intensity of primary energy is projected to decrease globally by about 3.5% yr^{-1} between 2020 and 2050 in modelled scenarios that limit warming to 2°C (>67%), and by about 7.7% yr^{-1} globally in scenarios that limit warming to 1.5°C (>50%) with no or limited overshoot.[16] (*high confidence*) {Figure 2.16, 2.2, 2.4, Table 3.4, 3.4, 6.3}

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[13] Sector definitions can be found in Annex II.9.1.

[14] Land overall constituted a net sink of –6.6 (±4.6) $GtCO_2\,yr^{-1}$ for the period 2010–2019, comprising a gross sink of –12.5 (±3.2) $GtCO_2\,yr^{-1}$ resulting from responses of all land to both anthropogenic environmental change and natural climate variability, and net anthropogenic CO_2-LULUCF emissions +5.7 (±4.0) $GtCO_2\,yr^{-1}$ based on bookkeeping models. {Table 2.1, 7.2, Table 7.1}

[15] This estimate is based on consumption-based accounting, including both direct emissions from within urban areas, and indirect emissions from outside urban areas related to the production of electricity, goods and services consumed in cities. These estimates include all CO_2 and CH_4 emission categories except for aviation and marine bunker fuels, land-use change, forestry and agriculture. {8.1, Annex I: Glossary}

[16] See Box SPM.1 for the categorisation of modelled long-term emission scenarios based on projected temperature outcomes and associated probabilities adopted in this report.

B.3 Regional contributions[17] to global GHG emissions continue to differ widely. Variations in regional, and national per capita emissions partly reflect different development stages, but they also vary widely at similar income levels. The 10% of households with the highest per capita emissions contribute a disproportionately large share of global household GHG emissions. At least 18 countries have sustained GHG emission reductions for longer than 10 years. (*high confidence*) (Figure SPM.2) {Figure 1.1, Figure 2.9, Figure 2.10, Figure 2.25, 2.2, 2.3, 2.4, 2.5, 2.6, Figure TS.4, Figure TS.5}

B.3.1 GHG emissions trends over 1990–2019 vary widely across regions and over time, and across different stages of development, as shown in Figure SPM.2. Average global per capita net anthropogenic GHG emissions increased from 7.7 to 7.8 tCO_2-eq, ranging from 2.6 tCO_2-eq to 19 tCO_2-eq across regions. Least developed countries (LDCs) and Small Island Developing States (SIDS) have much lower per capita emissions (1.7 tCO_2-eq and 4.6 tCO_2-eq, respectively) than the global average (6.9 tCO_2-eq), excluding CO_2-LULUCF.[18] (*high confidence*) (Figure SPM.2) {Figure1.2, Figure 2.9, Figure 2.10, 2.2, Figure TS.4}

B.3.2 Historical contributions to cumulative net anthropogenic CO_2 emissions between 1850 and 2019 vary substantially across regions in terms of total magnitude, but also in terms of contributions to CO_2-FFI (1650 ± 73 $GtCO_2$-eq) and net CO_2-LULUCF (760 ± 220 $GtCO_2$-eq) emissions.[10] Globally, the major share of cumulative CO_2-FFI emissions is concentrated in a few regions, while cumulative CO_2-LULUCF[9] emissions are concentrated in other regions. LDCs contributed less than 0.4% of historical cumulative CO_2-FFI emissions between 1850 and 2019, while SIDS contributed 0.5%. (*high confidence*) (Figure SPM.2) {Figure 2.10, 2.2, TS.3, Figure 2.7}

B.3.3 In 2019, around 48% of the global population lives in countries emitting on average more than 6 tCO_2-eq per capita, excluding CO_2-LULUCF. 35% live in countries emitting more than 9 tCO_2-eq per capita. Another 41% live in countries emitting less than 3 tCO_2-eq per capita. A substantial share of the population in these low-emitting countries lack access to modern energy services.[19] Eradicating extreme poverty, energy poverty, and providing decent living standards[20] to all in these regions in the context of achieving sustainable development objectives, in the near-term, can be achieved without significant global emissions growth. (*high confidence*) (Figure SPM.2) {Figure 1.2, 2.2, 2.4, 2.6, 3.7, 4.2, 6.7, Figure TS.4, Figure TS.5}

B.3.4 Globally, the 10% of households with the highest per capita emissions contribute 34–45% of global consumption-based household GHG emissions,[21] while the middle 40% contribute 40–53%, and the bottom 50% contribute 13–15%. (*high confidence*) {2.6, Figure 2.25}

B.3.5 At least 18 countries have sustained production-based GHG and consumption-based CO_2 emission reductions for longer than 10 years. Reductions were linked to energy supply decarbonisation, energy efficiency gains, and energy demand reduction, which resulted from both policies and changes in economic structure. Some countries have reduced production-based GHG emissions by a third or more since peaking, and some have achieved several years of consecutive reduction rates of around 4% yr^{-1}, comparable to global reductions in scenarios limiting warming to 2°C (>67%) or lower. These reductions have only partly offset global emissions growth. (*high confidence*) (Figure SPM.2) {Figure TS.4, 2.2, 1.3.2}

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17 See Annex II, Part 1 for regional groupings adopted in this report.

18 In 2019, LDCs are estimated to have emitted 3.3% of global GHG emissions, and SIDS are estimated to have emitted 0.6% of global GHG emissions, excluding CO_2-LULUCF. These country groupings cut across geographic regions and are not depicted separately in Figure SPM.2. {Figure 2.10}

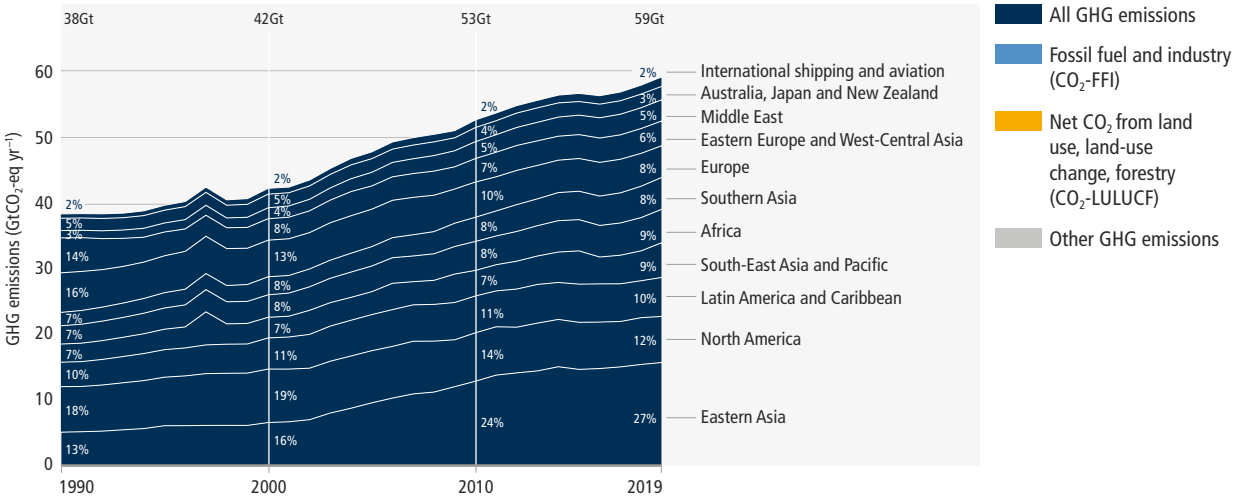
19 In this report, access to modern energy services is defined as access to clean, reliable and affordable energy services for cooking and heating, lighting, communications, and productive uses. {Annex I: Glossary}

20 In this report, decent living standards are defined as a set of minimum material requirements essential for achieving basic human well-being, including nutrition, shelter, basic living conditions, clothing, health care, education, and mobility. {5.1}

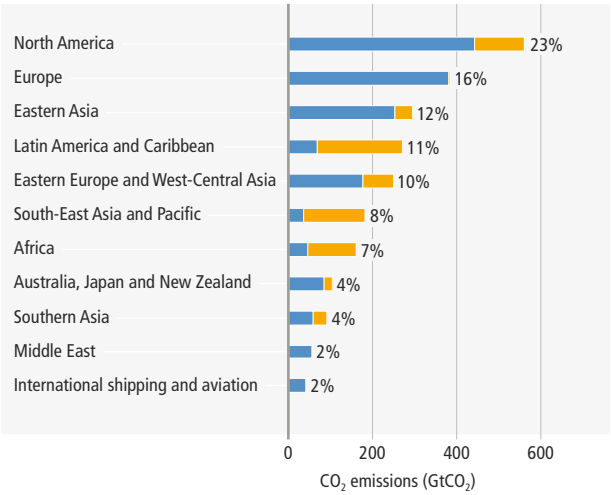
21 Consumption-based emissions refer to emissions released to the atmosphere to generate the goods and services consumed by a certain entity (e.g., a person, firm, country, or region). The bottom 50% of emitters spend less than USD3 PPP (purchasing power parity) per capita per day. The top 10% of emitters (an open-ended category) spend more than USD23 PPP per capita per day. The wide range of estimates for the contribution of the top 10% results from the wide range of spending in this category and differing methods in the assessed literature. {2.6, Annex I: Glossary}

Emissions have grown in most regions but are distributed unevenly, both in the present day and cumulatively since 1850.

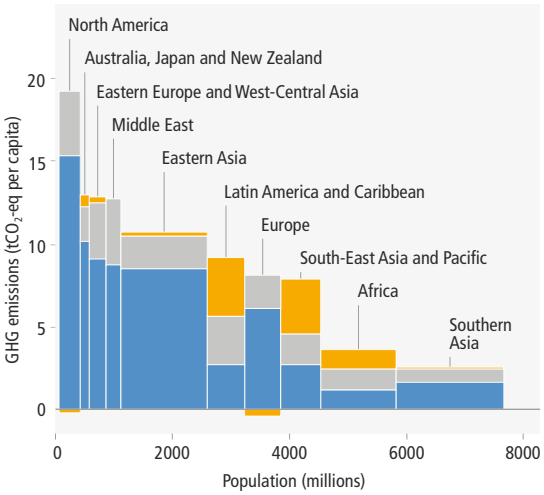
a. Global net anthropogenic GHG emissions by region (1990–2019)



b. Historical cumulative net anthropogenic CO_2 emissions per region (1850–2019)



c. Net anthropogenic GHG emissions per capita and for total population, per region (2019)



d. Regional indicators (2019) and regional production vs consumption accounting (2018)

	Africa	Australia, Japan, New Zealand	Eastern Asia	Eastern Europe, West-Central Asia	Europe	Latin America and Caribbean	Middle East	North America	South-East Asia and Pacific	Southern Asia
Population (million persons, 2019)	1292	157	1471	291	620	646	252	366	674	1836
GDP per capita (USD1000$_{ppp}$2017 per person)[1]	5.0	43	17	20	43	15	20	61	12	6.2
Net GHG 2019[2] (production basis)										
% GHG contributions	9%	3%	27%	6%	8%	10%	5%	12%	9%	8%
GHG emissions intensity (tCO_2-eq / USD1000$_{ppp}$ 2017)	0.78	0.30	0.62	0.64	0.18	0.61	0.64	0.31	0.65	0.42
GHG per capita (tCO_2-eq per person)	3.9	13	11	13	7.8	9.2	13	19	7.9	2.6
CO_2-FFI, 2018, per person										
Production-based emissions (tCO_2-FFI per person, based on 2018 data)	1.2	10	8.4	9.2	6.5	2.8	8.7	16	2.6	1.6
Consumption-based emissions (tCO_2-FFI per person, based on 2018 data)	0.84	11	6.7	6.2	7.8	2.8	7.6	17	2.5	1.5

[1] GDP per capita in 2019 in USD2017 currency purchasing power basis.
[2] Includes CO_2-FFI, CO_2-LULUCF and Other GHGs, excluding international aviation and shipping.

The regional groupings used in this figure are for statistical purposes only and are described in Annex II, Part I.

Figure SPM.2 | Regional GHG emissions, and the regional proportion of total cumulative production-based CO_2 emissions from 1850 to 2019.

Figure SPM.2 (continued): Regional GHG emissions, and the regional proportion of total cumulative production-based CO_2 emissions from 1850 to 2019. Panel a shows global net anthropogenic GHG emissions by region (in $GtCO_2$-eq yr^{-1} (GWP100-AR6)) for the time period 1990–2019.[6] Percentage values refer to the contribution of each region to total GHG emissions in each respective time period. The single-year peak of emissions in 1997 was due to higher CO_2-LULUCF emissions from a forest and peat fire event in South East Asia. Regions are as grouped in Annex II. **Panel b** shows the share of historical cumulative net anthropogenic CO_2 emissions per region from 1850 to 2019 in $GtCO_2$. This includes CO_2 from fossil fuel combustion and industrial processes (CO_2-FFI) and net CO_2 emissions from land use, land-use change, forestry (CO_2-LULUCF). Other GHG emissions are not included.[6] CO_2-LULUCF emissions are subject to high uncertainties, reflected by a global uncertainty estimate of ±70% (90% confidence interval). **Panel c** shows the distribution of regional GHG emissions in tonnes CO_2-eq per capita by region in 2019. GHG emissions are categorised into: CO_2-FFI; net CO_2-LULUCF; and other GHG emissions (methane, nitrous oxide, fluorinated gases, expressed in CO_2-eq using GWP100-AR6). The height of each rectangle shows per capita emissions, the width shows the population of the region, so that the area of the rectangles refers to the total emissions for each region. Emissions from international aviation and shipping are not included. In the case of two regions, the area for CO_2-LULUCF is below the axis, indicating net CO_2 removals rather than emissions. CO_2-LULUCF emissions are subject to high uncertainties, reflected by a global uncertainty estimate of ±70% (90% confidence interval). **Panel d** shows population, GDP per person, emission indicators by region in 2019 for percentage GHG contributions, total GHG per person, and total GHG emissions intensity, together with production-based and consumption-based CO_2-FFI data, which is assessed in this report up to 2018. Consumption-based emissions are emissions released to the atmosphere in order to generate the goods and services consumed by a certain entity (e.g., region). Emissions from international aviation and shipping are not included. {1.3, Figure 1.2, 2.2, Figure 2.9, Figure 2.10, Figure 2.11, Annex II}

B.4 The unit costs of several low-emission technologies have fallen continuously since 2010. Innovation policy packages have enabled these cost reductions and supported global adoption. Both tailored policies and comprehensive policies addressing innovation systems have helped overcome the distributional, environmental and social impacts potentially associated with global diffusion of low-emission technologies. Innovation has lagged in developing countries due to weaker enabling conditions. Digitalisation can enable emission reductions, but can have adverse side effects unless appropriately governed. (*high confidence*) (Figure SPM.3) {2.2, 6.3, 6.4, 7.2, 12.2, 16.2, 16.4, 16.5, Cross-Chapter Box 11 in Chapter 16}

B.4.1 From 2010 to 2019, there have been sustained decreases in the unit costs of solar energy (85%), wind energy (55%), and lithium-ion batteries (85%), and large increases in their deployment, e.g., >10× for solar and >100× for electric vehicles (EVs), varying widely across regions (Figure SPM.3). The mix of policy instruments which reduced costs and stimulated adoption includes public R&D, funding for demonstration and pilot projects, and demand pull instruments such as deployment subsidies to attain scale. In comparison to modular small-unit size technologies, the empirical record shows that multiple large-scale mitigation technologies, with fewer opportunities for learning, have seen minimal cost reductions and their adoption has grown slowly. (*high confidence*) {1.3, 1.5, Figure 2.5, 2.5, 6.3, 6.4, 7.2, 11.3, 12.2, 12.3, 12.6, 13.6, 16.3, 16.4, 16.6}

B.4.2 Policy packages tailored to national contexts and technological characteristics have been effective in supporting low-emission innovation and technology diffusion. Appropriately designed policies and governance have helped address distributional impacts and rebound effects. Innovation has provided opportunities to lower emissions and reduce emission growth and created social and environmental co-benefits (*high confidence*). Adoption of low-emission technologies lags in most developing countries, particularly least developed ones, due in part to weaker enabling conditions, including limited finance, technology development and transfer, and capacity. In many countries, especially those with limited institutional capacities, several adverse side effects have been observed as a result of diffusion of low-emission technology, for example, low-value employment, and dependency on foreign knowledge and suppliers. Low-emission innovation along with strengthened enabling conditions can reinforce development benefits, which can, in turn, create feedbacks towards greater public support for policy. (*medium confidence*) {9.9, 13.6, 13.7, 16.3, 16.4, 16.5, 16.6, Cross-Chapter Box 12 in Chapter 16, TS.3}

B.4.3 Digital technologies can contribute to mitigation of climate change and the achievement of several SDGs (*high confidence*). For example, sensors, internet of things, robotics, and artificial intelligence can improve energy management in all sectors, increase energy efficiency, and promote the adoption of many low-emission technologies, including decentralised renewable energy, while creating economic opportunities (*high confidence*). However, some of these climate change mitigation gains can be reduced or counterbalanced by growth in demand for goods and services due to the use of digital devices (*high confidence*). Digitalisation can involve trade-offs across several SDGs, for example, increasing electronic waste, negative impacts on labour markets, and exacerbating the existing digital divide. Digital technology supports decarbonisation only if appropriately governed (*high confidence*). {5.3, 10, 12.6, 16.2, Cross-Chapter Box 11 in Chapter 16, TS.5, Box TS.14}

The unit costs of some forms of renewable energy and of batteries for passenger EVs have fallen, and their use continues to rise.

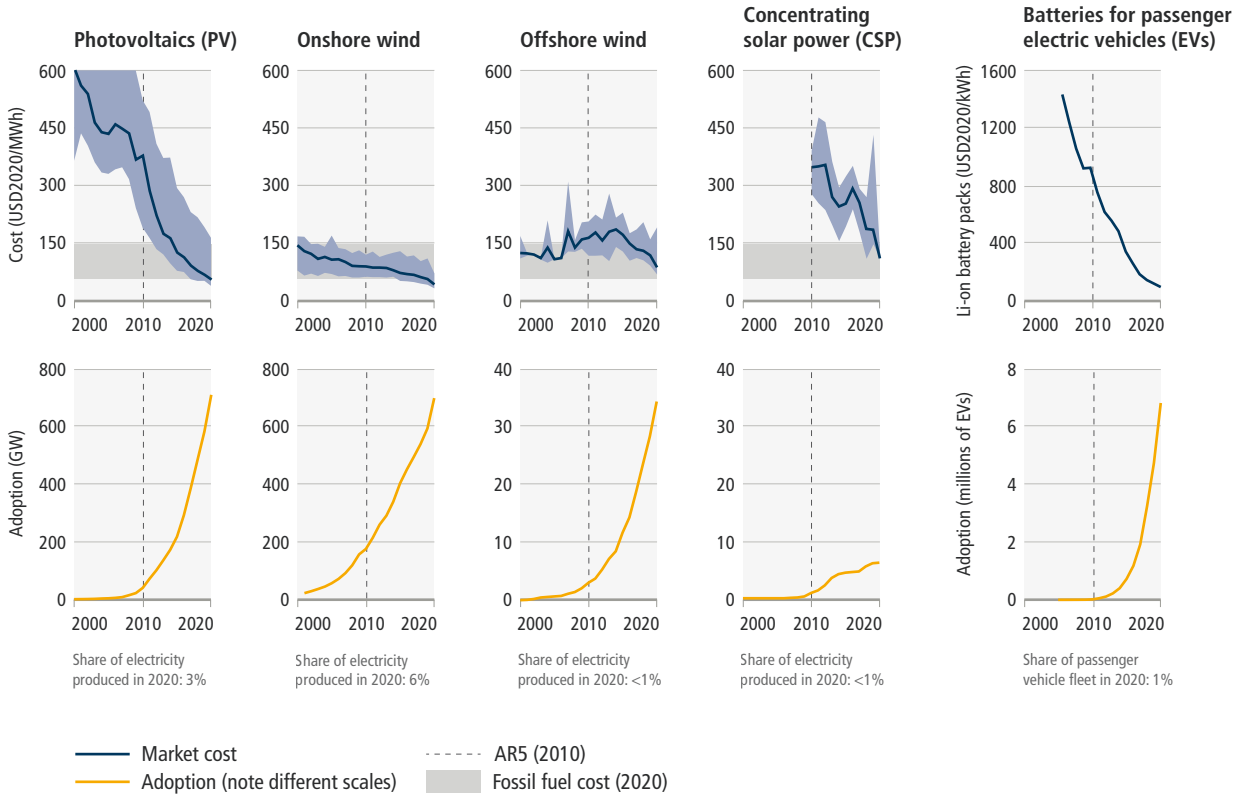


Figure SPM.3 | Unit cost reductions and use in some rapidly changing mitigation technologies. The **top panel** shows global costs per unit of energy (USD per MWh) for some rapidly changing mitigation technologies. Solid blue lines indicate average unit cost in each year. Light blue shaded areas show the range between the 5th and 95th percentiles in each year. Grey shading indicates the range of unit costs for new fossil fuel (coal and gas) power in 2020 (corresponding to USD55–148 per MWh). In 2020, the levelised costs of energy (LCOE) of the four renewable energy technologies could compete with fossil fuels in many places. For batteries, costs shown are for 1 kWh of battery storage capacity; for the others, costs are LCOE, which includes installation, capital, operations, and maintenance costs per MWh of electricity produced. The literature uses LCOE because it allows consistent comparisons of cost trends across a diverse set of energy technologies to be made. However, it does not include the costs of grid integration or climate impacts. Further, LCOE does not take into account other environmental and social externalities that may modify the overall (monetary and non-monetary) costs of technologies and alter their deployment. The **bottom panel** shows cumulative global adoption for each technology, in GW of installed capacity for renewable energy and in millions of vehicles for battery-electric vehicles. A vertical dashed line is placed in 2010 to indicate the change since AR5. Shares of electricity produced and share of passenger vehicle fleet are indicated in text for 2020 based on provisional data, i.e., percentage of total electricity production (for PV, onshore wind, offshore wind, CSP) and of total stock of passenger vehicles (for EVs). The electricity production share reflects different capacity factors; for example, for the same amount of installed capacity, wind produces about twice as much electricity as solar PV. {2.5, 6.4} Renewable energy and battery technologies were selected as illustrative examples because they have recently shown rapid changes in costs and adoption, and because consistent data are available. Other mitigation options assessed in the report are not included as they do not meet these criteria.

B.5 There has been a consistent expansion of policies and laws addressing mitigation since AR5. This has led to the avoidance of emissions that would otherwise have occurred and increased investment in low-GHG technologies and infrastructure. Policy coverage of emissions is uneven across sectors. Progress on the alignment of financial flows towards the goals of the Paris Agreement remains slow and tracked climate finance flows are distributed unevenly across regions and sectors. (*high confidence*) {5.6, 13.2, 13.4, 13.5, 13.6, 13.9, 14.3, 14.4, 14.5, Cross-Chapter Box 10 in Chapter 14, 15.3, 15.5}

B.5.1 The Kyoto Protocol led to reduced emissions in some countries and was instrumental in building national and international capacity for GHG reporting, accounting and emissions markets (*high confidence*). At least 18 countries that had Kyoto targets for the first commitment period have had sustained absolute emission reductions for at least a decade from 2005, of which two were countries with economies in transition (*very high confidence*). The Paris Agreement, with near universal participation, has led to policy development and target-setting at national and sub-national levels, in particular in relation to mitigation, as well as enhanced transparency of climate action and support (*medium confidence*). {14.3, 14.6}

B.5.2 The application of diverse policy instruments for mitigation at the national and sub-national levels has grown consistently across a range of sectors (*high confidence*). By 2020, over 20% of global GHG emissions were covered by carbon taxes or emissions trading systems, although coverage and prices have been insufficient to achieve deep reductions (*medium confidence*). By 2020, there were 'direct' climate laws focused primarily on GHG reductions in 56 countries covering 53% of global emissions (*medium confidence*). Policy coverage remains limited for emissions from agriculture and the production of industrial materials and feedstocks (*high confidence*). {5.6, 7.6, 11.5, 11.6, 13.2, 13.6}

B.5.3 In many countries, policies have enhanced energy efficiency, reduced rates of deforestation and accelerated technology deployment, leading to avoided and in some cases reduced or removed emissions (*high confidence*). Multiple lines of evidence suggest that mitigation policies have led to avoided global emissions of several $GtCO_2$-eq yr^{-1} (*medium confidence*). At least 1.8 $GtCO_2$-eq yr^{-1} can be accounted for by aggregating separate estimates for the effects of economic and regulatory instruments. Growing numbers of laws and executive orders have impacted global emissions and were estimated to result in 5.9 $GtCO_2$-eq yr^{-1} less emissions in 2016 than they otherwise would have been. (*medium confidence*) (Figure SPM.3) {2.2, 2.8, 6.7, 7.6, 9.9, 10.8, 13.6, Cross-chapter Box 10 in Chapter 14}

B.5.4 Annual tracked total financial flows for climate mitigation and adaptation increased by up to 60% between 2013/14 and 2019/20 (in USD2015), but average growth has slowed since 2018[22] (*medium confidence*). These financial flows remained heavily focused on mitigation, are uneven, and have developed heterogeneously across regions and sectors (*high confidence*). In 2018, public and publicly mobilised private climate finance flows from developed to developing countries were below the collective goal under the UNFCCC and Paris Agreement to mobilise USD100 billion per year by 2020 in the context of meaningful mitigation action and transparency on implementation (*medium confidence*). Public and private finance flows for fossil fuels are still greater than those for climate adaptation and mitigation (*high confidence*). Markets for green bonds, ESG (environmental, social and governance) and sustainable finance products have expanded significantly since AR5. Challenges remain, in particular around integrity and additionality, as well as the limited applicability of these markets to many developing countries. (*high confidence*) {Box 15.4, 15.3, 15.5, 15.6, Box 15.7}

[22] Estimates of financial flows (comprising both private and public, domestic and international flows) are based on a single report which assembles data from multiple sources and which has applied various changes to their methodology over the past years. Such data can suggest broad trends but is subject to uncertainties.

B.6 Global GHG emissions in 2030 associated with the implementation of Nationally Determined Contributions (NDCs) announced prior to COP26[23] would make it *likely* that warming will exceed 1.5°C during the 21st century.[24] *Likely* limiting warming to below 2°C would then rely on a rapid acceleration of mitigation efforts after 2030. Policies implemented by the end of 2020[25] are projected to result in higher global GHG emissions than those implied by NDCs. (*high confidence*) (Figure SPM.4) {3.3, 3.5, 4.2, Cross-Chapter Box 4 in Chapter 4}

B.6.1 Policies implemented by the end of 2020 are projected to result in higher global GHG emissions than those implied by NDCs, indicating an implementation gap. A gap remains between global GHG emissions in 2030 associated with the implementation of NDCs announced prior to COP26 and those associated with modelled mitigation pathways assuming immediate action (for quantification see Table SPM.1).[26] The magnitude of the emissions gap depends on the global warming level considered and whether only unconditional or also conditional elements of NDCs[27] are considered.[28] (*high confidence*) {3.5, 4.2, Cross-Chapter Box 4 in Chapter 4}

B.6.2 Global emissions in 2030 associated with the implementation of NDCs announced prior to COP26 are lower than the emissions implied by the original NDCs[29] (*high confidence*). The original emissions gap has fallen by about 20% to one-third relative to pathways that limit warming to 2°C (>67%) with immediate action (category C3a in Table SPM.2), and by about 15–20% relative to pathways limiting warming to 1.5°C (>50%) with no or limited overshoot (category C1 in Table SPM.2) (*medium confidence*). (Figure SPM.4) {3.5, 4.2, Cross-Chapter Box 4 in Chapter 4}

Table SPM.1 | Projected global emissions in 2030 associated with policies implemented by the end of 2020 and NDCs announced prior to COP26, and associated emissions gaps. *Emissions projections for 2030 and absolute differences in emissions are based on emissions of 52–56 $GtCO_2$-eq yr^{-1} in 2019 as assumed in underlying model studies. (*medium confidence*) {4.2, Table 4.3, Cross-Chapter Box 4 in Chapter 4}

	Implied by policies implemented by the end of 2020 ($GtCO_2$-eq yr^{-1})	Implied by NDCs announced prior to COP26	
		Unconditional elements ($GtCO_2$-eq yr^{-1})	Including conditional elements ($GtCO_2$-eq yr^{-1})
Median projected global emissions (min–max)*	57 [52–60]	53 [50–57]	50 [47–55]
Implementation gap between implemented policies and NDCs (median)		4	7
Emissions gap between NDCs and pathways that limit warming to 2°C (>67%) with immediate action		10–16	6–14
Emissions gap between NDCs and pathways that limit warming to 1.5°C (>50%) with no or limited overshoot with immediate action		19–26	16–23

[23] NDCs announced prior to COP26 refer to the most recent Nationally Determined Contributions submitted to the UNFCCC up to the literature cut-off date of this report, 11 October 2021, and revised NDCs announced by China, Japan and the Republic of Korea prior to October 2021 but only submitted thereafter. 25 NDC updates were submitted between 12 October 2021 and the start of COP26.

[24] This implies that mitigation after 2030 can no longer establish a pathway with less than 67% probability to exceed 1.5°C during the 21st century, a defining feature of the class of pathways that limit warming to 1.5°C (>50%) with no or limited overshoot assessed in this report (category C1 in Table SPM.2). These pathways limit warming to 1.6°C or lower throughout the 21st century with a 50% likelihood.

[25] The policy cut-off date in studies used to project GHG emissions of 'policies implemented by the end of 2020' varies between July 2019 and November 2020. {Table 4.2}

[26] Immediate action in modelled global pathways refers to the adoption between 2020 and at latest before 2025 of climate policies intended to limit global warming to a given level. Modelled pathways that limit warming to 2°C (>67%) based on immediate action are summarised in category C3a in Table SPM.2. All assessed modelled global pathways that limit warming to 1.5°C (>50%) with no or limited overshoot assume immediate action as defined here (Category C1 in Table SPM.2).

[27] In this report, 'unconditional' elements of NDCs refer to mitigation efforts put forward without any conditions. 'Conditional' elements refer to mitigation efforts that are contingent on international cooperation, for example bilateral and multilateral agreements, financing or monetary and/or technological transfers. This terminology is used in the literature and the UNFCCC's NDC Synthesis Reports, not by the Paris Agreement. {4.2.1, 14.3.2}

[28] Two types of gaps are assessed: the implementation gap is calculated as the difference between the median of global emissions in 2030 implied by policies implemented by the end of 2020 and those implied by NDCs announced prior to COP26. The emissions gap is calculated as the difference between GHG emissions implied by the NDCs (minimum/maximum emissions in 2030) and the median of global GHG emissions in modelled pathways limiting warming to specific levels based on immediate action and with stated likelihoods as indicated (Table SPM.2).

[29] Original NDCs refer to those submitted to the UNFCCC in 2015 and 2016. Unconditional elements of NDCs announced prior to COP26 imply global GHG emissions in 2030 that are 3.8 [3.0–5.3] $GtCO_2$-eq yr^{-1} lower than those from the original NDCs, and 4.5 [2.7–6.3] $GtCO_2$-eq yr^{-1} lower when conditional elements of NDCs are included. NDC updates at or after COP26 could further change the implied emissions.

B.6.3 Modelled global emission pathways consistent with NDCs announced prior to COP26 that limit warming to 2°C (>67%) (category C3b in Table SPM.2) imply annual average global GHG emissions reduction rates of 0–0.7 $GtCO_2$-eq yr^{-1} during the decade 2020–2030, with an unprecedented acceleration to 1.4–2.0 $GtCO_2$-eq yr^{-1} during 2030–2050 (*medium confidence*). Continued investments in unabated high-emitting infrastructure and limited development and deployment of low-emitting alternatives prior to 2030 would act as barriers to this acceleration and increase feasibility risks (*high confidence*). {3.3, 3.5, 3.8, Cross-Chapter Box 5 in Chapter 4}

B.6.4 Modelled global emission pathways consistent with NDCs announced prior to COP26 will *likely* exceed 1.5°C during the 21st century. Those pathways that then return warming to 1.5°C by 2100 with a likelihood of 50% or greater imply a temperature overshoot of 0.15°C–0.3°C (42 pathways in category C2 in Table SPM.2). In such pathways, global cumulative net-negative CO_2 emissions are –380 [–860 to –200] $GtCO_2$[30] in the second half of the century, and there is a rapid acceleration of other mitigation efforts across all sectors after 2030. Such overshoot pathways imply increased climate-related risk, and are subject to increased feasibility concerns,[31] and greater social and environmental risks, compared to pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. (*high confidence*) (Figure SPM.4, Table SPM.2) {3.3, 3.5, 3.8, 12.3; AR6 WGII SPM B.6}

Projected global GHG emissions from NDCs announced prior to COP26 would make it *likely* that warming will exceed 1.5°C and also make it harder after 2030 to limit warming to below 2°C.

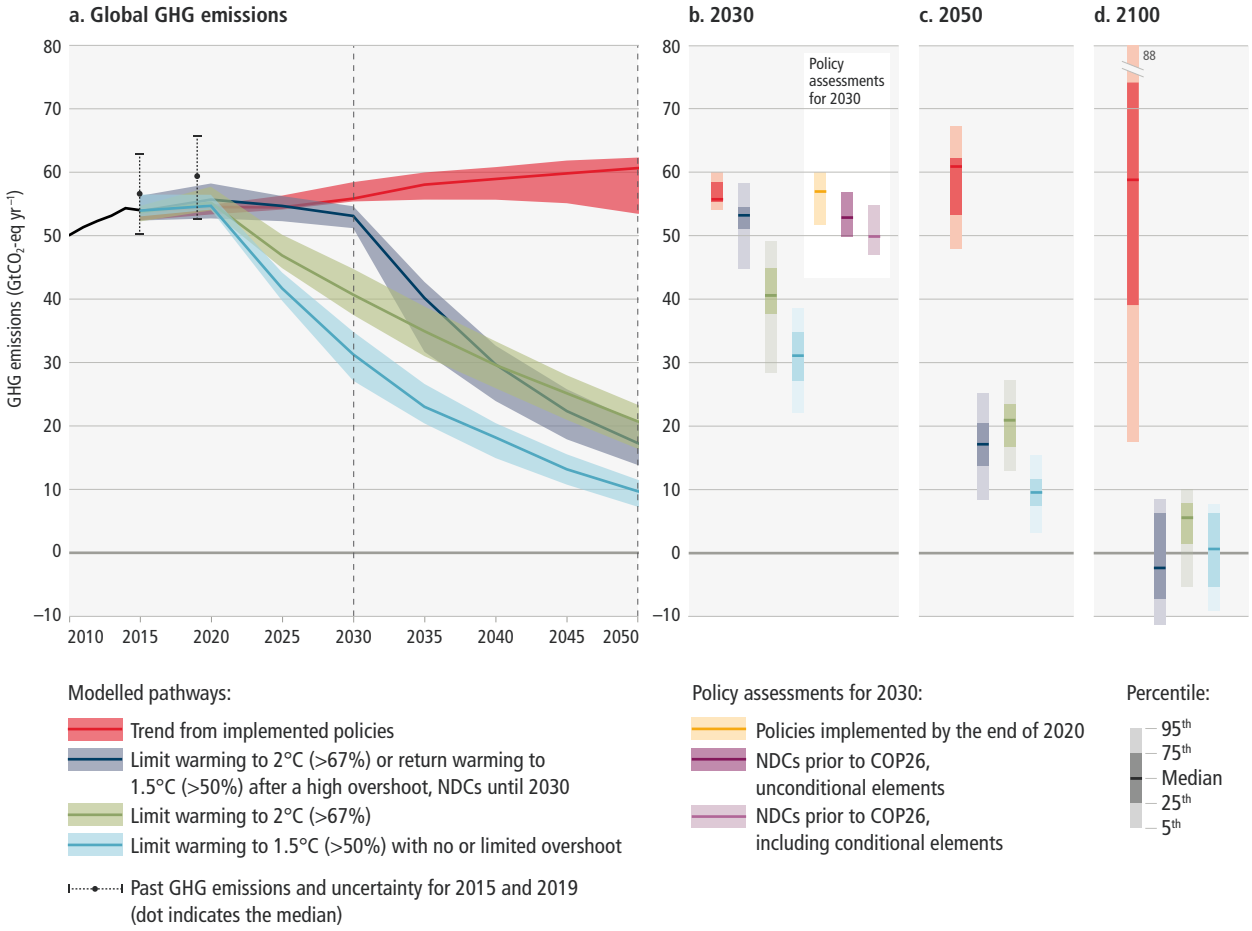


Figure SPM.4 | Global GHG emissions of modelled pathways (funnels in Panel a, and associated bars in Panels b, c, d) and projected emission outcomes from near-term policy assessments for 2030 (Panel b).

[30] Median and *very likely* range [5th to 95th percentile].

[31] Returning to below 1.5°C in 2100 from GHG emissions levels in 2030 associated with the implementation of NDCs is infeasible for some models due to model-specific constraints on the deployment of mitigation technologies and the availability of net negative CO_2 emissions.

Figure SPM.4 (continued): Global GHG emissions of modelled pathways (funnels in Panel a, and associated bars in Panels b, c, d) and projected emission outcomes from near-term policy assessments for 2030 (Panel b). Panel a shows global GHG emissions over 2015–2050 for four types of assessed modelled global pathways:

- Trend from implemented policies: Pathways with projected near-term GHG emissions in line with policies implemented until the end of 2020 and extended with comparable ambition levels beyond 2030 (29 scenarios across categories C5–C7, Table SPM.2).
- Limit to 2°C (>67%) or return warming to 1.5°C (>50%) after a high overshoot, NDCs until 2030: Pathways with GHG emissions until 2030 associated with the implementation of NDCs announced prior to COP26, followed by accelerated emissions reductions *likely* to limit warming to 2°C (C3b, Table SPM.2) or to return warming to 1.5°C with a probability of 50% or greater after high overshoot (subset of 42 scenarios from C2, Table SPM.2).
- Limit to 2°C (>67%) with immediate action: Pathways that limit warming to 2°C (>67%) with immediate action after 2020[26] (C3a, Table SPM.2).
- Limit to 1.5°C (>50%) with no or limited overshoot: Pathways limiting warming to 1.5°C with no or limited overshoot (C1, Table SPM.2 C1). All these pathways assume immediate action after 2020.

Past GHG emissions for 2010–2015 used to project global warming outcomes of the modelled pathways are shown by a black line[32] and past global GHG emissions in 2015 and 2019 as assessed in Chapter 2 are shown by whiskers. **Panels b, c and d** show snapshots of the GHG emission ranges of the modelled pathways in 2030, 2050, and 2100, respectively. Panel b also shows projected emissions outcomes from near-term policy assessments in 2030 from Chapter 4.2 (Tables 4.2 and 4.3; median and full range). GHG emissions are in CO_2-equivalent using GWP100 from AR6 WGI. {3.5, 4.2, Table 4.2, Table 4.3, Cross-Chapter Box 4 in Chapter 4}

B.7 Projected cumulative future CO_2 emissions over the lifetime of existing and currently planned fossil fuel infrastructure without additional abatement exceed the total cumulative net CO_2 emissions in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. They are approximately equal to total cumulative net CO_2 emissions in pathways that limit warming to 2°C (>67%). (*high confidence*) {2.7, 3.3}

B.7.1 If historical operating patterns are maintained,[33] and without additional abatement,[34] estimated cumulative future CO_2 emissions from existing fossil fuel infrastructure, the majority of which is in the power sector, would, from 2018 until the end of its lifetime, amount to 660 [460–890] $GtCO_2$. They would amount to 850 [600–1100] $GtCO_2$ when unabated emissions from currently planned infrastructure in the power sector is included. These estimates compare with cumulative global net CO_2 emissions from all sectors of 510 [330–710] $GtCO_2$ until the time of reaching net zero CO_2 emissions[35] in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and 890 [640–1160] $GtCO_2$ in pathways that limit warming to 2°C (>67%). (*high confidence*) (Table SPM.2) {2.7, Figure 2.26, Figure TS.8}

B.7.2 In modelled global pathways that limit warming to 2°C (>67%) or lower, most remaining fossil fuel CO_2 emissions until the time of global net zero CO_2 emissions are projected to occur outside the power sector, mainly in industry and transport. Decommissioning and reduced utilisation of existing fossil fuel-based power sector infrastructure, retrofitting existing installations with CCS,[36] switches to low-carbon fuels, and cancellation of new coal installations without CCS are major options that can contribute to aligning future CO_2 emissions from the power sector with emissions in the assessed global modelled least-cost pathways. The most appropriate strategies will depend on national and regional circumstances, including enabling conditions and technology availability. (*high confidence*) (Box SPM.1) {Table 2.7, 2.7, 3.4, 6.3, 6.5, 6.7}

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[32] See Box SPM.1 for a description of the approach to project global warming outcomes of modelled pathways and its consistency with the climate assessment in AR6 WGI.

[33] Historical operating patterns are described by load factors and lifetimes of fossil fuel installations as observed in the past (average and range).

[34] Abatement here refers to human interventions that reduce the amount of greenhouse gases that are released from fossil fuel infrastructure to the atmosphere.

[35] Total cumulative CO_2 emissions up to the time of global net zero CO_2 emissions are similar but not identical to the remaining carbon budget for a given temperature limit assessed by Working Group I. This is because the modelled emission scenarios assessed by Working Group III cover a range of temperature levels up to a specific limit, and exhibit a variety of reductions in non-CO_2 emissions that also contribute to overall warming. {Box 3.4}

[36] In this context, capture rates of new installations with CCS are assumed to be 90–95%+ {11.3.5}. Capture rates for retrofit installations can be comparable, if plants are specifically designed for CCS retrofits {11.3.6}.

C. System Transformations to Limit Global Warming

C.1 Global GHG emissions are projected to peak between 2020 and at the latest before 2025 in global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot and in those that limit warming to 2°C (>67%) and assume immediate action (see Table SPM.2 footnote i).[37] In both types of modelled pathways, rapid and deep GHG emissions reductions follow throughout 2030, 2040 and 2050 (*high confidence*). Without a strengthening of policies beyond those that are implemented by the end of 2020, GHG emissions are projected to rise beyond 2025, leading to a median global warming of 3.2 [2.2 to 3.5] °C by 2100[38,39] (*medium confidence*). (Table SPM.2, Figure SPM.4, Figure SPM.5) {3.3, 3.4}

C.1.1 Net global GHG emissions are projected to fall from 2019 levels by 27% [13–45%] by 2030 and 63% [52–76%][40] by 2050 in global modelled pathways that limit warming to 2°C (>67%) and assuming immediate action (category C3a, Table SPM.2). This compares with reductions of 43% [34–60%] by 2030 and 84% [73–98%] by 2050 in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot (C1, Table SPM.2) (*high confidence*).[41] In modelled pathways that return warming to 1.5°C (>50%) after a high overshoot,[42] GHG emissions are reduced by 23% [0–44%] in 2030 and by 75% [62–91%] in 2050 (C2, Table SPM.2) (*high confidence*). Modelled pathways that are consistent with NDCs announced prior to COP26 until 2030 and assume no increase in ambition thereafter have higher emissions, leading to a median global warming of 2.8 [2.1–3.4] °C by 2100 (*medium confidence*).[23] (Figure SPM.4) {3.3}

C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO_2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36–70%] in 2040; and global CH_4 emissions are reduced by 24% [9–53%] in 2030 and by 37% [20–60%] in 2040. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61–109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31–63%] in 2040. There are similar reductions of non-CO_2 emissions by 2050 in both types of pathways: CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [–5 to +55%]; and F-gases are reduced by 85% [20–90%].[43] Across most modelled pathways, this is the maximum technical potential for anthropogenic CH_4 reductions in the underlying models (*high confidence*). Further emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways (*medium confidence*). Higher emissions reductions of CH_4 could further reduce peak warming. (*high confidence*) (Figure SPM.5) {3.3}

C.1.3 In modelled pathways consistent with the continuation of policies implemented by the end of 2020, GHG emissions continue to rise, leading to global warming of 3.2 [2.2–3.5] °C by 2100 (within C5–C7, Table SPM.2) (*medium confidence*). Pathways that exceed warming of >4°C (≥50%) (C8, SSP5-8.5, Table SPM.2) would imply a reversal of current technology and/or mitigation policy trends (*medium confidence*). Such warming could occur in emission pathways consistent with policies implemented by the end of 2020 if climate sensitivity is higher than central estimates (*high confidence*). (Table SPM.2, Figure SPM.4) {3.3, Box 3.3}

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37 All reported warming levels are relative to the period 1850–1900. If not otherwise specified, 'pathways' always refer to pathways computed with a model. Immediate action in the pathways refers to the adoption of climate policies between 2020 and at latest 2025 intended to limit global warming at a given level.

38 Long-term warming is calculated from all modelled pathways assuming mitigation efforts consistent with national policies that were implemented by the end of 2020 (scenarios that fall into policy category P1b of Chapter 3) and that pass through the 2030 GHG emissions ranges of such pathways assessed in Chapter 4 (see footnote 25). {3.2, Table 4.2}

39 Warming estimates refer to the 50th and [5th–95th] percentile across the modelled pathways and the median temperature change estimate of the probabilistic WGI climate model emulators (see Table SPM.2 footnote a).

40 In this report, emissions reductions are reported relative to 2019 modelled emission levels, while in SR1.5 emissions reductions were calculated relative to 2010. Between 2010 and 2019 global GHG and global CO_2 emissions have grown by 12% (6.5 $GtCO_2$-eq) and 13% (5.0 $GtCO_2$) respectively. In global modelled pathways assessed in this report that limit warming to 1.5°C (>50%) with no or limited overshoot, GHG emissions are projected to be reduced by 37% [28–57%] in 2030 relative to 2010. In the same type of pathways assessed in SR1.5, reported GHG emissions reductions in 2030 were 39–51% (interquartile range) relative to 2010. In absolute terms, the 2030 GHG emissions levels of pathways that limit warming to 1.5°C (>50%) with no or limited overshoot are higher in AR6 (31 [21–36] $GtCO_2$-eq) than in SR1.5 (28 (26–31 interquartile range) $GtCO_2$-eq). (Figure SPM.1, Table SPM.2) {3.3, SR1.5 Figure SPM.3b}

41 Scenarios in this category limit peak warming to 2°C throughout the 21st century with close to, or more than, 90% likelihood.

42 This category contains 91 scenarios with immediate action and 42 scenarios that are consistent with the NDCs until 2030.

43 These numbers for CH_4, N_2O, and F-gases are rounded to the nearest 5% except numbers below 5%.

Table SPM.2 | Key characteristics of the modelled global emissions pathways. Summary of projected CO_2 and GHG emissions, projected net zero timings and the resulting global warming outcomes. Pathways are categorised (rows), according to their likelihood of limiting warming to different peak warming levels (if peak temperature occurs before 2100) and 2100 warming levels. Values shown are for the median [p50] and 5th–95th percentiles [p5–p95], noting that not all pathways achieve net zero CO_2 or GHGs.

p50 [p5–p95] [a]			GHG emissions ($GtCO_2$-eq yr^{-1}) [g]			GHG emissions reductions from 2019 (%) [h]			Emissions milestones [i, j]				Cumulative CO_2 emissions ($GtCO_2$) [m]		Cumulative net-negative CO_2 emissions ($GtCO_2$)	Global mean temperature changes 50% probability (°C) [n]		Likelihood of peak global warming staying below (%) [o]		
Category [b, c, d] [# pathways]	Category/subset label	WGI SSP & WGIII IPs/IMPs alignment [e, f]	2030	2040	2050	2030	2040	2050	Peak CO_2 emissions (% peak before 2100)	Peak GHG emissions (% peak before 2100)	Net zero CO_2 (% net zero pathways)	Net zero GHGs (% net zero pathways) [k, l]	2020 to net zero CO_2	2020–2100	Year of net zero CO_2 to 2100	at peak warming	2100	<1.5°C	<2.0°C	<3.0°C
Modelled global emissions pathways categorised by projected global warming levels (GWL). Detailed likelihood definitions are provided in SPM Box 1. The five illustrative scenarios (SSPx-yy) considered by AR6 WGI and the Illustrative (Mitigation) Pathways assessed in WGIII are aligned with the temperature categories and are indicated in a separate column. Global emission pathways contain regionally differentiated information. This assessment focuses on their global characteristics.			Projected median annual GHG emissions in the year across the scenarios, with the 5th–95th percentile in brackets. Modelled GHG emissions in 2019: 55 [53–58] $GtCO_2$-eq.			Projected median GHG emissions reductions of pathways in the year across the scenarios compared to modelled 2019, with the 5th–95th percentile in brackets. Negative numbers indicate increase in emissions compared to 2019.			Median 5-year intervals at which projected CO_2 & GHG emissions peak, with the 5th–95th percentile interval in square brackets. Percentage of peaking pathways is denoted in round brackets. Three dots (…) denotes emissions peak in 2100 or beyond for that percentile.		Median 5-year intervals at which projected CO_2 & GHG emissions of pathways in this category reach net zero, with the 5th–95th percentile interval in square brackets. Percentage of net zero pathways is denoted in round brackets. Three dots (…) denotes net zero not reached for that percentile.		Median cumulative net CO_2 emissions across the projected scenarios in this category until reaching net zero or until 2100, with the 5th–95th percentile interval in square brackets.		Median cumulative net-negative CO_2 emissions between the year of net zero CO_2 and 2100. More net-negative results in greater temperature declines after peak.	Projected temperature change of pathways in this category (50% probability across the range of climate uncertainties), relative to 1850–1900, at peak warming and in 2100, for the median value across the scenarios and the 5th–95th percentile interval in square brackets.		Median likelihood that the projected pathways in this category stay below a given global warming level, with the 5th–95th percentile interval in square brackets.		
C1 [97]	**limit warming to 1.5°C (>50%) with no or limited overshoot**		31 [21–36]	17 [6–23]	9 [1–15]	43 [34–60]	69 [58–90]	84 [73–98]	2020–2025 (100%) [2020–2025]		2050–2055 (100%) [2035–2070]	2095–2100 (52%) [2050–…]	510 [330–710]	320 [–210 to 570]	–220 [–660 to –20]	1.6 [1.4–1.6]	1.3 [1.1–1.5]	38 [33–58]	90 [86–97]	100 [99–100]
C1a [50]	**… with net zero GHGs**	SSP1–1.9, SP LD	33 [22–37]	18 [6–24]	8 [0–15]	41 [31–59]	66 [58–89]	85 [72–100]				2070–2075 (100%) [2050–2090]	550 [340–760]	160 [–220 to 620]	–360 [–680 to –140]	1.6 [1.4–1.6]	1.2 [1.1–1.4]	38 [34–60]	90 [85–98]	100 [99–100]
C1b [47]	**… without net zero GHGs**	Ren	29 [21–36]	16 [7–21]	9 [4–13]	48 [35–61]	70 [62–87]	84 [76–93]				…–… [0%] […–…]	460 [320–590]	360 [10–540]	–60 [–440 to 0]	1.6 [1.5–1.6]	1.4 [1.3–1.5]	37 [33–56]	89 [87–96]	100 [99–100]
C2 [133]	**return warming to 1.5°C (>50%) after a high overshoot**	Neg	42 [31–55]	25 [17–34]	14 [5–21]	23 [0–44]	55 [40–71]	75 [62–91]	2020–2025 (100%) [2020–2030]	[2020–2025]	2055–2060 (100%) [2045–2070]	2070–2075 (87%) [2055–…]	720 [530–930]	400 [–90 to 620]	–360 [–680 to –60]	1.7 [1.5–1.8]	1.4 [1.2–1.5]	24 [15–42]	82 [71–93]	100 [99–100]
C3 [311]	**limit warming to 2°C (>67%)**		44 [32–55]	29 [20–36]	20 [13–26]	21 [1–42]	46 [34–63]	64 [53–77]	2020–2025 (100%) [2020–2030]	[2020–2025]	2070–2075 (93%) [2055–…]	…–… (30%) [2075–…]	890 [640–1160]	800 [510–1140]	–40 [–290 to 0]	1.7 [1.6–1.8]	1.6 [1.5–1.8]	20 [13–41]	76 [68–91]	99 [98–100]
C3a [204]	**… with action starting in 2020**	SSP1–2.6	40 [30–49]	29 [21–36]	20 [14–27]	27 [13–45]	47 [35–63]	63 [52–76]	2020–2025 (100%) [2020–2025]		2070–2075 (91%) [2055–…]	…–… (24%) [2080–…]	860 [640–1180]	790 [480–1150]	–30 [–280 to 0]	1.7 [1.6–1.8]	1.6 [1.5–1.8]	21 [14–42]	78 [69–91]	100 [98–100]

Table SPM.2 (continued):

p50 [p5–p95] [a]			GHG emissions ($GtCO_2$-eq yr^{-1}) [g]			GHG emissions reductions from 2019 (%) [h]			Emissions milestones [i,j]				Cumulative CO_2 emissions ($GtCO_2$) [m]		Cumulative net-negative CO_2 emissions ($GtCO_2$)	Global mean temperature changes 50% probability (°C) [n]		Likelihood of peak global warming staying below (%) [o]		
Category [b,c,d] [# pathways]	Category/subset label	WGI SSP & WGIII IPs/IMPs alignment [e,f]	2030	2040	2050	2030	2040	2050	Peak CO_2 emissions (% peak before 2100)	Peak GHG emissions (% peak before 2100)	Net zero CO_2 (% net zero pathways)	Net zero GHGs (% net zero pathways) [k,l]	2020 to net zero CO_2	2020–2100	Year of net zero CO_2 to 2100	at peak warming	2100	<1.5°C	<2.0°C	<3.0°C
Modelled global emissions pathways categorised by projected global warming levels (GWL). Detailed likelihood definitions are provided in SPM Box 1. The five illustrative scenarios (SSPx-yy) considered by AR6 WGI and the Illustrative (Mitigation) Pathways assessed in WGIII are aligned with the temperature categories and are indicated in a separate column. Global emission pathways contain regionally differentiated information. This assessment focuses on their global characteristics.			Projected median annual GHG emissions in the year across the scenarios, with the 5th–95th percentile in brackets. Modelled GHG emissions in 2019: 55 [53–58] $GtCO_2$-eq.			Projected median GHG emissions reductions of pathways in the year across the scenarios compared to modelled 2019, with the 5th–95th percentile in brackets. Negative numbers indicate increase in emissions compared to 2019.			Median 5-year intervals at which projected CO_2 & GHG emissions peak, with the 5th–95th percentile interval in square brackets. Percentage of peaking pathways is denoted in round brackets. Three dots (…) denotes emissions peak in 2100 or beyond for that percentile.		Median 5-year intervals at which projected CO_2 & GHG emissions of pathways in this category reach net zero, with the 5th–95th percentile interval in square brackets. Percentage of net zero pathways is denoted in round brackets. Three dots (…) denotes net zero not reached for that percentile.		Median cumulative net CO_2 emissions across the projected scenarios in this category until reaching net zero or until 2100, with the 5th–95th percentile interval in square brackets.		Median cumulative net-negative CO_2 emissions between the year of net zero CO_2 and 2100. More net-negative results in greater temperature declines after peak.	Projected temperature change of pathways in this category (50% probability across the range of climate uncertainties), relative to 1850–1900, at peak warming and in 2100, for the median value across the scenarios and the 5th–95th percentile interval in square brackets.		Median likelihood that the projected pathways in this category stay below a given global warming level, with the 5th–95th percentile interval in square brackets.		
C3b [97]	**… NDCs until 2030**	GS	52 [47–56]	29 [20–36]	18 [10–25]	5 [0–14]	46 [34–63]	68 [56–82]			2065–2070 (97%) [2055–2090]	…–… (41%) [2075–…]	910 [720–1150]	800 [560–1050]	–60 [–300 to 0]	1.8 [1.6–1.8]	1.6 [1.5–1.7]	17 [12–35]	73 [67–87]	99 [98–99]
C4 [159]	**limit warming to 2°C (>50%)**		50 [41–56]	38 [28–44]	28 [19–35]	10 [0–27]	31 [20–50]	49 [35–65]	2020–2025 (100%) [2020–2030]		2080–2085 (86%) [2065–…]	…–… (31%) [2075–…]	1210 [970–1490]	1160 [700–1490]	–30 [–390 to 0]	1.9 [1.7–2.0]	1.8 [1.5–2.0]	11 [7–22]	59 [50–77]	98 [95–99]
C5 [212]	**limit warming to 2.5°C (>50%)**		52 [46–56]	45 [37–53]	39 [30–49]	6 [–1 to 18]	18 [4–33]	29 [11–48]			…–… (41%) [2080–…]	…–… (12%) [2090–…]	1780 [1400–2360]	1780 [1260–2360]	0 [–160 to 0]	2.2 [1.9–2.5]	2.1 [1.9–2.5]	4 [0–10]	37 [18–59]	91 [83–98]
C6 [97]	**limit warming to 3°C (>50%)**	SSP2–4.5 ModAct	54 [50–62]	53 [48–61]	52 [45–57]	2 [–10 to 11]	3 [–14 to 14]	5 [–2 to 18]	2030–2035 (96%)	2020–2025 (97%) [2020–2090]	no net zero		no net zero	2790 [2440–3520]	no net zero	temperature does not peak by 2100	2.7 [2.4–2.9]	0 [0–0]	8 [2–18]	71 [53–88]
C7 [164]	**limit warming to 4°C (>50%)**	SSP3–7.0 CurPol	62 [53–69]	67 [56–76]	70 [58–83]	–11 [–18 to 3]	–19 [–31 to 1]	–24 [–41 to –2]	2085–2090 (57%)	2090–2095 (56%) [2040–…]				4220 [3160–5000]			3.5 [2.8–3.9]	0 [0–0]	0 [0–2]	22 [7–60]
C8 [29]	**exceed warming of 4°C (≥50%)**	SSP5–8.5	71 [69–81]	80 [78–96]	88 [82–112]	–20 [–34 to –17]	–35 [–65 to –29]	–46 [–92 to –36]	2080–2085 (90%) [2070–…]					5600 [4910–7450]			4.2 [3.7–5.0]	0 [0–0]	0 [0–0]	4 [0–11]

Table SPM.2 (continued):

[a] Values in the table refer to the 50th and [5th–95th] percentile values across the pathways falling within a given category as defined in Box SPM.1. For emissions-related columns these values relate to the distribution of all the pathways in that category. Harmonised emissions values are given for consistency with projected global warming outcomes using climate emulators. Based on the assessment of climate emulators in AR6 WGI (WG1 Chapter 7, Box 7.1), two climate emulators are used for the probabilistic assessment of the resulting warming of the pathways. For the 'Temperature change' and 'Likelihood' columns, the single upper-row values represent the 50th percentile across the pathways in that category and the median [50th percentile] across the warming estimates of the probabilistic MAGICC climate model emulator. For the bracketed ranges, the median warming for every pathway in that category is calculated for each of the two climate model emulators (MAGICC and FaIR). Subsequently, the 5th and 95th percentile values across all pathways for each emulator are calculated. The coolest and warmest outcomes (i.e., the lowest p5 of two emulators, and the highest p95, respectively) are shown in square brackets. These ranges therefore cover both the uncertainty of the emissions pathways as well as the climate emulators' uncertainty.

[b] For a description of pathways categories see Box SPM.1.

[c] All global warming levels are relative to 1850–1900. (See footnote n below and Box SPM.1[45] for more details.)

[d] C3 pathways are sub-categorised according to the timing of policy action to match the emissions pathways in Figure SPM.4. Two pathways derived from a cost-benefit analysis have been added to C3a, whilst 10 pathways with specifically designed near-term action until 2030, whose emissions fall below those implied by NDCs announced prior to COP26, are not included in either of the two subsets.

[e] Alignment with the categories of the illustrative SSP scenarios considered in AR6 WGI, and the Illustrative (Mitigation) Pathways (IPs/IMPs) of WGIII. The IMPs have common features such as deep and rapid emissions reductions, but also different combinations of sectoral mitigation strategies. See Box SPM.1 for an introduction of the IPs and IMPs, and Chapter 3 for full descriptions. {3.2, 3.3, Annex III.II.4}

[f] The Illustrative Mitigation Pathway 'Neg' has extensive use of carbon dioxide removal (CDR) in the AFOLU, energy and the industry sectors to achieve net negative emissions. Warming peaks around 2060 and declines to below 1.5°C (50% likelihood) shortly after 2100. Whilst technically classified as C3, it strongly exhibits the characteristics of C2 high-overshoot pathways, hence it has been placed in the C2 category. See Box SPM.1 for an introduction of the IPs and IMPs.

[g] The 2019 range of harmonised GHG emissions across the pathways [53–58 $GtCO_2$-eq] is within the uncertainty ranges of 2019 emissions assessed in Chapter 2 [53–66 $GtCO_2$-eq].[49] (Figure SPM.1, Figure SPM.2, Box SPM.1)

[h] Rates of global emission reduction in mitigation pathways are reported on a pathway-by-pathway basis relative to harmonised modelled global emissions in 2019 rather than the global emissions reported in SPM Section B and Chapter 2; this ensures internal consistency in assumptions about emission sources and activities, as well as consistency with temperature projections based on the physical climate science assessment by WGI.[49] {Annex III.II.2.5}. Negative values (e.g., in C7, C8) represent an increase in emissions.

[i] Emissions milestones are provided for five-year intervals in order to be consistent with the underlying five-year time-step data of the modelled pathways. Peak emissions (CO_2 and GHGs) are assessed for five-year reporting intervals starting in 2020. The interval 2020–2025 signifies that projected emissions peak as soon as possible between 2020 and at latest before 2025. The upper five-year interval refers to the median interval within which the emissions peak or reach net zero. Ranges in square brackets underneath refer to the range across the pathways, comprising the lower bound of the 5th percentile five-year interval and the upper bound of the 95th percentile five-year interval. Numbers in round brackets signify the fraction of pathways that reach specific milestones.

[j] Percentiles reported across all pathways in that category include those that do not reach net zero before 2100 (fraction of pathways reaching net zero is given in round brackets). If the fraction of pathways that reach net zero before 2100 is lower than the fraction of pathways covered by a percentile (e.g., 0.95 for the 95th percentile), the percentile is not defined and denoted with '…'. The fraction of pathways reaching net zero includes all with reported non-harmonised, and/or harmonised emissions profiles that reach net zero. Pathways were counted when at least one of the two profiles fell below 100 $MtCO_2\ yr^{-1}$ until 2100.

[k] The timing of net zero is further discussed in SPM C2.4 and Cross-Chapter Box 3 in Chapter 3 on net zero CO_2 and net zero GHG emissions.

[l] For cases where models do not report all GHGs, missing GHG species are infilled and aggregated into a Kyoto basket of GHG emissions in CO_2-eq defined by the 100-year global warming potential. For each pathway, reporting of CO_2, CH_4, and N_2O emissions was the minimum required for the assessment of the climate response and the assignment to a climate category. Emissions pathways without climate assessment are not included in the ranges presented here. {See Annex III.II.5}

[m] Cumulative emissions are calculated from the start of 2020 to the time of net zero and 2100, respectively. They are based on harmonised net CO_2 emissions, ensuring consistency with the WGI assessment of the remaining carbon budget.[50] {Box 3.4}

[n] Global mean temperature change for category (at peak, if peak temperature occurs before 2100, and in 2100) relative to 1850–1900, based on the median global warming for each pathway assessed using the probabilistic climate model emulators calibrated to the AR6 WGI assessment.[12] (See also Box SPM.1) {Annex III.II.2.5; WGI Cross-Chapter Box 7.1}

[o] Probability of staying below the temperature thresholds for the pathways in each category, taking into consideration the range of uncertainty from the climate model emulators consistent with the AR6 WGI assessment. The probabilities refer to the probability at peak temperature. Note that in the case of temperature overshoot (e.g., category C2 and some pathways in C1), the probabilities of staying below at the end of the century are higher than the probabilities at peak temperature.

C.1.4 Global modelled pathways falling into the lowest temperature category of the assessed literature (C1, Table SPM.2) are on average associated with a higher median peak warming in AR6 compared to pathways in the same category in SR1.5. In the modelled pathways in AR6, the likelihood of limiting warming to 1.5°C has on average declined compared to SR1.5. This is because GHG emissions have risen since 2017, and many recent pathways have higher projected emissions by 2030, higher cumulative net CO_2 emissions and slightly later dates for reaching net zero CO_2 or net zero GHG emissions. High mitigation challenges, for example, due to assumptions of slow technological change, high levels of global population growth, and high fragmentation as in the Shared Socio-economic Pathway SSP3, may render modelled pathways that limit warming to 2°C (>67%) or lower infeasible. (*medium confidence*) (Table SPM.2, Box SPM.1) {3.3, 3.8, Annex III Figure II.1, Annex III Figure II.3}

Box SPM.1 | Assessment of Modelled Global Emission Scenarios

A wide range of modelled global emission pathways and scenarios from the literature is assessed in this report, including pathways and scenarios with and without mitigation.[44] Emissions pathways and scenarios project the evolution of GHG emissions based on a set of internally consistent assumptions about future socio-economic conditions and related mitigation measures.[45] These are quantitative projections and are neither predictions nor forecasts. Around half of all modelled global emission scenarios assume cost-effective approaches that rely on least-cost emission abatement options globally. The other half look at existing policies and regionally and sectorally differentiated actions. Most do not make explicit assumptions about global equity, environmental justice or intra-regional income distribution. Global emission pathways, including those based on cost-effective approaches, contain regionally differentiated assumptions and outcomes, and have to be assessed with the careful recognition of these assumptions. This assessment focuses on their global characteristics. The majority of the assessed scenarios (about 80%) have become available since the SR1.5, but some were assessed in that report. Scenarios with and without mitigation were categorised based on their projected global warming over the 21st century, following the same scheme as in the SR1.5 for warming up to and including 2°C. {1.5, 3.2, 3.3, Annex III.II.2, Annex III.II.3}

Scenario categories are defined by their likelihood of exceeding global warming levels (at peak and in 2100) and referred to in this report as follows:[46,47]

- Category C1 comprises modelled scenarios that limit warming to 1.5°C in 2100 with a likelihood of greater than 50%, and reach or exceed warming of 1.5°C during the 21st century with a likelihood of 67% or less. In this report, these scenarios are referred to as scenarios that limit warming to 1.5°C (>50%) with no or limited overshoot. Limited overshoot refers to exceeding 1.5°C global warming by up to about 0.1°C and for up to several decades.[48]
- Category C2 comprises modelled scenarios that limit warming to 1.5°C in 2100 with a likelihood of greater than 50%, and exceed warming of 1.5°C during the 21st century with a likelihood of greater than 67%. In this report, these scenarios are also referred to as scenarios that return warming to 1.5°C (>50%) after a high overshoot. High overshoot refers to temporarily exceeding 1.5°C global warming by 0.1°C–0.3°C for up to several decades.
- Category C3 comprises modelled scenarios that limit peak warming to 2°C throughout the 21st century with a likelihood of greater than 67%. In this report, these scenarios are also referred to as scenarios that limit warming to 2°C (>67%).
- Categories C4, C5, C6 and C7 comprise modelled scenarios that limit warming to 2°C, 2.5°C, 3°C, 4°C, respectively, throughout the 21st century with a likelihood of greater than 50%. In some scenarios in C4 and many scenarios in C5–C7, warming continues beyond the 21st century.

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[44] In the literature, the terms 'pathways' and 'scenarios' are used interchangeably, with the former more frequently used in relation to climate goals. For this reason, this SPM uses mostly the term (emissions and mitigation) pathways. {Annex III.II.1.1}

[45] Key assumptions relate to technology development in agriculture and energy systems and socio-economic development, including demographic and economic projections. IPCC is neutral with regard to the assumptions underlying the scenarios in the literature assessed in this report, which do not cover all possible futures. Additional scenarios may be developed. The underlying population assumptions range from 8.5 to 9.7 billion in 2050 and 7.4 to 10.9 billion in 2100 (5–95th percentile) starting from 7.6 billion in 2019. The underlying assumptions on global GDP growth (ppp) range from 2.5 to 3.5% per year in the 2019–2050 period and 1.3 to 2.1% per year in the 2050–2100 (5–95th percentile). Many underlying assumptions are regionally differentiated. {1.5; 3.2; 3.3; Figure 3.9; Annex III.II.1.4; Annex III.II.3}

[46] The future scenario projections presented here are consistent with the total observed increase in global surface temperature between 1850–1900 and 1995–2014 as well as to 2011–2020 (with best estimates of 0.85°C and 1.09°C, respectively) assessed in WGI. The largest contributor to historical human-induced warming is CO_2, with historical cumulative CO_2 emissions from 1850 to 2019 being 2400 ± 240 $GtCO_2$. {WGI SPM A.1.2, WGI Table SPM.2, WGI Table 5.1, WGIII SPM Section B}.

[47] In case no explicit likelihood is provided, the reported warming levels are associated with a likelihood of >50%.

[48] Scenarios in this category are found to have simultaneous likelihood to limit peak global warming to 2°C throughout the 21st century of close to and more than 90%.

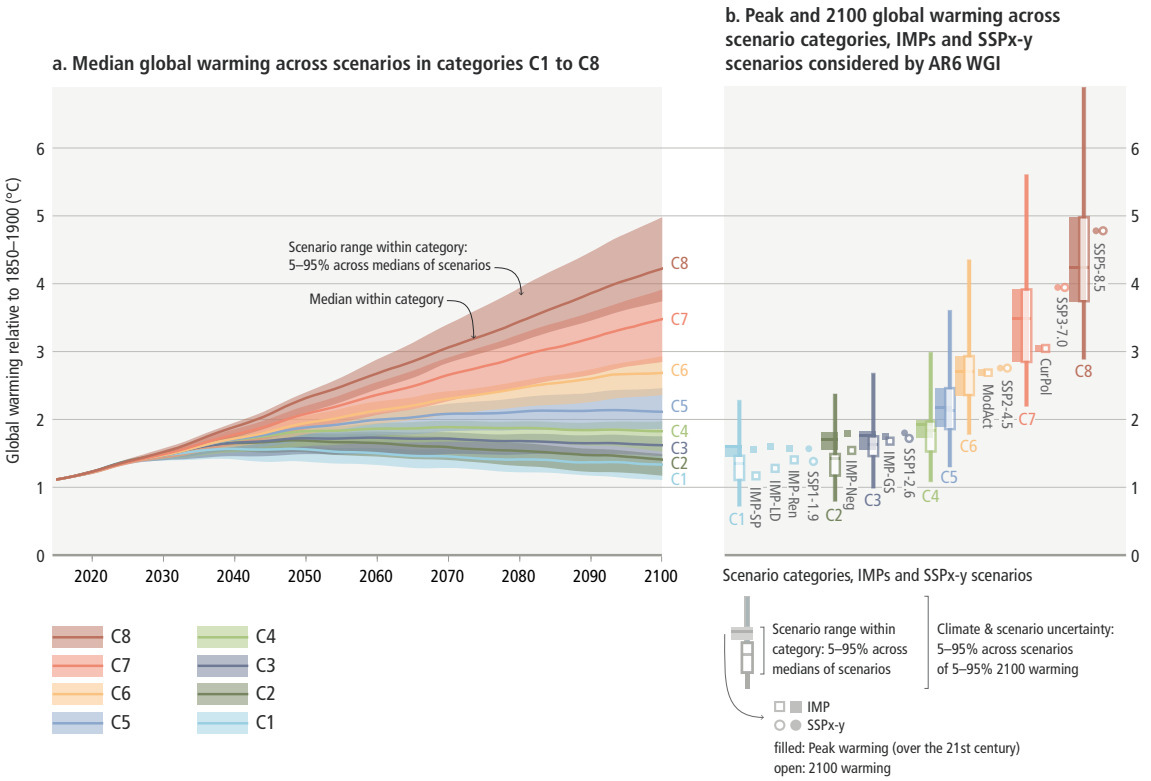
Box SPM.1 (continued)

- Category C8 comprises modelled scenarios that exceed warming of 4°C during the 21st century with a likelihood of 50% or greater. In these scenarios warming continues to rise beyond the 21st century.

Categories of modelled scenarios are distinct and do not overlap; they do not contain categories consistent with lower levels of global warming, for example, the category of C3 scenarios that limit warming to 2°C (>67%) does not include the C1 and C2 scenarios that limit or return warming to 1.5°C (>50%). Where relevant, scenarios belonging to the group of categories C1–C3 are referred to in this report as scenarios that limit warming to 2°C (>67%) or lower.

Methods to project global warming associated with the scenarios were updated to ensure consistency with the AR6 WGI assessment of physical climate science.[49] {3.2, Annex III.II.2.5; AR6 WGI Cross-Chapter Box 7.1}

The range of assessed scenarios results in a range of 21st century projected global warming.



Box SPM.1, Figure 1 | Projected global mean warming of the ensemble of modelled scenarios included in the climate categories C1–C8 and IMPs (based on emulators calibrated to the WGI assessment), as well as five illustrative scenarios (SSPx-y) as considered by AR6 WGI. **Panel a** shows the p5–p95 range of projected median warming across global modelled pathways within a category, with the category medians (line). **Panel b** shows the peak and 2100 emulated temperature outcomes for the categories C1 to C8 and for IMPs, and the five illustrative scenarios (SSPx-y) as considered by AR6 WGI. The boxes show the p5–p95 range within each scenario category, as in panel a. The combined p5–p95 range across scenarios and the climate uncertainty for each category C1–C8 is also shown for 2100 warming (thin vertical lines). (Table SPM.2) {Figure 3.11; AR6 WGI Figure SPM.8}

[49] This involved improved methodologies to use climate emulators (MAGICC7 and FAIR v1.6), which were evaluated and calibrated to closely match the global warming response to emissions as assessed in AR6 WGI. It included harmonisation of global GHG emissions in 2015 in modelled scenarios (51–56 $GtCO_2$-eq; 5th to 95th percentiles) with the corresponding emission value underlying the CMIP6 projected climate response assessed by WGI (54 $GtCO_2$-eq), based on similar data sources of historical emissions that are updated over time. The assessment of past GHG emissions in Chapter 2 of the report is based on a more recent dataset providing emissions of 57 [±6.3] $GtCO_2$-eq in 2015 (B.1). Differences are well within the assessed uncertainty range, and arise mainly from differences in estimated CO_2-LULUCF emissions, which are subject to large uncertainties, high annual variability and revisions over time. Projected rates of global emission reduction in mitigation scenarios are reported relative to modelled global emissions in 2019 rather than the global emissions reported in Chapter 2; this ensures internal consistency in assumptions about emission sources and activities, as well as consistency with temperature projections based on the physical climate science assessment by WG I. {Annex III.II.2.5}

Box SPM.1 (continued)

These updated methods affect the categorisation of some scenarios. On average across scenarios, peak global warming is projected to be lower by up to about 0.05 [±0.1] °C than if the same scenarios were evaluated using the SR1.5 methodology, and global warming in 2100 is projected to be lower by about 0.1 [±0.1] °C. {Annex III.II.2.5.1, Annex III Figure II.3}

Resulting changes to the emission characteristics of scenario categories described in Table SPM.2 interact with changes in the characteristics of the wider range of emission scenarios published since the SR1.5. Proportionally more scenarios assessed in AR6 are designed to limit temperature overshoot and more scenarios limit large-scale net negative CO_2 emissions than in SR1.5. As a result, AR6 scenarios in the lowest temperature category (C1) generally reach net zero GHG emissions later in the 21st century than scenarios in the same category assessed in SR1.5, and about half do not reach net zero GHG by 2100. The rate of decline of GHG emissions in the near term by 2030 in category C1 scenarios is very similar to the assessed rate in SR1.5, but absolute GHG emissions of category C1 scenarios in AR6 are slightly higher in 2030 than in SR1.5, since the reductions start from a higher emissions level in 2020. (Table SPM.2) {Annex III, 2.5, 3.2, 3.3}

The large number of global emissions scenarios assessed, including 1202 scenarios with projected global warming outcomes using climate emulators, come from a wide range of modelling approaches. They include the five illustrative scenarios (Shared Socio-economic Pathways; SSPs) assessed by WGI for their climate outcomes but cover a wider and more varied set in terms of assumptions and modelled outcomes. For this assessment, Illustrative Mitigation Pathways (IMPs) were selected from this larger set to illustrate a range of different mitigation strategies that would be consistent with different warming levels. The IMPs illustrate pathways that achieve deep and rapid emissions reductions through different combinations of mitigation strategies. The IMPs are not intended to be comprehensive and do not address all possible themes in the underlying report. They differ in terms of their focus, for example, placing greater emphasis on renewables (IMP-Ren), deployment of carbon dioxide removal that results in net negative global GHG emissions (IMP-Neg), and efficient resource use as well as shifts in consumption patterns globally, leading to low demand for resources, while ensuring a high level of services and satisfying basic needs (IMP-LD) (Figure SPM.5). Other IMPs illustrate the implications of a less rapid introduction of mitigation measures followed by a subsequent gradual strengthening (IMP-GS), and how shifting global pathways towards sustainable development, including by reducing inequality, can lead to mitigation (IMP-SP). The IMPs reach different climate goals as indicated in Table SPM.2 and Box SPM.1, Figure 1. {1.5, 3.1, 3.2, 3.3, 3.6, Figure 3.7, Figure 3.8, Box 3.4, Annex III.II.2.4}

C.2 Global net zero CO_2 emissions are reached in the early 2050s in modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and around the early 2070s in modelled pathways that limit warming to 2°C (>67%). Many of these pathways continue to net negative CO_2 emissions after the point of net zero. These pathways also include deep reductions in other GHG emissions. The level of peak warming depends on cumulative CO_2 emissions until the time of net zero CO_2 and the change in non-CO_2 climate forcers by the time of peaking. Deep GHG emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net negative CO_2 emissions that reverse warming in the latter half of the century. Reaching and sustaining global net zero GHG emissions results in a gradual decline in warming. (*high confidence*) (Table SPM.2) {3.3, 3.5, Box 3.4, Cross-Chapter Box 3 in Chapter 3, AR6 WGI SPM D1.8}

C.2.1 Modelled global pathways limiting warming to 1.5°C (>50%) with no or limited overshoot are associated with projected cumulative net CO_2 emissions[50] until the time of net zero CO_2 of 510 [330–710] $GtCO_2$. Pathways limiting warming to 2°C (>67%) are associated with 890 [640–1160] $GtCO_2$ (Table SPM.2). (*high confidence*) {3.3, Box 3.4}

C.2.2 Modelled global pathways that limit warming to 1.5°C (>50%) with no or limited overshoot involve more rapid and deeper near-term GHG emissions reductions through to 2030, and are projected to have less net negative CO_2 emissions and less carbon dioxide removal (CDR) in the longer term, than pathways that return warming to 1.5°C (>50%) after a high overshoot (C2 category). Modelled pathways that limit warming to 2°C (>67%) have on average lower net negative CO_2 emissions compared to pathways that limit warming to 1.5°C (>50%) with no or limited overshoot and pathways that return warming

[50] Cumulative net CO_2 emissions from the beginning of the year 2020 until the time of net zero CO_2 in assessed pathways are consistent with the remaining carbon budgets assessed by WGI, taking account of the ranges in the WGIII temperature categories and warming from non-CO_2 gases. {Box 3.4}

to 1.5°C (>50%) after a high overshoot (C1 and C2 categories respectively). Modelled pathways that return warming to 1.5°C (>50%) after a high overshoot (C2 category) show near-term GHG emissions reductions similar to pathways that limit warming to 2°C (>67%) (C3 category). For a given peak global warming level, greater and more rapid near-term GHG emissions reductions are associated with later net zero CO_2 dates. (*high confidence*) (Table SPM.2) {3.3, Table 3.5, Cross-Chapter Box 3 in Chapter 3, Annex I: Glossary}

C.2.3 Future non-CO_2 warming depends on reductions in non-CO_2 GHGs, aerosols and their precursors, and ozone precursor emissions. In modelled global low-emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls. Non-CO_2 GHG emissions at the time of net zero CO_2 are projected to be of similar magnitude in modelled pathways that limit warming to 2°C (>67%) or lower. These non-CO_2 GHG emissions are about 8 [5–11] $GtCO_2$-eq yr^{-1}, with the largest fraction from CH_4 (60% [55–80%]), followed by N_2O (30% [20–35%]) and F-gases (3% [2–20%]).[51] Due to the short lifetime of CH_4 in the atmosphere, projected deep reduction of CH_4 emissions up until the time of net zero CO_2 in modelled mitigation pathways effectively reduces peak global warming. (*high confidence*) {3.3; AR6 WGI SPM D1.7}

C.2.4 At the time of global net zero GHG emissions, net negative CO_2 emissions counterbalance metric-weighted non-CO_2 GHG emissions. Typical emissions pathways that reach and sustain global net zero GHG emissions based on the 100-year global warming potential (GWP-100)[7] are projected to result in a gradual decline of global warming. About half of the assessed pathways that limit warming to 1.5°C (>50%) with no or limited overshoot (C1 category) reach net zero GHG emissions during the second half of the 21st century. These pathways show greater reduction in global warming after the peak to 1.2 [1.1–1.4] °C by 2100 than modelled pathways in the same category that do not reach net zero GHG emissions before 2100 and that result in warming of 1.4 [1.3–1.5] °C by 2100. In modelled pathways that limit warming to 2°C (>67%) (C3 category), there is no significant difference in warming by 2100 between those pathways that reach net zero GHGs (around 30%) and those that do not (*high confidence*). In pathways that limit warming to 2°C (>67%) or lower and that do reach net zero GHG, net zero GHG occurs around 10–40 years later than net zero CO_2 emissions (*medium confidence*). {Cross-Chapter Box 2 in Chapter 2, 3.3, Cross-Chapter Box 3 in Chapter 3; AR6 WGI SPM D1.8}

C.3 All global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and those that limit warming to 2°C (>67%), involve rapid and deep and in most cases immediate GHG emission reductions in all sectors. Modelled mitigation strategies to achieve these reductions include transitioning from fossil fuels without CCS to very low- or zero-carbon energy sources, such as renewables or fossil fuels with CCS, demand side measures and improving efficiency, reducing non-CO_2 emissions, and deploying carbon dioxide removal (CDR) methods to counterbalance residual GHG emissions. Illustrative Mitigation Pathways (IMPs) show different combinations of sectoral mitigation strategies consistent with a given warming level. (*high confidence*) (Figure SPM.5) {3.2, 3.3, 3.4, 6.4, 6.6}

C.3.1 There is a variation in the contributions of different sectors in modelled mitigation pathways, as illustrated by the Illustrative Mitigation Pathways (IMPs). However, modelled pathways that limit warming to 2°C (>67%) or lower share common characteristics, including rapid and deep GHG emission reductions. Doing less in one sector needs to be compensated by further reductions in other sectors if warming is to be limited. (*high confidence*) (Figure SPM.5) {3.2, 3.3, 3.4}

C.3.2 In modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, the global use of coal, oil and gas in 2050 is projected to decline with median values of about 95%, 60% and 45% respectively, compared to 2019. The interquartile ranges are (80 to 100%), (40 to 75%) and (20 to 60%) and the p5–p95 ranges are [60 to 100%], [25 to 90%] and [–30 to +85%], respectively. In modelled pathways that limit warming to 2°C (>67%), these projected declines have a median value and interquartile range of 85% (65 to 95%), 30% (15 to 50%) and 15% (–10 to +40%) respectively by 2050. The use of coal, oil and gas without CCS in modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot is projected to be reduced to a greater degree, with median values of about 100%, 60% and 70% in 2050 compared to 2019. The interquartile ranges are (95 to 100%), (45 to 75%) and (60 to 80%) and the p5–p95 ranges about [85 to 100%], [25 to 90%] and [35 to 90%] for coal, oil and gas respectively. In these global modelled pathways, in 2050 almost all electricity is supplied from zero- or low-carbon sources, such as renewables or fossil fuels with CCS, combined with increased

[51] All numbers here rounded to the closest 5%, except values below 5% (for F-gases).

electrification of energy demand. As indicated by the ranges, choices in one sector can be compensated for by choices in another while being consistent with assessed warming levels.[52] (*high confidence*) {3.4, 3.5, Table 3.6, Figure 3.22, Figure 6.35}

C.3.3 In modelled pathways that reach global net zero CO_2 emissions: at the point they reach net zero, 5–16 $GtCO_2$ of emissions from some sectors are compensated for by net negative CO_2 emissions in other sectors. In most global modelled pathways that limit warming to 2°C (>67%) or lower, the AFOLU sector, via reforestation and reduced deforestation, and the energy supply sector reach net zero CO_2 emissions earlier than the buildings, industry and transport sectors. (*high confidence*) (Figure SPM.5e,f) {3.4}

C.3.4 In modelled pathways that reach global net zero GHG emissions, at the point they reach net zero GHG, around 74% [54 to 90%] of global emissions reductions are achieved by CO_2 reductions in energy supply and demand, 13% [4 to 20%] by CO_2 mitigation options in the AFOLU sector, and 13% [10 to 18%] through the reduction of non-CO_2 emissions from land-use, energy and industry (*medium confidence*). (Figure SPM.5f) {3.3, 3.4}

C.3.5 Methods and levels of CDR deployment in global modelled mitigation pathways vary depending on assumptions about costs, availability and constraints.[53] In modelled pathways that report CDR and that limit warming to 1.5°C (>50%) with no or limited overshoot, global cumulative CDR during 2020–2100 from bioenergy with carbon dioxide capture and storage (BECCS) and direct air carbon dioxide capture and storage (DACCS) is 30–780 $GtCO_2$ and 0–310 $GtCO_2$, respectively. In these modelled pathways, the AFOLU sector contributes 20–400 $GtCO_2$ net negative emissions. Total cumulative net negative CO_2 emissions including CDR deployment across all options represented in these modelled pathways are 20–660 $GtCO_2$. In modelled pathways that limit warming to 2°C (>67%), global cumulative CDR during 2020–2100 from BECCS and DACCS is 170–650 $GtCO_2$ and 0–250 $GtCO_2$ respectively, the AFOLU sector contributes 10–250 $GtCO_2$ net negative emissions, and total cumulative net negative CO_2 emissions are around 40 [0–290] $GtCO_2$. (Table SPM.2) (*high confidence*) {Table 3.2, 3.3, 3.4}

C.3.6 All mitigation strategies face implementation challenges, including technology risks, scaling, and costs. Many challenges, such as dependence on CDR, pressure on land and biodiversity (e.g., bioenergy) and reliance on technologies with high upfront investments (e.g., nuclear), are significantly reduced in modelled pathways that assume using resources more efficiently (e.g., IMP-LD) or that shift global development towards sustainability (e.g., IMP-SP). (*high confidence*) (Figure SPM.5) {3.2, 3.4, 3.7, 3.8, 4.3, 5.1}

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[52] Most but not all models include the use of fossil fuels for feedstock with varying underlying standards.

[53] Aggregate levels of CDR deployment are higher than total net negative CO_2 emissions given that some of the deployed CDR is used to counterbalance remaining gross emissions. Total net negative CO_2 emissions in modelled pathways might not match the aggregated net negative CO_2 emissions attributed to individual CDR methods. Ranges refer to the 5–95th percentile across modelled pathways that include the specific CDR method. Cumulative levels of CDR from AFOLU cannot be quantified precisely given that: (i) some pathways assess CDR deployment relative to a baseline; and (ii) different models use different reporting methodologies that in some cases combine gross emissions and removals in AFOLU. Total CDR from AFOLU equals or exceeds the net negative emissions mentioned.

Modelled mitigation pathways that limit warming to 1.5°C, and 2°C, involve deep, rapid and sustained emissions reductions.

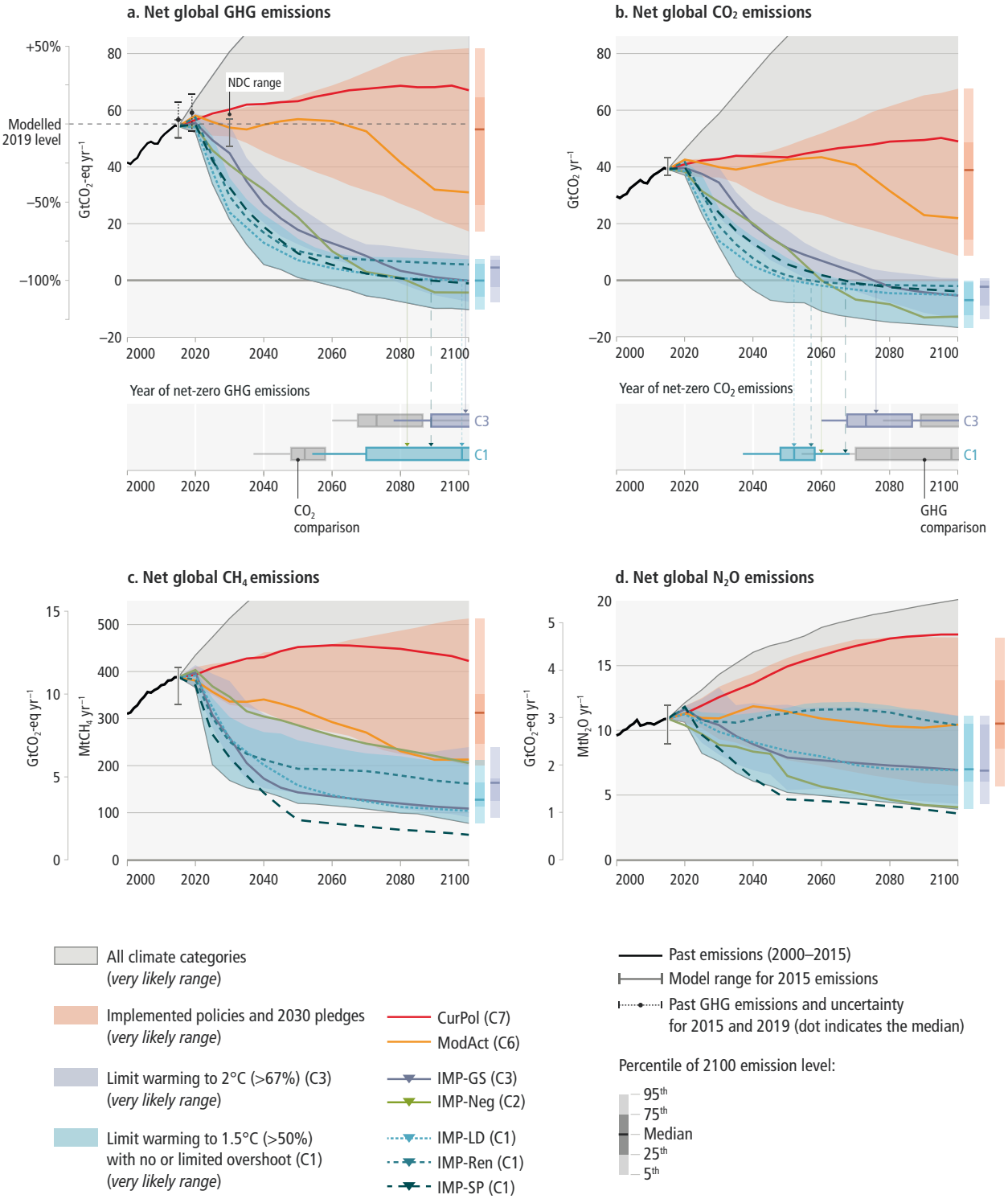

Figure SPM.5 | Illustrative Mitigation Pathways (IMPs) and net zero CO_2 and GHG emissions strategies.

Net zero CO_2 and net zero GHG emissionsare possible through different modelled mitigation pathways.

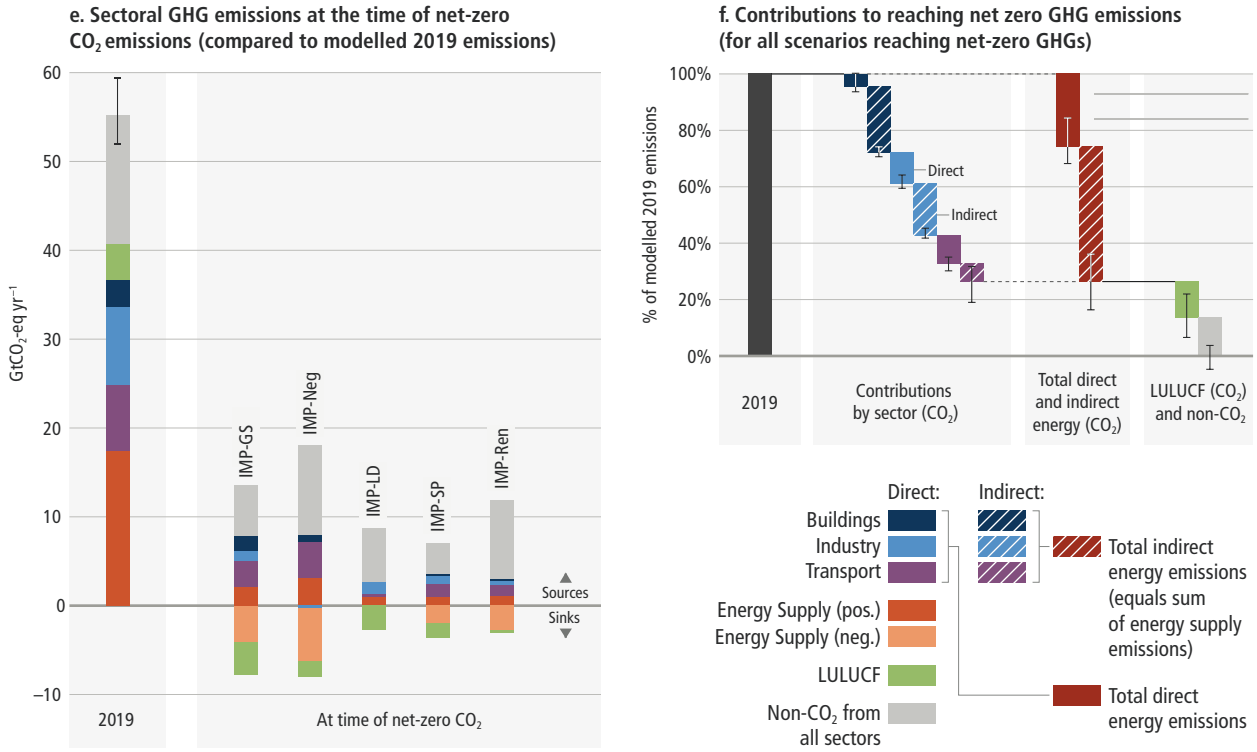

Figure SPM.5 (continued): Illustrative Mitigation Pathways (IMPs) and net zero CO_2 and GHG emissions strategies. Panels a and b show the development of global GHG and CO_2 emissions in modelled global pathways (upper sub-panels) and the associated timing of when GHG and CO_2 emissions reach net zero (lower sub-panels). **Panels c and d** show the development of global CH_4 and N_2O emissions, respectively. Coloured ranges denote the 5th to 95th percentile across pathways. The red ranges depict emissions pathways assuming policies that were implemented by the end of 2020 and pathways assuming implementation of NDCs (announced prior to COP26). Ranges of modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot are shown in light blue (category C1) and pathways that limit warming to 2°C (>67%) are shown in light purple (category C3). The grey range comprises all assessed pathways (C1–C8) from the 5th percentile of the lowest warming category (C1) to the 95th percentile of the highest warming category (C8). The modelled pathway ranges are compared to the emissions from two pathways illustrative of high emissions (CurPol and ModAct) and five IMPs: IMP-LD, IMP-Ren, IMP-SP, IMP-Neg and IMP-GS. Emissions are harmonised to the same 2015 base year. The vertical error bars in 2015 show the 5–95th percentile uncertainty range of the non-harmonised emissions across the pathways, and the uncertainty range, and median value, in emission estimates for 2015 and 2019. The vertical error bars in 2030 (panel a) depict the assessed range of the NDCs, as announced prior to COP26 (Figure SPM.4).[23] **Panel e** shows the sectoral contributions of CO_2 and non-CO_2 emissions sources and sinks at the time when net zero CO_2 emissions are reached in the IMPs. Positive and negative emissions for different IMPs are compared to the GHG emissions from the year 2019. Energy supply (neg.) includes BECCS and DACCS. DACCS features in only two of the five IMPs (IMP-REN and IMP-GS) and contributes <1% and 64%, respectively, to the net negative emissions in Energy Supply (neg.). **Panel f** shows the contribution of different sectors and sources to the emissions reductions from a 2019 baseline for reaching net zero GHG emissions. Bars denote the median emissions reductions for all pathways that reach net zero GHG emissions. The whiskers indicate the p5–p95 range. The contributions of the service sectors (transport, buildings, industry) are split into direct (demand-side) as well as indirect (supply-side) CO_2 emissions reductions. Direct emissions represent demand-side emissions due to the fuel use in the respective demand sector. Indirect emissions represent upstream emissions due to industrial processes and energy conversion, transmission and distribution. In addition, the contributions from the LULUCF sector and reductions from non-CO_2 emissions sources (green and grey bars) are displayed. {3.3, 3.4}

C.4 Reducing GHG emissions across the full energy sector requires major transitions, including a substantial reduction in overall fossil fuel use, the deployment of low-emission energy sources, switching to alternative energy carriers, and energy efficiency and conservation. The continued installation of unabated fossil fuel[54] infrastructure will 'lock-in' GHG emissions. (*high confidence*) {2.7, 6.6, 6.7, 16.4}

C.4.1 Net-zero CO_2 energy systems entail: a substantial reduction in overall fossil fuel use, minimal use of unabated fossil fuels, and use of CCS in the remaining fossil fuel system;[54] electricity systems that emit no net CO_2; widespread electrification of the energy system including end uses; energy carriers such as sustainable biofuels, low-emissions hydrogen, and derivatives in applications less amenable to electrification; energy conservation and efficiency; and greater physical, institutional, and operational integration across the energy system. CDR will be needed to counterbalance residual emissions in the energy sector. The most appropriate strategies depend on national and regional circumstances, including enabling conditions and technology availability. (*high confidence*) {3.4, 6.6, 11.3, 16.4}

C.4.2 Unit cost reductions in key technologies, notably wind power, solar power, and storage, have increased the economic attractiveness of low-emission energy sector transitions through 2030. Maintaining emission-intensive systems may, in some regions and sectors, be more expensive than transitioning to low emission systems. Low-emission energy sector transitions will have multiple co-benefits, including improvements in air quality and health. The long-term economic attractiveness of deploying energy system mitigation options depends, *inter alia*, on policy design and implementation, technology availability and performance, institutional capacity, equity, access to finance, and public and political support. (*high confidence*) (Figure SPM.3) {3.4, 6.4, 6.6, 6.7, 13.7}

C.4.3 Electricity systems powered predominantly by renewables are becoming increasingly viable. Electricity systems in some countries and regions are already predominantly powered by renewables. It will be more challenging to supply the entire energy system with renewable energy. Even though operational, technological, economic, regulatory, and social challenges remain, a variety of systemic solutions to accommodate large shares of renewables in the energy system have emerged. A broad portfolio of options, such as integrating systems, coupling sectors, energy storage, smart grids, demand-side management, sustainable biofuels, electrolytic hydrogen and derivatives, and others will ultimately be needed to accommodate large shares of renewables in energy systems. (*high confidence*) {Box 6.8, 6.4, 6.6}

C.4.4 Limiting global warming to 2°C or below will leave a substantial amount of fossil fuels unburned and could strand considerable fossil fuel infrastructure (*high confidence*). Depending on its availability, CCS could allow fossil fuels to be used longer, reducing stranded assets (*high confidence*). The combined global discounted value of the unburned fossil fuels and stranded fossil fuel infrastructure has been projected to be around USD1–4 trillion from 2015 to 2050 to limit global warming to approximately 2°C, and it will be higher if global warming is limited to approximately 1.5°C (*medium confidence*). In this context, coal assets are projected to be at risk of being stranded before 2030, while oil and gas assets are projected to be more at risk of being stranded towards mid-century. A low-emission energy sector transition is projected to reduce international trade in fossil fuels. (*high confidence*) {6.7, Figure 6.35}

C.4.5 Global methane emissions from energy supply, primarily fugitive emissions from production and transport of fossil fuels, accounted for about 18% [13–23%] of global GHG emissions from energy supply, 32% [22–42%] of global CH_4 emissions, and 6% [4–8%] of global GHG emissions in 2019 (*high confidence*). About 50–80% of CH_4 emissions from these fossil fuels could be avoided with currently available technologies at less than USD50 tCO_2-eq^{-1} (*medium confidence*). {6.3, 6.4.2, Box 6.5, 11.3, 2.2.2, Table 2.1, Figure 2.5, Annex1: Glossary}

C.4.6 CCS is an option to reduce emissions from large-scale fossil-based energy and industry sources, provided geological storage is available. When CO_2 is captured directly from the atmosphere (DACCS), or from biomass (BECCS), CCS provides the storage component of these CDR methods. CO_2 capture and subsurface injection is a mature technology for gas processing and enhanced oil recovery. In contrast to the oil and gas sector, CCS is less mature in the power sector, as well as in cement and chemicals production, where it is a critical mitigation option. The technical geological CO_2 storage capacity is estimated to be on the order of 1000 $GtCO_2$, which is more than the CO_2 storage requirements through 2100 to limit global warming to 1.5°C, although the regional availability of geological storage could be a limiting factor. If the geological storage site is appropriately selected and managed, it is estimated that the CO_2 can be permanently isolated from the atmosphere. Implementation of CCS currently faces technological, economic, institutional, ecological-environmental and socio-cultural barriers. Currently, global rates of CCS deployment are far below those in modelled pathways limiting global warming to 1.5°C or 2°C. Enabling

[54] In this context, 'unabated fossil fuels' refers to fossil fuels produced and used without interventions that substantially reduce the amount of GHG emitted throughout the life cycle; for example, capturing 90% or more CO_2 from power plants, or 50–80% of fugitive methane emissions from energy supply. {Box 6.5, 11.3}

conditions such as policy instruments, greater public support and technological innovation could reduce these barriers. (*high confidence*) {2.5, 6.3, 6.4, 6.7, 11.3, 11.4, Cross-Chapter Box 8 in Chapter 12, Figure TS.31; SRCCL Chapter 5}

C.5 Net zero CO_2 emissions from the industrial sector are challenging but possible. Reducing industry emissions will entail coordinated action throughout value chains to promote all mitigation options, including demand management, energy and materials efficiency, circular material flows, as well as abatement technologies and transformational changes in production processes. Progressing towards net zero GHG emissions from industry will be enabled by the adoption of new production processes using low- and zero-GHG electricity, hydrogen, fuels, and carbon management. (*high confidence*) {11.2, 11.3, 11.4, Box TS.4}

C.5.1 The use of steel, cement, plastics, and other materials is increasing globally, and in most regions. There are many sustainable options for demand management, materials efficiency, and circular material flows that can contribute to reduced emissions, but how these can be applied will vary across regions and different materials. These options have a potential for being more used in industrial practice and would need more attention from industrial policy. These options, as well as new production technologies, are generally not considered in recent global scenarios nor in national economy-wide scenarios due to relative newness. As a consequence, the mitigation potential in some scenarios is underestimated compared to bottom-up industry-specific models. (*high confidence*) {3.4, 5.3, Figure 5.7, 11.2, Box 11.2, 11.3, 11.4, 11.5.2, 11.6}

C.5.2 For almost all basic materials – primary metals,[55] building materials and chemicals – many low- to zero-GHG intensity production processes are at the *pilot* to *near-commercial* and in some cases *commercial* stage but they are not yet established industrial practice. Introducing new sustainable production processes for basic materials could increase production costs but, given that only a small fraction of consumer costs are based on materials, such new processes are expected to translate into minimal cost increases for final consumers. Hydrogen direct reduction for primary steelmaking is *near-commercial* in some regions. Until new chemistries are mastered, deep reduction of cement process emissions will rely on already commercialised cementitious material substitution and the availability of CCS. Reducing emissions from the production and use of chemicals would need to rely on a life cycle approach, including increased plastics recycling, fuel and feedstock switching, and carbon sourced through biogenic sources, and, depending on availability, carbon capture and use (CCU), direct air CO_2 capture, as well as CCS. Light industry, mining and manufacturing have the potential to be decarbonised through available abatement technologies (e.g., material efficiency, circularity), electrification (e.g., electrothermal heating, heat pumps) and low- or zero-GHG emitting fuels (e.g., hydrogen, ammonia, and bio-based and other synthetic fuels). (*high confidence*) {Table 11.4, Box 11.2, 11.3, 11.4}

C.5.3 Action to reduce industry sector emissions may change the location of GHG-intensive industries and the organisation of value chains. Regions with abundant low-GHG energy and feedstocks have the potential to become exporters of hydrogen-based chemicals and materials processed using low-carbon electricity and hydrogen. Such reallocation will have global distributional effects on employment and economic structure. (*medium confidence*) {Box 11.1}

C.5.4 Emissions-intensive and highly traded basic materials industries are exposed to international competition, and international cooperation and coordination may be particularly important in enabling change. For sustainable industrial transitions, broad and sequential national and sub-national policy strategies reflecting regional contexts will be required. These may combine policy packages including: transparent GHG accounting and standards; demand management; materials and energy efficiency policies; R&D and niche markets for commercialisation of low-emission materials and products; economic and regulatory instruments to drive market uptake; high quality recycling, low-emissions energy and other abatement infrastructure (e.g., for CCS); and socially inclusive phase-out plans of emissions-intensive facilities within the context of just transitions. The coverage of mitigation policies could be expanded nationally and sub-nationally to include all industrial emission sources, and both available and emerging mitigation options. (*high confidence*) {11.6}

[55] Primary metals refers to virgin metals produced from ore.

C.6 Urban areas can create opportunities to increase resource efficiency and significantly reduce GHG emissions through the systemic transition of infrastructure and urban form through low-emission development pathways towards net-zero emissions. Ambitious mitigation efforts for established, rapidly growing and emerging cities will encompass (i) reducing or changing energy and material consumption, (ii) electrification, and (iii) enhancing carbon uptake and storage in the urban environment. Cities can achieve net-zero emissions, but only if emissions are reduced within and outside of their administrative boundaries through supply chains, which will have beneficial cascading effects across other sectors. (*very high confidence*) {8.2, 8.3, 8.4, 8.5, 8.6, Figure 8.21, 13.2}

C.6.1 In modelled scenarios, global consumption-based urban CO_2 and CH_4 emissions[15] are projected to rise from 29 $GtCO_2$-eq in 2020 to 34 $GtCO_2$-eq in 2050 with moderate mitigation efforts (intermediate GHG emissions, SSP2-4.5), and up to 40 $GtCO_2$-eq in 2050 with low mitigation efforts (high GHG emissions, SSP3-7.0). With ambitious and immediate mitigation efforts, including high levels of electrification and improved energy and material efficiency, global consumption-based urban CO_2 and CH_4 emissions could be reduced to 3 $GtCO_2$-eq in 2050 in the modelled scenario with very low GHG emissions (SSP1-1.9).[56] (*medium confidence*) {8.3}

C.6.2 The potential and sequencing of mitigation strategies to reduce GHG emissions will vary depending on a city's land use, spatial form, development level, and state of urbanisation (*high confidence*). Strategies for established cities to achieve large GHG emissions savings include efficiently improving, repurposing or retrofitting the building stock, targeted infilling, and supporting non-motorised (e.g., walking, bicycling) and public transport. Rapidly growing cities can avoid future emissions by co-locating jobs and housing to achieve compact urban form, and by leapfrogging or transitioning to low-emissions technologies. New and emerging cities will have significant infrastructure development needs to achieve high quality of life, which can be met through energy efficient infrastructures and services, and people-centred urban design (*high confidence*). For cities, three broad mitigation strategies have been found to be effective when implemented concurrently: (i) reducing or changing energy and material use towards more sustainable production and consumption; (ii) electrification in combination with switching to low-emission energy sources; and (iii) enhancing carbon uptake and storage in the urban environment, for example through bio-based building materials, permeable surfaces, green roofs, trees, green spaces, rivers, ponds and lakes.[57] (*very high confidence*) {5.3, Figure 5.7, Supplementary Material Table 5.SM.2, 8.2, 8.4, 8.6, Figure 8.21, 9.4, 9.6, 10.2}

C.6.3 The implementation of packages of multiple city-scale mitigation strategies can have cascading effects across sectors and reduce GHG emissions both within and outside a city's administrative boundaries. The capacity of cities to develop and implement mitigation strategies varies with the broader regulatory and institutional settings, as well as enabling conditions, including access to financial and technological resources, local governance capacity, engagement of civil society, and municipal budgetary powers. (*very high confidence*) {Figure 5.7, Supplementary Material Table 5.SM.2, 8.4, 8.5, 8.6, 13.2, 13.3, 13.5, 13.7, Cross-Chapter Box 9 in Chapter 13}

C.6.4 A growing number of cities are setting climate targets, including net-zero GHG targets. Given the regional and global reach of urban consumption patterns and supply chains, the full potential for reducing consumption-based urban emissions to net zero GHG can be met only when emissions beyond cities' administrative boundaries are also addressed. The effectiveness of these strategies depends on cooperation and coordination with national and sub-national governments, industry, and civil society, and whether cities have adequate capacity to plan and implement mitigation strategies. Cities can play a positive role in reducing emissions across supply chains that extend beyond cities' administrative boundaries, for example through building codes and the choice of construction materials. (*very high confidence*) {8.4, Box 8.4, 8.5, 9.6, 9.9, 13.5, 13.9}

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[56] These scenarios have been assessed by WGI to correspond to intermediate, high and very low GHG emissions.

[57] These examples are considered to be a subset of nature-based solutions or ecosystem-based approaches.

C.7. In modelled global scenarios, existing buildings, if retrofitted, and buildings yet to be built, are projected to approach net zero GHG emissions in 2050 if policy packages, which combine ambitious sufficiency, efficiency, and renewable energy measures, are effectively implemented and barriers to decarbonisation are removed. Low ambition policies increase the risk of locking-in buildings' carbon for decades, while well-designed and effectively implemented mitigation interventions (in both new buildings and existing ones if retrofitted), have significant potential to contribute to achieving SDGs in all regions while adapting buildings to future climate. (*high confidence*) {9.1, 9.3, 9.4, 9.5, 9.6, 9.9}

C.7.1 In 2019, global direct and indirect GHG emissions from buildings and emissions from cement and steel use for building construction and renovation were 12 $GtCO_2$-eq. These emissions include indirect emissions from offsite generation of electricity and heat, direct emissions produced onsite and emissions from cement and steel used for building construction and renovation. In 2019, global direct and indirect emissions from non-residential buildings increased by about 55% and those from residential buildings increased by about 50% compared to 1990. The latter increase, according to the decomposition analysis, was mainly driven by the increase of the floor area per capita, population growth and the increased use of emission-intensive electricity and heat while efficiency improvements have partly decreased emissions. There are great differences in the contribution of each of these drivers to regional emissions. (*high confidence*) {9.3}

C.7.2 Integrated design approaches to the construction and retrofit of buildings have led to increasing examples of zero energy or zero carbon buildings in several regions. However, the low renovation rates and low ambition of retrofitted buildings have hindered the decrease of emissions. Mitigation interventions at the design stage include buildings typology, form, and multi-functionality to allow for adjusting the size of buildings to the evolving needs of their users and repurposing unused existing buildings to avoid using GHG-intensive materials and additional land. Mitigation interventions include: at the construction phase, low-emission construction materials, highly efficient building envelope and the integration of renewable energy solutions;[58] at the use phase, highly efficient appliances/equipment, the optimisation of the use of buildings and their supply with low-emission energy sources; and at the disposal phase, recycling and re-using construction materials. (*high confidence*) {9.4, 9.5, 9.6, 9.7}

C.7.3 By 2050, bottom-up studies show that up to 61% (8.2 $GtCO_2$) of global building emissions could be mitigated. Sufficiency policies[59] that avoid the demand for energy and materials contribute 10% to this potential, energy efficiency policies contribute 42%, and renewable energy policies 9%. The largest share of the mitigation potential of new buildings is available in developing countries while in developed countries the highest mitigation potential is within the retrofit of existing buildings. The 2020–2030 decade is critical for accelerating the learning of know-how, building the technical and institutional capacity, setting the appropriate governance structures, ensuring the flow of finance, and in developing the skills needed to fully capture the mitigation potential of buildings. (*high confidence*) {9.3, 9.4, 9.5, 9.6, 9.7, 9.9}

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[58] Integration of renewable energy solutions refers to the integration of solutions such as solar photovoltaics, small wind turbines, solar thermal collectors, and biomass boilers.

[59] Sufficiency policies are a set of measures and daily practices that avoid demand for energy, materials, land and water while delivering human well-being for all within planetary boundaries.

C.8 Demand-side options and low-GHG emissions technologies can reduce transport sector emissions in developed countries and limit emissions growth in developing countries (*high confidence*). Demand-focused interventions can reduce demand for all transport services and support the shift to more energy efficient transport modes (*medium confidence*). Electric vehicles powered by low-emissions electricity offer the largest decarbonisation potential for land-based transport, on a life cycle basis (*high confidence*). Sustainable biofuels can offer additional mitigation benefits in land-based transport in the short and medium term (*medium confidence*). Sustainable biofuels, low-emissions hydrogen, and derivatives (including synthetic fuels) can support mitigation of CO_2 emissions from shipping, aviation, and heavy-duty land transport but require production process improvements and cost reductions (*medium confidence*). Many mitigation strategies in the transport sector would have various co-benefits, including air quality improvements, health benefits, equitable access to transportation services, reduced congestion, and reduced material demand (*high confidence*). {10.2, 10.4, 10.5, 10.6, 10.7}

C.8.1 In scenarios that limit warming to 1.5°C (>50%) with no or limited overshoot, global transport-related CO_2 emissions fall by 59% (42–68% interquartile range) by 2050 relative to modelled 2020 emissions, but with regionally differentiated trends (*high confidence*). In global modelled scenarios that limit warming to 2°C (>67%), transport-related CO_2 emissions are projected to decrease by 29% [14–44% interquartile range] by 2050 compared to modelled 2020 emissions. In both categories of scenarios, the transport sector likely does not reach zero CO_2 emissions by 2100 so negative emissions are likely needed to counterbalance residual CO_2 emissions from the sector (*high confidence*). {3.4, 10.7}

C.8.2 Changes in urban form (e.g., density, land-use mix, connectivity, and accessibility) in combination with programmes that encourage changes in consumer behaviour (e.g., transport pricing) could reduce transport-related greenhouse gas emissions in developed countries and slow growth in emissions in developing countries (*high confidence*). Investments in public inter- and intra-city transport and active transport infrastructure (e.g., bicycle and pedestrian pathways) can further support the shift to less GHG-intensive transport modes (*high confidence*). Combinations of systemic changes, including teleworking, digitalisation, dematerialisation, supply chain management, and smart and shared mobility may reduce demand for passenger and freight services across land, air, and sea (*high confidence*). Some of these changes could lead to induced demand for transport and energy services, which may decrease their GHG emissions reduction potential (*medium confidence*). {5.3, 10.2, 10.8}

C.8.3 Electric vehicles powered by low-GHG emissions electricity have large potential to reduce land-based transport GHG emissions, on a life cycle basis (*high confidence*). Costs of electrified vehicles, including automobiles, two- and three-wheelers, and buses, are decreasing and their adoption is accelerating, but they require continued investments in supporting infrastructure to increase scale of deployment (*high confidence*). Advances in battery technologies could facilitate the electrification of heavy-duty trucks and complement conventional electric rail systems (*medium confidence*). There are growing concerns about critical minerals needed for batteries. Material and supply diversification strategies, energy and material efficiency improvements, and circular material flows can reduce the environmental footprint and material supply risks for battery production (*medium confidence*). Sourced sustainably and with low-GHG emissions feedstocks, bio-based fuels, blended or unblended with fossil fuels, can provide mitigation benefits, particularly in the short and medium term (*medium confidence*). Low-GHG emissions hydrogen and hydrogen derivatives, including synthetic fuels, can offer mitigation potential in some contexts and land-based transport segments (*medium confidence*). {3.4, 6.3, 10.3, 10.4, 10.7, 10.8, Box 10.6}

C.8.4 While efficiency improvements (e.g., optimised aircraft and vessel designs, mass reduction, and propulsion system improvements) can provide some mitigation potential, additional CO_2 emissions mitigation technologies for aviation and shipping will be required (*high confidence*). For aviation, such technologies include high energy density biofuels (*high confidence*), and low-emission hydrogen and synthetic fuels (*medium confidence*). Alternative fuels for shipping include low-emission hydrogen, ammonia, biofuels, and other synthetic fuels (*medium confidence*). Electrification could play a niche role for aviation and shipping for short trips (*medium confidence*) and can reduce emissions from port and airport operations (*high confidence*). Improvements to national and international governance structures would further enable the decarbonisation of shipping and aviation (*medium confidence*). Such improvements could include, for example, the implementation of stricter efficiency and carbon intensity standards for the sectors (*medium confidence*). {10.3. 10.5, 10.6, 10.7, 10.8, Box 10.5}

C.8.5 The substantial potential for GHG emissions reductions, both direct and indirect, in the transport sector largely depends on power sector decarbonisation, and low-emissions feedstocks and production chains (*high confidence*). Integrated transport and energy infrastructure planning and operations can enable sectoral synergies and reduce the environmental, social, and economic impacts of decarbonising the transport and energy sectors (*high confidence*). Technology transfer and financing can support developing countries leapfrogging or transitioning to low-emissions transport systems thereby providing multiple co-benefits (*high confidence*). {10.2, 10.3, 10.4, 10.5, 10.6, 10.7, 10.8}

C.9 AFOLU mitigation options, when sustainably implemented, can deliver large-scale GHG emission reductions and enhanced removals, but cannot fully compensate for delayed action in other sectors. In addition, sustainably sourced agricultural and forest products can be used instead of more GHG-intensive products in other sectors. Barriers to implementation and trade-offs may result from the impacts of climate change, competing demands on land, conflicts with food security and livelihoods, the complexity of land ownership and management systems, and cultural aspects. There are many country-specific opportunities to provide co-benefits (such as biodiversity conservation, ecosystem services, and livelihoods) and avoid risks (for example, through adaptation to climate change). (*high confidence*) {7.4, 7.6, 7.7, 12.5, 12.6}

C.9.1 The projected economic mitigation potential of AFOLU options between 2020 and 2050, at costs below USD100 tCO_2-eq^{-1}, is 8–14 $GtCO_2$-eq yr^{-1} [60] (*high confidence*). 30–50% of this potential is available at less than USD20 tCO_2-eq and could be upscaled in the near term across most regions (*high confidence*). The largest share of this economic potential [4.2–7.4 $GtCO_2$-eq yr^{-1}] comes from the conservation, improved management, and restoration of forests and other ecosystems (coastal wetlands, peatlands, savannas and grasslands), with reduced deforestation in tropical regions having the highest total mitigation. Improved and sustainable crop and livestock management, and carbon sequestration in agriculture (the latter including soil carbon management in croplands and grasslands, agroforestry and biochar), can contribute 1.8–4.1 $GtCO_2$-eq yr^{-1} reduction. Demand-side and material substitution measures, such as shifting to balanced, sustainable healthy diets,[61] reducing food loss and waste, and using bio-materials, can contribute 2.1 [1.1–3.6] $GtCO_2$-eq yr^{-1} reduction. In addition, demand-side measures together with the sustainable intensification of agriculture can reduce ecosystem conversion and CH_4 and N_2O emissions, and free up land for reforestation and restoration, and the production of renewable energy. The improved and expanded use of wood products sourced from sustainably managed forests also has potential through the allocation of harvested wood to longer-lived products, increasing recycling or material substitution. AFOLU mitigation measures cannot compensate for delayed emission reductions in other sectors. Persistent and region-specific barriers continue to hamper the economic and political feasibility of deploying AFOLU mitigation options. Assisting countries to overcome barriers will help to achieve significant mitigation (*medium confidence*). (Figure SPM.6) {7.1, 7.4, 7.5, 7.6}

C.9.2 AFOLU carbon sequestration and GHG emission reduction options have both co-benefits and risks in terms of biodiversity and ecosystem conservation, food and water security, wood supply, livelihoods and land tenure and land-use rights of Indigenous Peoples, local communities and small land owners. Many options have co-benefits but those that compete for land and land-based resources can pose risks. The scale of benefit or risk largely depends on the type of activity undertaken, deployment strategy (e.g., scale, method), and context (e.g., soil, biome, climate, food system, land ownership) that vary geographically and over time. Risks can be avoided when AFOLU mitigation is pursued in response to the needs and perspectives of multiple stakeholders to achieve outcomes that maximize co-benefits while limiting trade-offs. (*high confidence*) {7.4, 7.6, 12.3}

C.9.3 Realising the AFOLU mitigation potential entails overcoming institutional, economic and policy constraints and managing potential trade-offs (*high confidence*). Land-use decisions are often spread across a wide range of land owners; demand-side measures depend on billions of consumers in diverse contexts. Barriers to the implementation of AFOLU mitigation include insufficient institutional and financial support, uncertainty over long-term additionality and trade-offs, weak governance, insecure land ownership, low incomes and the lack of access to alternative sources of income, and the risk of reversal. Limited access to technology, data, and know-how is a barrier to implementation. Research and development are key for all measures. For example, measures for the mitigation of agricultural CH_4 and N_2O emissions with emerging technologies show promising results. However, the mitigation of agricultural CH_4 and N_2O emissions is still constrained by cost, the diversity and complexity of agricultural systems, and by increasing demands to raise agricultural yields, and increasing demand for livestock products. (*high confidence*) {7.4, 7.6}

C.9.4 Net costs of delivering 5–6 $GtCO_2$ yr^{-1} of forest-related carbon sequestration and emission reduction as assessed with sectoral models are estimated to reach to about USD400 billion yr^{-1} by 2050. The costs of other AFOLU mitigation measures are highly context specific. Financing needs in AFOLU, and in particular in forestry, include both the direct effects of any changes in

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[60] The global top-down estimates and sectoral bottom-up estimates described here do not include the substitution of emissions from fossil fuels and GHG-intensive materials. 8–14 $GtCO_2$-eq yr^{-1} represents the mean of the AFOLU economic mitigation potential estimates from top-down estimates (lower bound of range) and global sectoral bottom-up estimates (upper bound of range). The full range from top-down estimates is 4.1–17.3 $GtCO_2$-eq yr^{-1} using a 'no policy' baseline. The full range from global sectoral studies is 6.7–23.4 $GtCO_2$-eq yr^{-1} using a variety of baselines. (*high confidence*)

[61] 'Sustainable healthy diets' promote all dimensions of individuals' health and well-being; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable, as described in FAO and WHO. The related concept of 'balanced diets' refers to diets that feature plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, and animal-sourced food produced in resilient, sustainable and low-GHG emission systems, as described in SRCCL.

activities as well as the opportunity costs associated with land-use change. Enhanced monitoring, reporting and verification capacity, and the rule of law, are crucial for land-based mitigation in combination with policies also recognising interactions with wider ecosystem services, could enable engagement by a wider array of actors, including private businesses, NGOs, and Indigenous Peoples and local communities. (*medium confidence*) {7.6, 7.7}

C.9.5 Context specific policies and measures have been effective in demonstrating the delivery of AFOLU carbon sequestration and GHG emission reduction options but the above-mentioned constraints hinder large scale implementation (*medium confidence*). Deploying land-based mitigation can draw on lessons from experience with regulations, policies, economic incentives, payments (e.g., for biofuels, control of nutrient pollution, water regulations, conservation and forest carbon, ecosystem services, and rural livelihoods), and from diverse forms of knowledge such as Indigenous knowledge, local knowledge and scientific knowledge. Indigenous Peoples, private forest owners, local farmers and communities manage a significant share of global forests and agricultural land and play a central role in land-based mitigation options. Scaling successful policies and measures relies on governance that emphasises integrated land-use planning and management framed by SDGs, with support for implementation. (*high confidence*) {7.4, Box 7.2, 7.6}

C.10 Demand-side mitigation encompasses changes in infrastructure use, end-use technology adoption, and socio-cultural and behavioural change. Demand-side measures and new ways of end-use service provision can reduce global GHG emissions in end-use sectors by 40–70% by 2050 compared to baseline scenarios, while some regions and socioeconomic groups require additional energy and resources. Demand-side mitigation response options are consistent with improving basic well-being for all. (*high confidence*) (Figure SPM.6) {5.3, 5.4, Figure 5.6, Figure 5.14, 8.2, 9.4, 10.2, 11.3, 11.4, 12.4, Figure TS.22}

C.10.1 Infrastructure design and access, and technology access and adoption, including information and communication technologies, influence patterns of demand and ways of providing services, such as mobility, shelter, water, sanitation, and nutrition. Illustrative global low-demand scenarios, accounting for regional differences, indicate that more efficient end-use energy conversion can improve services while reducing the need for upstream energy by 45% by 2050 compared to 2020. Demand-side mitigation potential differs between and within regions, and some regions and populations require additional energy, capacity, and resources for human well-being. The lowest population quartile by income worldwide faces shortfalls in shelter, mobility, and nutrition. (*high confidence*) {5.2, 5.3, 5.4, 5.5, Figure 5.6, Figure 5.10, Table 5.2, Figure TS.20, Figure TS.22}

C.10.2 By 2050, comprehensive demand-side strategies could reduce direct and indirect CO_2 and non-CO_2 GHG emissions in three end-use sectors (buildings, land transport, and food) globally by 40%–70% compared to the 2050 emissions projection of two scenarios consistent with policies announced by national governments until 2020. With policy support, socio-cultural options and behavioural change can reduce global GHG emissions of end-use sectors by at least 5% rapidly, with most of the potential in developed countries, and more until 2050, if combined with improved infrastructure design and access. Individuals with high socio-economic status contribute disproportionately to emissions and have the highest potential for emissions reductions, e.g., as citizens, investors, consumers, role models, and professionals. (*high confidence*) (Figure SPM.6) {5.2, 5.3, 5.4, 5.5, 5.6, Supplementary Material Table 5.SM.2, 8.4, 9.9, 13.2, 13.5, 13.8, Figure TS.20}

C.10.3 A range of 5–30% of global annual GHG emissions from end-use sectors are avoidable by 2050, compared to 2050 emissions projection of two scenarios consistent with policies announced by national governments until 2020, through changes in the built environment, new and repurposed infrastructures and service provision through compact cities, co-location of jobs and housing, more efficient use of floor space and energy in buildings, and reallocation of street space for active mobility (*high confidence*). (Figure SPM.6) {5.3.1, 5.3.3, 5.4, Figure 5.7, Figure 5.13, Table 5.1, Table 5.5, Supplementary Material Table 5. SM.2, 8.4, 9.5, 10.2, 11.3, 11.4, Table 11.6, Box TS.12}

C.10.4 Choice architecture[62] can help end-users adopt, as relevant to consumers, culture and country contexts, low-GHG-intensive options such as balanced, sustainable healthy diets[61] acknowledging nutritional needs; food waste reduction; adaptive heating and cooling choices for thermal comfort; building-integrated renewable energy; and electric light-duty vehicles, and shifts to walking, cycling, shared pooled and public transit; and sustainable consumption by intensive use of longer-lived repairable products (*high confidence*). Addressing inequality and many forms of status consumption[63] and focusing on wellbeing supports climate change mitigation efforts (*high confidence*). (Figure SPM.6) {2.4.3, 2.6.2, 4.2.5, 5.1, 5.2, 5.3, 5.4, Figure 5.4, Figure 5.10, Table 5.2, Supplementary Material Table 5.SM.2, 7.4.5, 8.2, 8.4, 9.4, 10.2, 12.4, Figure TS.20}

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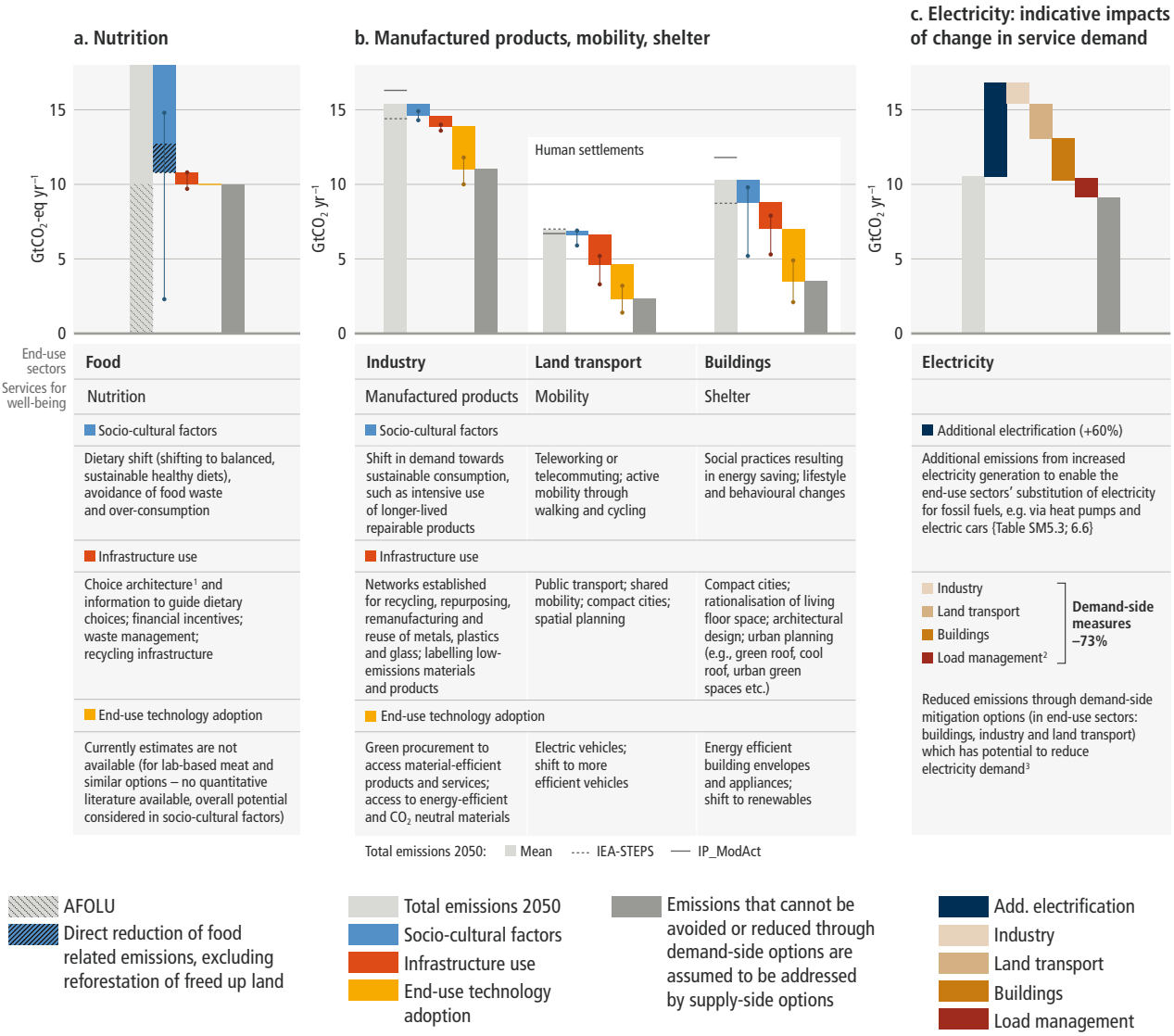
62 'Choice architecture' describes the presentation of choices to consumers, and the impact that presentation has on consumer decision-making.

63 'Status consumption' refers to the consumption of goods and services which publicly demonstrates social prestige.

Demand-side mitigation can be achieved through changes in socio-cultural factors, infrastructure design and use, and end-use technology adoption by 2050.



[1] The presentation of choices to consumers, and the impact of that presentation on consumer decision-making.

[2] Load management refers to demand-side flexibility that cuts across all sectors and can be achieved through incentive design like time of use pricing/monitoring by artificial intelligence, diversification of storage facilities, etc.

[3] The impact of demand-side mitigation on electricity sector emissions depends on the baseline carbon intensity of electricity supply, which is scenario dependent.

Figure SPM.6 | Indicative potential of demand-side mitigation options by 2050. Figure SPM.6 covers the indicative potential of demand-side options for the year 2050. Figure SPM.7 covers cost and potentials for the year 2030. Demand-side mitigation response options are categorised into three broad domains: 'socio-cultural factors', associated with individual choices, behaviour, lifestyle changes, social norms, and culture; 'infrastructure use', related to the design and use of supporting hard and soft infrastructure that enables changes in individual choices and behaviour; and 'end-use technology adoption', referring to the uptake of technologies by end-users. Demand-side mitigation is a central element of the IMP-LD and IMP-SP scenarios (Figure SPM.5). **Panel a** (Nutrition) demand-side potentials in 2050 assessment is based on bottom-up studies and is estimated following the 2050 baseline for the food sector presented in peer-reviewed literature (more information in Supplementary Material 5.II, and Section 7.4.5). **Panel b** (Manufactured products, mobility, shelter) the assessment of potentials for total emissions in 2050 are estimated based on approximately 500 bottom-up studies representing all global regions (detailed list is in Supplementary Material Table 5.SM.2). Baseline is provided by the sectoral mean GHG emissions in 2050 of the two scenarios consistent with policies announced by national governments until 2020. The heights of the coloured columns represent the potentials represented by the median value. These are based on a range of values available in the case studies from literature shown in Supplementary Material 5.SM.II. The range is shown by the dots connected by dotted lines representing the highest and the lowest potentials reported in the literature. **Panel a** shows the demand-side potential of socio-cultural factors and infrastructure use. The median value of direct emissions (mostly non-CO_2) reduction through socio-cultural factors is 1.9 $GtCO_2$-eq without considering land-use change through reforestation of freed up land. If changes in land-use pattern enabled by this change in food demand are considered, the indicative potential could reach 7 $GtCO_2$-eq. Panel b illustrates mitigation potential in industry, land transport and buildings end-use sectors through demand-side options. Key options are presented in the summary table below the figure and the details are in Supplementary Material Table 5.SM.2. **Panel c** visualises how sectoral demand-side mitigation options (presented in panel b) change demand on the electricity distribution system. Electricity accounts for an increasing proportion of final energy demand in 2050 (additional electricity bar) in line with multiple bottom-up studies (detailed list is in Supplementary Material Table 5.SM.3), and Chapter 6 (Section 6.6). These studies are used to compute the impact of end-use electrification which increases overall electricity demand. Some of the projected increase in electricity demand can be avoided through demand-side mitigation options in the domains of socio-cultural factors and infrastructure use in end-use electricity use in buildings, industry, and land transport found in literature based on bottom-up assessments. Dark grey columns show the emissions that cannot be avoided through demand-side mitigation options. {5.3, Figure 5.7, Supplementary Material 5.SM.II}

C.11 The deployment of carbon dioxide removal (CDR) to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO_2 or GHG emissions are to be achieved. The scale and timing of deployment will depend on the trajectories of gross emission reductions in different sectors. Upscaling the deployment of CDR depends on developing effective approaches to address feasibility and sustainability constraints especially at large scales. (*high confidence*) {3.4, 7.4, 12.3, Cross-Chapter Box 8 in Chapter 12}

C.11.1 CDR refers to anthropogenic activities that remove CO_2 from the atmosphere and store it durably in geological, terrestrial, or ocean reservoirs, or in products. CDR methods vary in terms of their maturity, removal process, time scale of carbon storage, storage medium, mitigation potential, cost, co-benefits, impacts and risks, and governance requirements (*high confidence*). Specifically, maturity ranges from lower maturity (e.g., ocean alkalinisation) to higher maturity (e.g., reforestation); removal and storage potential ranges from lower potential (<1 $GtCO_2$ yr^{-1}, e.g., blue carbon management) to higher potential (>3 $GtCO_2$ yr^{-1}, e.g., agroforestry); costs range from lower cost (e.g., USD-45–100 per tCO_2 for soil carbon sequestration) to higher cost (e.g., USD100–300 per tCO_2 for DACCS) (*medium confidence*). Estimated storage time scales vary from decades to centuries for methods that store carbon in vegetation and through soil carbon management, to 10,000 years or more for methods that store carbon in geological formations (*high confidence*). The processes by which CO_2 is removed from the atmosphere are categorised as biological, geochemical or chemical. Afforestation, reforestation, improved forest management, agroforestry and soil carbon sequestration are currently the only widely practiced CDR methods (*high confidence*). {7.4, 7.6, 12.3, Table 12.6, Cross-Chapter Box 8 in Chapter 12, Table TS.7; AR6 WGI 5.6}

C.11.2 The impacts, risks and co-benefits of CDR deployment for ecosystems, biodiversity and people will be highly variable depending on the method, site-specific context, implementation and scale (*high confidence*). Reforestation, improved forest management, soil carbon sequestration, peatland restoration and blue carbon management are examples of methods that can enhance biodiversity and ecosystem functions, employment and local livelihoods, depending on context (*high confidence*). In contrast, afforestation or production of biomass crops for BECCS or biochar, when poorly implemented, can have adverse socio-economic and environmental impacts, including on biodiversity, food and water security, local livelihoods and on the rights of Indigenous Peoples, especially if implemented at large scales and where land tenure is insecure (*high confidence*). Ocean fertilisation, if implemented, could lead to nutrient redistribution, restructuring of ecosystems, enhanced oxygen consumption and acidification in deeper waters (*medium confidence*). {7.4, 7.6, 12.3, 12.5}

C.11.3 The removal and storage of CO_2 through vegetation and soil management can be reversed by human or natural disturbances; it is also prone to climate change impacts. In comparison, CO_2 stored in geological and ocean reservoirs (via BECCS, DACCS, ocean alkalinisation) and as carbon in biochar is less prone to reversal. (*high confidence*) {6.4, 7.4, 12.3}

C.11.4 In addition to deep, rapid, and sustained emission reductions CDR can fulfil three different complementary roles globally or at country level: lowering net CO_2 or net GHG emissions in the near term; counterbalancing 'hard-to-abate' residual emissions (e.g., emissions from agriculture, aviation, shipping, industrial processes) in order to help reach net zero CO_2 or net zero GHG emissions in the mid-term; and achieving net negative CO_2 or GHG emissions in the long term if deployed at levels exceeding annual residual emissions. (*high confidence*) {3.3, 7.4, 11.3, 12.3, Cross-Chapter Box 8 in Chapter 12}

C.11.5 Rapid emission reductions in all sectors interact with future scale of deployment of CDR methods, and their associated risks, impacts and co-benefits. Upscaling the deployment of CDR methods depends on developing effective approaches to address sustainability and feasibility constraints, potential impacts, co-benefits and risks. Enablers of CDR include accelerated research, development and demonstration, improved tools for risk assessment and management, targeted incentives and development of agreed methods for measurement, reporting and verification of carbon flows. (*high confidence*) {3.4, 7.6, 12.3}

C.12 Mitigation options costing USD100 tCO_2-eq^{-1} or less could reduce global GHG emissions by at least half the 2019 level by 2030 (*high confidence*). Global GDP continues to grow in modelled pathways[64] but, without accounting for the economic benefits of mitigation action from avoided damages from climate change nor from reduced adaptation costs, it is a few percent lower in 2050 compared to pathways without mitigation beyond current policies. The global economic benefit of limiting warming to 2°C is reported to exceed the cost of mitigation in most of the assessed literature (*medium confidence*). (Figure SPM.7) {3.6, 3.8, Cross-Working Group Box 1 in Chapter 3, 12.2, Box TS.7}

C.12.1 Based on a detailed sectoral assessment of mitigation options, it is estimated that mitigation options costing USD100 tCO_2-eq^{-1} or less could reduce global GHG emissions by at least half of the 2019 level by 2030 (options costing less than USD20 tCO_2-eq^{-1} are estimated to make up more than half of this potential).[65] For a smaller part of the potential, deployment leads to net cost savings. Large contributions with costs less than USD20 tCO_2-eq^{-1} come from solar and wind energy, energy efficiency improvements, reduced conversion of natural ecosystems, and CH_4 emissions reductions (coal mining, oil and gas, waste). The mitigation potentials and mitigation costs of individual technologies in a specific context or region may differ greatly from the provided estimates. The assessment of the underlying literature suggests that the relative contribution of the various options could change beyond 2030. (*medium confidence*) (Figure SPM.7) {12.2}

C.12.2 The aggregate effects of climate change mitigation on global GDP are small compared to global projected GDP growth in assessed modelled global scenarios that quantify the macroeconomic implications of climate change mitigation, but that do not account for damages from climate change nor adaptation costs (*high confidence*). For example, compared to pathways that assume the continuation of policies implemented by the end of 2020, assessed global GDP reached in 2050 is reduced by 1.3–2.7% in modelled pathways assuming coordinated global action starting between now and 2025 at the latest to limit warming to 2°C (>67%). The corresponding average reduction in annual global GDP growth over 2020–2050 is 0.04–0.09 percentage points. In assessed modelled pathways, regardless of the level of mitigation action, global GDP is projected to at least double (increase by at least 100%) over 2020–2050. For modelled global pathways in other temperature categories, the reductions in global GDP in 2050 compared to pathways that assume the continuation of policies implemented by the end of 2020 are as follows: 2.6–4.2% (C1), 1.6–2.8% (C2), 0.8–2.1% (C4), 0.5–1.2% (C5). The corresponding reductions in average annual global GDP growth over 2020–2050, in percentage points, are as follows: 0.09–0.14 (C1), 0.05–0.09 (C2), 0.03–0.07 (C4), 0.02–0.04 (C5).[66] There are large variations in the modelled effects of mitigation on GDP across regions, depending notably on economic structure, regional emissions reductions, policy design and level of international cooperation[67] (*high confidence*). Country-level studies also show large variations in the effect of mitigation on GDP depending notably on the level of mitigation and on the way it is achieved (*high confidence*). Macroeconomic implications of mitigation co-benefits and trade-offs are not quantified comprehensively across the above scenarios and depend strongly on mitigation strategies (*high confidence*). {3.6, 4.2, Box TS.7, Annex III.I.2, Annex III.I.9, Annex III.I.10 and Annex III.II.3}

C.12.3 Estimates of aggregate economic benefits from avoiding damages from climate change, and from reduced adaptation costs, increase with the stringency of mitigation (*high confidence*). Models that incorporate the economic damages from climate change find that the global cost of limiting warming to 2°C over the 21st century is lower than the global economic benefits of reducing warming, unless: (i) climate damages are towards the low end of the range; or, (ii) future damages are discounted at high rates (*medium confidence*).[68] Modelled pathways with a peak in global emissions between now and 2025 at the latest, compared to modelled pathways with a later peak in global emissions, entail more rapid near-term transitions and higher up-front investments, but bring long-term gains for the economy, as well as earlier benefits of avoided climate change impacts (*high confidence*). The precise magnitude of these gains and benefits is difficult to quantify. {1.7, 3.6, Cross-Working Group Box 1 in Chapter 3, Box TS.7; AR6 WGII SPM B.4}

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64 In modelled pathways that limit warming to 2°C (>67%) or lower.

65 The methodology underlying the assessment is described in the caption to Figure SPM.7.

66 These estimates are based on 311 pathways that report effects of mitigation on GDP and that could be classified in temperature categories, but that do not account for damages from climate change nor adaptation costs and that mostly do not reflect the economic impacts of mitigation co-benefits and trade-offs. The ranges given are interquartile ranges. The macroeconomic implications quantified vary largely depending on technology assumptions, climate/emissions target formulation, model structure and assumptions, and the extent to which pre-existing inefficiencies are considered. Models that produced the pathways classified in temperature categories do not represent the full diversity of existing modelling paradigms, and there are in the literature models that find higher mitigation costs, or conversely lower mitigation costs and even gains. {1.7, 3.2, 3.6, Annex III.I.2, Annex III.I.9, Annex III.I.10 and Annex III.II.3}

67 In modelled cost-effective pathways with a globally uniform carbon price, without international financial transfers or complementary policies, carbon intensive and energy exporting countries are projected to bear relatively higher mitigation costs because of a deeper transformation of their economies and changes in international energy markets. {3.6}

68 The evidence is too limited to make a similar robust conclusion for limiting warming to 1.5°C.

Many options available now in all sectors are estimated to offer substantial potential to reduce net emissions by 2030. Relative potentials and costs will vary across countries and in the longer term compared to 2030.

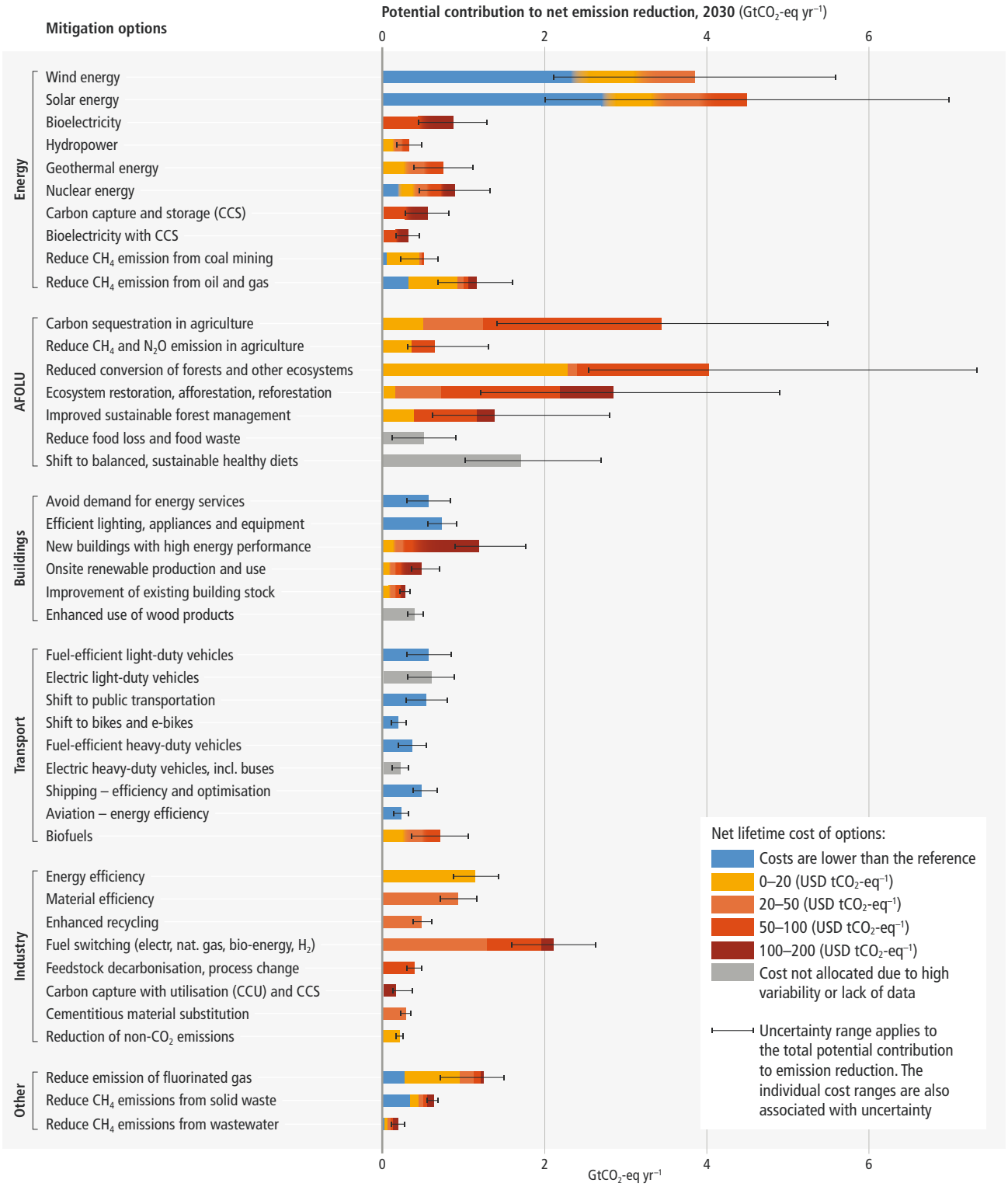

Figure SPM.7 | Overview of mitigation options and their estimated ranges of costs and potentials in 2030.

Figure SPM.7 (continued): Overview of mitigation options and their estimated ranges of costs and potentials in 2030. Costs shown are net lifetime costs of avoided greenhouse gas emissions. Costs are calculated relative to a reference technology. The assessments per sector were carried out using a common methodology, including definition of potentials, target year, reference scenarios, and cost definitions. The mitigation potential (shown in the horizontal axis) is the quantity of net GHG emission reductions that can be achieved by a given mitigation option relative to a specified emission baseline. Net GHG emission reductions are the sum of reduced emissions and/or enhanced sinks. The baseline used consists of current policy (around 2019) reference scenarios from the AR6 scenarios database (25/75 percentile values). The assessment relies on approximately 175 underlying sources, that together give a fair representation of emission reduction potentials across all regions. The mitigation potentials are assessed independently for each option and are not necessarily additive. {12.2.1, 12.2.2} The length of the solid bars represents the mitigation potential of an option. The error bars display the full ranges of the estimates for the total mitigation potentials. Sources of uncertainty for the cost estimates include assumptions on the rate of technological advancement, regional differences, and economies of scale, among others. Those uncertainties are not displayed in the figure. Potentials are broken down into cost categories, indicated by different colours (see legend). Only discounted lifetime monetary costs are considered. Where a gradual colour transition is shown, the breakdown of the potential into cost categories is not well known or depends heavily on factors such as geographical location, resource availability, and regional circumstances, and the colours indicate the range of estimates. Costs were taken directly from the underlying studies (mostly in the period 2015–2020) or recent datasets. No correction for inflation was applied, given the wide cost ranges used. The cost of the reference technologies were also taken from the underlying studies and recent datasets. Cost reductions through technological learning are taken into account.[69]

- When interpreting this figure, the following should be taken into account:
- The mitigation potential is uncertain, as it will depend on the reference technology (and emissions) being displaced, the rate of new technology adoption, and several other factors.
- Cost and mitigation potential estimates were extrapolated from available sectoral studies. Actual costs and potentials would vary by place, context and time.
- Beyond 2030, the relative importance of the assessed mitigation options is expected to change, in particular while pursuing long-term mitigation goals, recognising also that the emphasis for particular options will vary across regions (for specific mitigation options see SPM Sections C4.1, C5.2, C7.3, C8.3 and C9.1).
- Different options have different feasibilities beyond the cost aspects, which are not reflected in the figure (compare with SPM Section E.1).
- The potentials in the cost range USD100–200 tCO_2-eq^{-1} may be underestimated for some options.
- Costs for accommodating the integration of variable renewable energy sources in electricity systems are expected to be modest until 2030, and are not included because of complexities in attributing such costs to individual technology options.
- Cost range categories are ordered from low to high. This order does not imply any sequence of implementation.
- Externalities are not taken into account. {12.2, Table 12.3, 6.4, Table 7.3, Supplementary Material Table 9.SM.2, Supplementary Material Table 9.SM.3, 10.6, 11.4, Figure 11.13, Supplementary Material 12.SM.1.2.3}

[69] For nuclear energy, modelled costs for long-term storage of radioactive waste are included.

D. Linkages between Mitigation, Adaptation, and Sustainable Development

D.1 Accelerated and equitable climate action in mitigating, and adapting to, climate change impacts is critical to sustainable development. Climate change actions can also result in some trade-offs. The trade-offs of individual options could be managed through policy design. The Sustainable Development Goals (SDGs) adopted under the UN 2030 Agenda for Sustainable Development can be used as a basis for evaluating climate action in the context of sustainable development. (*high confidence*) (Figure SPM.8) {1.6, 3.7, 17.3, Figure TS.29}

D.1.1 Human-induced climate change is a consequence of more than a century of net GHG emissions from unsustainable energy use, land-use and land use change, lifestyle and patterns of consumption and production. Without urgent, effective and equitable mitigation actions, climate change increasingly threatens the health and livelihoods of people around the globe, ecosystem health and biodiversity. There are both synergies and trade-offs between climate action and the pursuit of other SDGs. Accelerated and equitable climate action in mitigating, and adapting to, climate change impacts is critical to sustainable development. (*high confidence*) {1.6, Cross-Chapter Box 5 in Chapter 4, 7.2, 7.3, 17.3; AR6 WGI SPM.A, Figure SPM.2; AR6 WGII SPM.B2, Figure SPM.3, Figure SPM.4b, Figure SPM.5}

D.1.2 Synergies and trade-offs depend on the development context including inequalities, with consideration of climate justice. They also depend on means of implementation, intra- and inter-sectoral interactions, cooperation between countries and regions, the sequencing, timing and stringency of mitigation actions, governance, and policy design. Maximising synergies and avoiding trade-offs pose particular challenges for developing countries, vulnerable populations, and Indigenous Peoples with limited institutional, technological and financial capacity, and with constrained social, human, and economic capital. Trade-offs can be evaluated and minimised by giving emphasis to capacity building, finance, governance, technology transfer, investments, and development and social equity considerations with meaningful participation of Indigenous Peoples and vulnerable populations. (*high confidence*) {1.6, 1.7, 3.7, 5.2, 5.6, 7.4, 7.6, 17.4}

D.1.3 There are potential synergies between sustainable development and energy efficiency, renewable energy, urban planning with more green spaces, reduced air pollution, and demand-side mitigation including shifts to balanced, sustainable healthy diets (*high confidence*). Electrification combined with low-GHG energy, and shifts to public transport can enhance health, employment, and can elicit energy security and deliver equity (*high confidence*). In industry, electrification and circular material flows contribute to reduced environmental pressures and increased economic activity and employment. However, some industrial options could impose high costs (*medium confidence*). (Figure SPM.8) {5.2, 8.2, 11.3, 11.5, 17.3, Figure TS.29}

D.1.4 Land-based options such as reforestation and forest conservation, avoided deforestation, restoration and conservation of natural ecosystems and biodiversity, improved sustainable forest management, agroforestry, soil carbon management and options that reduce CH_4 and N_2O emissions in agriculture from livestock and soil, can have multiple synergies with the SDGs. These include enhancing sustainable agricultural productivity and resilience, food security, providing additional biomass for human use, and addressing land degradation. Maximising synergies and managing trade-offs depend on specific practices, scale of implementation, governance, capacity building, integration with existing land use, and the involvement of local communities and Indigenous Peoples and through benefit-sharing, supported by frameworks such as Land Degradation Neutrality within the UNCCD. (*high confidence*) {3.7, 7.4, 12.5, 17.3}

D.1.5 Trade-offs in terms of employment, water use, land-use competition and biodiversity, as well as access to, and the affordability of, energy, food, and water can be avoided by well-implemented land-based mitigation options, especially those that do not threaten existing sustainable land uses and land rights, though more frameworks for integrated policy implementation are required. The sustainability of bioenergy and other bio-based products is influenced by feedstock, land management practice, climatic region, the context of existing land management, and the timing, scale and speed of deployment. (*medium confidence*) {3.5, 3.7, 7.4, 12.4, 12.5, 17.1}

D.1.6 CDR methods such as soil carbon sequestration and biochar[70] can improve soil quality and food production capacity. Ecosystem restoration and reforestation sequester carbon in plants and soil, and can enhance biodiversity and provide additional

[70] Potential risks, knowledge gaps due to the relative immaturity of use of biochar as a soil amendment and unknown impacts of widespread application, and co-benefits of biochar are reviewed in Section 7.4.3.2.

biomass, but can displace food production and livelihoods, which calls for integrated approaches to land-use planning, to meet multiple objectives including food security. However, due to limited application of some of the options today, there are some uncertainties about potential benefits. (*high confidence*) {3.7, 7.4, 7.6, 12.5, 17.3, Table TS.7}

Mitigation options have synergies with many Sustainable Development Goals, but some options can also have trade-offs. The synergies and trade-offs vary dependent on context and scale.

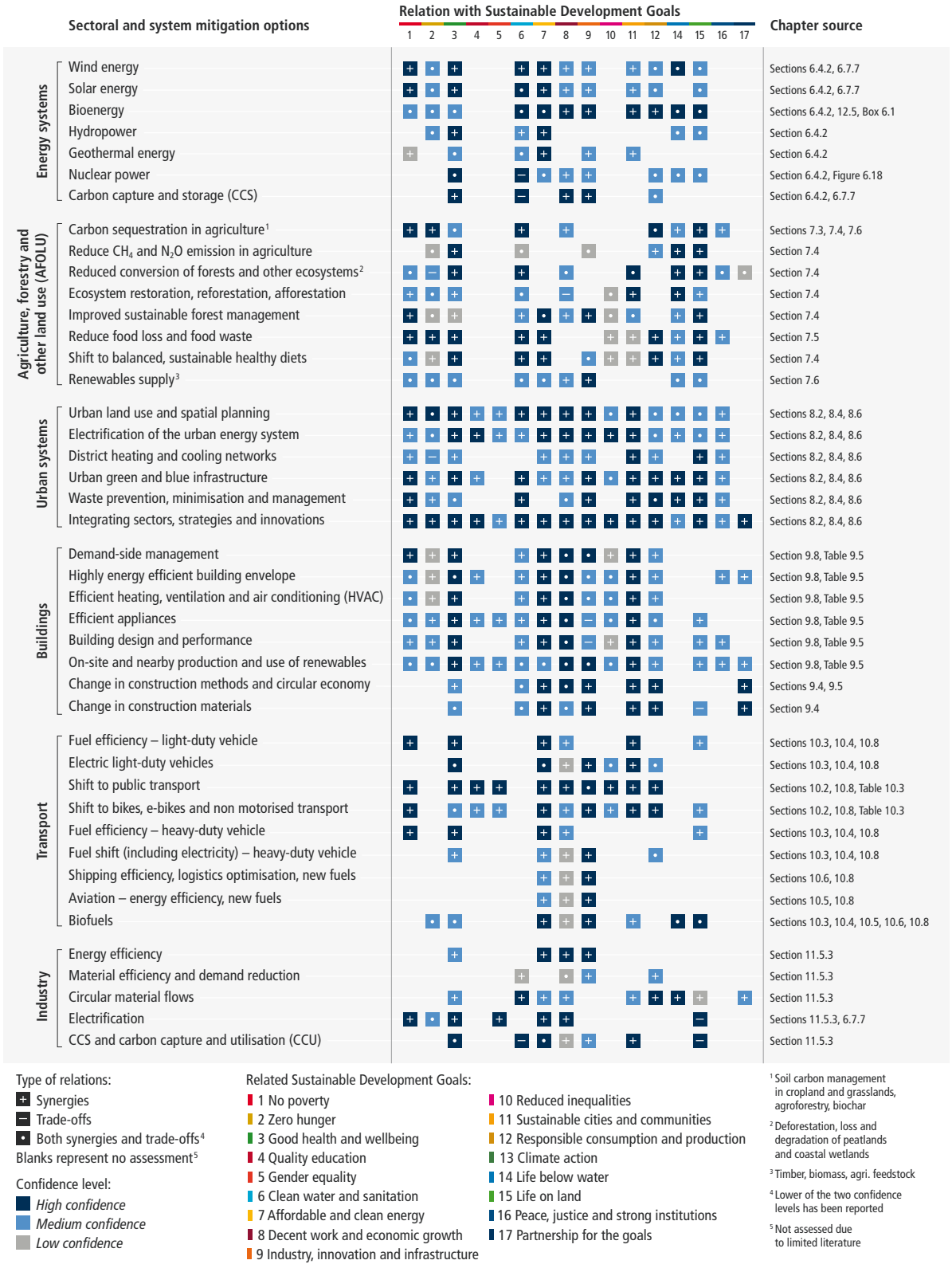

Figure SPM.8 | Synergies and trade-offs between sectoral and system mitigation options and the SDGs.

Figure SPM.8 (continued): Synergies and trade-offs between sectoral and system mitigation options and the SDGs. The sectoral chapters (Chapters 6–11) include qualitative assessments of synergies and trade-offs between sectoral mitigation options and the SDGs. Figure SPM.8 presents a summary of the chapter-level assessment for selected mitigation options (see Supplementary Material Table 17.SM.1 for the underlying assessment). The last column provides a line of sight to the sectoral chapters, which provide details on context specificity and dependence of interactions on the scale of implementation. Blank cells indicate that interactions have not been assessed due to limited literature. They do not indicate the absence of interactions between mitigation options and the SDGs. Confidence levels depend on the quality of evidence and level of agreement in the underlying literature assessed by the sectoral chapters. Where both synergies and trade-offs exist, the lower of the confidence levels for these interactions is used. Some mitigation options may have applications in more than one sector or system. The interactions between mitigation options and the SDGs might differ depending on the sector or system, and also on the context and the scale of implementation. Scale of implementation particularly matters when there is competition for scarce resources. {6.3, 6.4, 6.7, 7.3, 7.4, 7.5, 7.6, 8.2, 8.4, 8.6, Figure 8.4, Supplementary Material Table 8.SM.1, Supplementary Material Table 8.SM.2, 9.4, 9.5, 9.8, Table 9.5, 10.3, 10.4, 10.5, 10.6, 10.8, Table 10.3, 11.5, 12.5, 17.3, Figure 17.1, Supplementary Material Table 17.SM.1, Annex II.IV.12}

D.2 There is a strong link between sustainable development, vulnerability and climate risks. Limited economic, social and institutional resources often result in high vulnerability and low adaptive capacity, especially in developing countries (*medium confidence*). Several response options deliver both mitigation and adaptation outcomes, especially in human settlements, land management, and in relation to ecosystems. However, land and aquatic ecosystems can be adversely affected by some mitigation actions, depending on their implementation (*medium confidence*). Coordinated cross-sectoral policies and planning can maximise synergies and avoid or reduce trade-offs between mitigation and adaptation (*high confidence*). {3.7, 4.4, 13.8, 17.3; AR6 WGII}

D.2.1 Sustainable urban planning and infrastructure design including green roofs and facades, networks of parks and open spaces, management of urban forests and wetlands, urban agriculture, and water-sensitive design can deliver both mitigation and adaptation benefits in settlements (*medium confidence*). These options can also reduce flood risks, pressure on urban sewer systems, urban heat island effects, and can deliver health benefits from reduced air pollution (*high confidence*). There could also be trade-offs. For example, increasing urban density to reduce travel demand, could imply high vulnerability to heat waves and flooding (*high confidence*). (Figure SPM.8) {3.7, 8.2, 8.4, 12.5, 13.8, 17.3}

D.2.2 Land-related mitigation options with potential co-benefits for adaptation include agroforestry, cover crops, intercropping, perennial plants, restoring natural vegetation and rehabilitating degraded land. These can enhance resilience by maintaining land productivity and protecting and diversifying livelihoods. Restoration of mangroves and coastal wetlands sequesters carbon, while also reducing coastal erosion and protecting against storm surges, thus, reducing the risks from sea level rise and extreme weather. (*high confidence*) {4.4, 7.4, 7.6, 12.5, 13.8}

D.2.3 Some mitigation options can increase competition for scarce resources including land, water and biomass. Consequently, these can also reduce adaptive capacity, especially if deployed at larger scale and with high expansion rates thus exacerbating existing risks, in particular where land and water resources are very limited. Examples include the large-scale or poorly planned deployment of bioenergy, biochar, and afforestation of naturally unforested land. (*high confidence*) {12.5, 17.3}

D.2.4 Coordinated policies, equitable partnerships and integration of adaptation and mitigation within and across sectors can maximise synergies and minimise trade-offs and thereby enhance the support for climate action (*medium confidence*). Even if extensive global mitigation efforts are implemented, there will be a large need for financial, technical, and human resources for adaptation. Absence or limited resources in social and institutional systems can lead to poorly coordinated responses, thus reducing the potential for maximising mitigation and adaptation benefits, and increasing risk (*high confidence*). {12.6, 13.8, 17.1, 17.3}

D.3 Enhanced mitigation and broader action to shift development pathways towards sustainability will have distributional consequences within and between countries. Attention to equity and broad and meaningful participation of all relevant actors in decision-making at all scales can build social trust, and deepen and widen support for transformative changes. (*high confidence*) {3.6, 4.2, 4.5, 5.2, 13.2, 17.3, 17.4}

D.3.1 Countries at all stages of economic development seek to improve the well-being of people, and their development priorities reflect different starting points and contexts. Different contexts include social, economic, environmental, cultural, or political conditions, resource endowment, capabilities, international environment, and history. The enabling conditions for shifting development pathways towards increased sustainability will therefore also differ, giving rise to different needs. (*high confidence*) (Figure SPM.2) {1.6, 1.7, 2.4, 2.6, Cross-Chapter Box 5 in Chapter 4, 4.3.2, 17.4}

D.3.2 Ambitious mitigation pathways imply large and sometimes disruptive changes in economic structure, with significant distributional consequences, within and between countries. Equity remains a central element in the UN climate regime, notwithstanding shifts in differentiation between states over time and challenges in assessing fair shares. Distributional consequences within and between countries include shifting of income and employment during the transition from high- to low-emissions activities. While some jobs may be lost, low-emissions development can also open more opportunities to enhance skills and create more jobs that last, with differences across countries and sectors. Integrated policy packages can improve the ability to integrate considerations of equity, gender equality and justice. (*high confidence*) {1.4, 1.6, 3.6, 4.2, 5.2, Box 11.1, 14.3, 15.2, 15.5, 15.6}

D.3.3 Inequalities in the distribution of emissions and in the impacts of mitigation policies within countries affect social cohesion and the acceptability of mitigation and other environmental policies. Equity and just transitions can enable deeper ambitions for accelerated mitigation. Applying just transition principles and implementing them through collective and participatory decision-making processes is an effective way of integrating equity principles into policies at all scales, in different ways depending on national circumstances (*medium confidence*). This is already taking place in many countries and regions, as national just transition commissions or task forces, and related national policies, have been established in several countries. A multitude of actors, networks, and movements are engaged (*high confidence*). {1.6, 1.7, 2.4, 2.6, 4.5, 13.2, 13.9, 14.3, 14.5}

D.3.4 Broadening equitable access to domestic and international finance, technologies that facilitate mitigation, and capacity, while explicitly addressing needs can further integrate equity and justice into national and international policies and act as a catalyst for accelerating mitigation and shifting development pathways (*medium confidence*). The consideration of ethics and equity can help address the uneven distribution of adverse impacts associated with 1.5°C and higher levels of global warming, in all societies (*high confidence*). Consideration of climate justice can help to facilitate shifting development pathways towards sustainability, including through equitable sharing of benefits and burdens of mitigation, increasing resilience to the impacts of climate change, especially for vulnerable countries and communities, and equitably supporting those in need (*high confidence*). {1.4, 1.6, 1.7, 3.6, 4.2, 4.5, Box 5.10, 13.4, 13.8, 13.9, 14.3, 14.5, 15.2, 15.5, 15.6, 16.5, 17.3, 17.4; SR1.5 SPM, AR6 WGII Chapter 18}

E. Strengthening the Response

E.1 There are mitigation options which are feasible[71] to deploy at scale in the near term. Feasibility differs across sectors and regions, and according to capacities and the speed and scale of implementation. Barriers to feasibility would need to be reduced or removed, and enabling conditions[72] strengthened to deploy mitigation options at scale. These barriers and enablers include geophysical, environmental-ecological, technological, and economic factors, and especially institutional and socio-cultural factors. Strengthened near-term action beyond the NDCs (announced prior to UNFCCC COP26) can reduce and/or avoid long-term feasibility challenges of global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. (*high confidence*) {3.8, 6.4, 8.5, 9.9, 10.8, 12.3, Figure TS.31, Annex II.IV.11}

E.1.1 Several mitigation options, notably solar energy, wind energy, electrification of urban systems, urban green infrastructure, energy efficiency, demand-side management, improved forest- and crop/grassland management, and reduced food waste and loss, are technically viable, are becoming increasingly cost effective, and are generally supported by the public. This enables deployment in many regions (*high confidence*). While many mitigation options have environmental co-benefits, including improved air quality and reducing toxic waste, many also have adverse environmental impacts, such as reduced biodiversity, when applied at very large scale, for example very large scale bioenergy or large scale use of battery storage, that would have to be managed (*medium confidence*). Almost all mitigation options face institutional barriers that need to be addressed to enable their application at scale (*medium confidence*). {6.4, Figure 6.19, 7.4, 8.5, Figure 8.19, 9.9, Figure 9.20, 10.8, Figure 10.23, 12.3, Figure 12.4, Figure TS.31}

E.1.2 The feasibility of mitigation options varies according to context and time. For example, the institutional capacity to support deployment varies across countries; the feasibility of options that involve large-scale land-use changes varies across regions; spatial planning has a higher potential at early stages of urban development; the potential of geothermal is site specific; and capacities, cultural and local conditions can either inhibit or enable demand-side responses. The deployment of solar and wind energy has been assessed to become increasingly feasible over time. The feasibility of some options can increase when combined or integrated, such as using land for both agriculture and centralised solar production. (*high confidence*) {6.4, 6.6, Supplementary Material Table 6.SM, 7.4, 8.5, Supplementary Material Table 8.SM.2, 9.9, Supplementary Material Table 9.SM.1, 10.8, Appendix 10.3, 12.3, Tables 12.SM.2.1 to 12.SM.2.6}

E.1.3 Feasibility depends on the scale and speed of implementation. Most options face barriers when they are implemented rapidly at a large scale, but the scale at which barriers manifest themselves varies. Strengthened and coordinated near-term actions in cost-effective modelled global pathways that limit warming to 2°C (>67%) or lower, reduce the overall risks to the feasibility of the system transitions, compared to modelled pathways with relatively delayed or uncoordinated action.[73] (*high confidence*) {3.8, 6.4, 10.8, 12.3}

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[71] In this report, the term 'feasibility' refers to the potential for a mitigation or adaptation option to be implemented. Factors influencing feasibility are context-dependent and may change over time. Feasibility depends on geophysical, environmental-ecological, technological, economic, socio-cultural and institutional factors that enable or constrain the implementation of an option. The feasibility of options may change when different options are combined and increase when enabling conditions are strengthened.

[72] In this report, the term 'enabling conditions' refers to conditions that enhance the feasibility of adaptation and mitigation options. Enabling conditions include finance, technological innovation, strengthening policy instruments, institutional capacity, multi-level governance, and changes in human behaviour and lifestyles.

[73] The future feasibility challenges described in the modelled pathways may differ from the real-world feasibility experiences of the past.

E.2 In all countries, mitigation efforts embedded within the wider development context can increase the pace, depth and breadth of emissions reductions (*medium confidence*). Policies that shift development pathways towards sustainability can broaden the portfolio of available mitigation responses, and enable the pursuit of synergies with development objectives (*medium confidence*). Actions can be taken now to shift development pathways and accelerate mitigation and transitions across systems (*high confidence*). {4.3, 4.4, Cross-Chapter Box 5 in Chapter 4, 5.2, 5.4, 13.9, 14.5, 15.6, 16.3, 16.4, 16.5}

E.2.1 Current development pathways may create behavioural, spatial, economic and social barriers to accelerated mitigation at all scales (*high confidence*). Choices made by policymakers, citizens, the private sector and other stakeholders influence societies' development pathways (*high confidence*). Actions that steer, for example, energy and land systems transitions, economy-wide structural change, and behaviour change, can shift development pathways towards sustainability[74] (*medium confidence*). {4.3, Cross-Chapter Box 5 in Chapter 4, 5.4, 13.9}

E.2.2 Combining mitigation with policies to shift development pathways, such as broader sectoral policies, policies that induce lifestyle or behaviour changes, financial regulation, or macroeconomic policies can overcome barriers and open up a broader range of mitigation options (*high confidence*). It can also facilitate the combination of mitigation and other development goals (*high confidence*). For example, measures promoting walkable urban areas combined with electrification and renewable energy can create health co-benefits from cleaner air and benefits from enhanced mobility (*high confidence*). Coordinated housing policies that broaden relocation options can make mitigation measures in transport more effective (*medium confidence*). {3.2, 4.3, 4.4, Cross-Chapter Box 5 in Chapter 4, 5.3, 8.2, 8.4}

E.2.3 Institutional and regulatory capacity, innovation, finance, improved governance and collaboration across scales, and multi-objective policies enable enhanced mitigation and shifts in development pathways. Such interventions can be mutually reinforcing and establish positive feedback mechanisms, resulting in accelerated mitigation. (*high confidence*) {4.4, 5.4, Figure 5.14, 5.6, 9.9, 13.9, 14.5, 15.6, 16.3, 16.4, 16.5, Cross-Chapter Box 12 in Chapter 16}

E.2.4 Enhanced action on all the above enabling conditions can be taken now (*high confidence*). In some situations, such as with innovation in technology at an early stage of development and some changes in behaviour towards low emissions, because the enabling conditions may take time to be established, action in the near term can yield accelerated mitigation in the mid-term (*medium confidence*). In other situations, the enabling conditions can be put in place and yield results in a relatively short time frame, for example the provision of energy related information, advice and feedback to promote energy saving behaviour (*high confidence*). {4.4, 5.4, Figure 5.14, 5.6, 6.7, 9.9, 13.9, 14.5, 15.6, 16.3, 16.4, 16.5, Cross-Chapter Box 12 in Chapter 16}

E.3 Climate governance, acting through laws, strategies and institutions, based on national circumstances, supports mitigation by providing frameworks through which diverse actors interact, and a basis for policy development and implementation (*medium confidence*). Climate governance is most effective when it integrates across multiple policy domains, helps realise synergies and minimise trade-offs, and connects national and sub-national policymaking levels (*high confidence*). Effective and equitable climate governance builds on engagement with civil society actors, political actors, businesses, youth, labour, media, Indigenous Peoples and local communities (*medium confidence*). {5.4, 5.6, 8.5, 9.9, 13.2, 13.7, 13.9}

E.3.1 Climate governance enables mitigation by providing an overall direction, setting targets, mainstreaming climate action across policy domains, enhancing regulatory certainty, creating specialised organisations and creating the context to mobilise finance (*medium confidence*). These functions can be promoted by climate-relevant laws, which are growing in number, or climate strategies, among others, based on national and sub-national context (*medium confidence*). Framework laws set an overarching legal basis, either operating through a target and implementation approach, or a sectoral mainstreaming approach, or both, depending on national circumstance (*medium confidence*). Direct national and sub-national laws that explicitly target mitigation and indirect laws that impact emissions through mitigation-related policy domains have both been shown to be relevant to mitigation outcomes (*medium confidence*). {13.2}

[74] Sustainability may be interpreted differently in various contexts as societies pursue a variety of sustainable development objectives.

E.3.2 Effective national climate institutions address coordination across sectors, scales and actors, build consensus for action among diverse interests, and inform strategy setting (*medium confidence*). These functions are often accomplished through independent national expert bodies, and high-level coordinating bodies that transcend departmental mandates. Complementary sub-national institutions tailor mitigation actions to local context and enable experimentation but can be limited by inequities and resource and capacity constraints (*high confidence*). Effective governance requires adequate institutional capacity at all levels (*high confidence*). {4.4, 8.5, 9.9, 11.3, 11.5, 11.6, 13.2, 13.5, 13.7, 13.9}

E.3.3 The extent to which civil society actors, political actors, businesses, youth, labour, media, Indigenous Peoples, and local communities are engaged influences political support for climate change mitigation and eventual policy outcomes. Structural factors of national circumstances and capabilities (e.g., economic and natural endowments, political systems and cultural factors and gender considerations) affect the breadth and depth of climate governance. Mitigation options that align with prevalent ideas, values and beliefs are more easily adopted and implemented. Climate-related litigation, for example by governments, private sector, civil society and individuals, is growing - with a large number of cases in some developed countries, and with a much smaller number in some developing countries - and in some cases, has influenced the outcome and ambition of climate governance. (*medium confidence*) {5.2, 5.4, 5.5, 5.6, 9.9, 13.3, 13.4}

E.4 Many regulatory and economic instruments have already been deployed successfully. Instrument design can help address equity and other objectives. These instruments could support deep emissions reductions and stimulate innovation if scaled up and applied more widely (*high confidence*). Policy packages that enable innovation and build capacity are better able to support a shift towards equitable low-emission futures than are individual policies (*high confidence*). Economy-wide packages, consistent with national circumstances, can meet short-term economic goals while reducing emissions and shifting development pathways towards sustainability (*medium confidence*). {Cross-Chapter Box 5 in Chapter 4, 13.6, 13.7, 13.9, 16.3, 16.4, 16.6}

E.4.1 A wide range of regulatory instruments at the sectoral level have proven effective in reducing emissions. These instruments, and broad-based approaches including relevant economic instruments,[75] are complementary (*high confidence*). Regulatory instruments that are designed to be implemented with flexibility mechanisms can reduce costs (*medium confidence*). Scaling up and enhancing the use of regulatory instruments, consistent with national circumstances, could improve mitigation outcomes in sectoral applications, including but not limited to renewable energy, land use and zoning, building codes, vehicle and energy efficiency, fuel standards, and low-emissions industrial processes and materials (*high confidence*). {6.7, 7.6, 8.4, 9.9, 10.4, 11.5, 11.6, 13.6}

E.4.2 Economic instruments have been effective in reducing emissions, complemented by regulatory instruments mainly at the national and also sub-national and regional level (*high confidence*). Where implemented, carbon pricing instruments have incentivised low-cost emissions reduction measures, but have been less effective, on their own and at prevailing prices during the assessment period, in promoting the higher-cost measures necessary for further reductions (*medium confidence*). Equity and distributional impacts of such carbon pricing instruments can be addressed by using revenue from carbon taxes or emissions trading to support low-income households, among other approaches (*high confidence*). Practical experience has informed instrument design and helped to improve predictability, environmental effectiveness, economic efficiency, distributional goals and social acceptance (*high confidence*). Removing fossil fuel subsidies would reduce emissions, improve public revenue and macroeconomic performance, and yield other environmental and sustainable development benefits; subsidy removal may have adverse distributional impacts especially on the most economically vulnerable groups which, in some cases can be mitigated by measures such as redistributing revenue saved, all of which depend on national circumstances (*high confidence*); fossil fuel subsidy removal is projected by various studies to reduce global CO_2 emissions by 1–4%, and GHG emissions by up to 10% by 2030, varying across regions (*medium confidence*). {6.3, 13.6}

E.4.3 Low-emission technological innovation is strengthened through the combination of dedicated technology-push policies and investments (e.g., for scientific training, R&D, demonstration), with tailored demand-pull policies (e.g., standards, feed-in tariffs, taxes), which create incentives and market opportunities. Developing countries' abilities to deploy low-emission technologies, seize socio-economic benefits and manage trade-offs would be enhanced with increased financial resources and capacity for innovation which are currently concentrated in developed countries, alongside technology transfer. (*high confidence*) {16.2, 16.3, 16.4, 16.5}

[75] Economic instruments are structured to provide a financial incentive to reduce emissions and include, among others, market- and price-based instruments.

E.4.4 Effective policy packages would be comprehensive in coverage, harnessed to a clear vision for change, balanced across objectives, aligned with specific technology and system needs, consistent in terms of design and tailored to national circumstances. They are better able to realise synergies and avoid trade-offs across climate and development objectives. Examples include: emissions reductions from buildings through a mix of efficiency targets, building codes, appliance performance standards, information provision, carbon pricing, finance and technical assistance; and industrial GHG emissions reductions through innovation support, market creation and capacity building. (*high confidence*) {4.4, 6.7, 9.9, 11.6, 13.7, 13.9, 16.3, 16.4}

E.4.5 Economy-wide packages that support mitigation and avoid negative environmental outcomes include: long-term public spending commitments; pricing reform; and investment in education and training, natural capital, R&D and infrastructure (*high confidence*). They can meet short-term economic goals while reducing emissions and shifting development pathways towards sustainability (*medium confidence*). Infrastructure investments can be designed to promote low-emissions futures that meet development needs (*medium confidence*). {Cross-Chapter Box 5 in Chapter 4, 5.4, 5.6, 8.5, 13.6, 13.9, 16.3, 16.5, 16.6}

E.4.6 National policies to support technology development and diffusion, and participation in international markets for emission reduction, can bring positive spillover effects for other countries (*medium confidence*), although reduced demand for fossil fuels could result in costs to exporting countries (*high confidence*). There is no consistent evidence that current emission trading systems have led to significant emissions leakage, which can be attributed to design features aimed at minimising competitiveness effects, among other reasons (*medium confidence*). {13.6, 13.7, 13.8, 16.2, 16.3, 16.4}

E.5 Tracked financial flows fall short of the levels needed to achieve mitigation goals across all sectors and regions. The challenge of closing gaps is largest in developing countries as a whole. Scaling up mitigation financial flows can be supported by clear policy choices and signals from governments and the international community (*high confidence*). Accelerated international financial cooperation is a critical enabler of low-GHG and just transitions, and can address inequities in access to finance and the costs of, and vulnerability to, the impacts of climate change (*high confidence*). {15.2, 15.3, 15.4, 15.5, 15.6}

E.5.1 Average annual modelled investment requirements for 2020 to 2030 in scenarios that limit warming to 2°C or 1.5°C are a factor of three to six greater than current levels, and total mitigation investments (public, private, domestic and international) would need to increase across all sectors and regions (*medium confidence*). Mitigation investment gaps are wide for all sectors, and widest for the AFOLU sector in relative terms and for developing countries[76] (*high confidence*). Financing and investment requirements for adaptation, reduction of losses and damages, general infrastructure, regulatory environment and capacity building, and climate-responsive social protection further exacerbate the magnitude of the challenges for developing countries to attract financing (*high confidence*). {3.2, 14.4, 15.1, 15.2, 15.3, 15.4, 15.5}

E.5.2 There is sufficient global capital and liquidity to close global investment gaps, given the size of the global financial system, but there are barriers to redirect capital to climate action both within and outside the global financial sector, and in the macroeconomic headwinds facing developing regions. Barriers to the deployment of commercial finance from within the financial sector as well as macroeconomic considerations include: inadequate assessment of climate-related risks and investment opportunities; regional mismatch between available capital and investment needs; home bias factors; country indebtedness levels; economic vulnerability; and limited institutional capacities (*high confidence*). Challenges from outside the financial sector include: limited local capital markets; unattractive risk-return profiles, in particular due to missing or weak regulatory environments consistent with ambition levels; limited institutional capacity to ensure safeguards; standardisation, aggregation, scalability and replicability of investment opportunities and financing models; and, a pipeline ready for commercial investments. (*high confidence*) {15.2, 15.3, 15.5, 15.6}

E.5.3 Accelerated financial support for developing countries from developed countries and other sources is a critical enabler to enhance mitigation action and address inequities in access to finance, including its costs, terms and conditions, and economic vulnerability to climate change for developing countries (*high confidence*). Scaled-up public grants for mitigation and adaptation funding for vulnerable regions, especially in Sub-Saharan Africa, would be cost-effective and have high social returns in terms of access to basic energy (*high confidence*). Options for scaling up mitigation in developing regions include: increased levels of public finance and publicly mobilised private finance flows from developed to developing countries in the context of the USD100 billion-a-year goal; increase the use of public guarantees to reduce risks and leverage private flows

[76] In modelled pathways, regional investments are projected to occur when and where they are most cost-effective to limit global warming. The model quantifications help to identify high-priority areas for cost-effective investments, but do not provide any indication on who would finance the regional investments.

at lower cost; local capital markets development; and building greater trust in international cooperation processes (*high confidence*). A coordinated effort to make the post-pandemic recovery sustainable and increased flows of financing over the next decade can accelerate climate action, including in developing regions and countries facing high debt costs, debt distress and macroeconomic uncertainty (*high confidence*). {15.2, 15.3, 15.4, 15.5, 15.6, Box 15.6}

E.5.4 Clear signalling by governments and the international community, including a stronger alignment of public sector finance and policy, and higher levels of public sector climate finance, reduces uncertainty and transition risks for the private sector. Depending on national contexts, investors and financial intermediaries, central banks, and financial regulators can support climate action and can shift the systemic underpricing of climate-related risk by increasing awareness, transparency and consideration of climate-related risk, and investment opportunities. Financial flows can also be aligned with funding needs through: greater support for technology development; a continued role for multilateral and national climate funds and development banks; lowering financing costs for underserved groups through entities such as green banks existing in some countries, funds and risk-sharing mechanisms; economic instruments which consider economic and social equity and distributional impacts; gender-responsive and women-empowerment programmes as well as enhanced access to finance for local communities and Indigenous Peoples and small land owners; and greater public-private cooperation. (*high confidence*) {15.2, 15.5, 15.6}

E.6 International cooperation is a critical enabler for achieving ambitious climate change mitigation goals. The UNFCCC, Kyoto Protocol, and Paris Agreement are supporting rising levels of national ambition and encouraging development and implementation of climate policies, although gaps remain. Partnerships, agreements, institutions and initiatives operating at the sub-global and sectoral levels and engaging multiple actors are emerging, with mixed levels of effectiveness. (*high confidence*) {8.5, 14.2, 14.3, 14.5, 14.6, 15.6, 16.5}

E.6.1 Internationally agreed processes and goals, such as those in the UNFCCC, Kyoto Protocol, and Paris Agreement – including transparency requirements for national reporting on emissions, actions and support, and tracking progress towards the achievement of Nationally Determined Contributions – are enhancing international cooperation, national ambition and policy development. International financial, technology and capacity building support to developing countries will enable greater implementation and encourage ambitious Nationally Determined Contributions over time. (*medium confidence*) {14.3}

E.6.2 International cooperation on technology development and transfer accompanied by capacity building, knowledge sharing, and technical and financial support can accelerate the global diffusion of mitigation technologies, practices and policies at national and sub-national levels, and align these with other development objectives (*high confidence*). Challenges in and opportunities to enhance innovation cooperation exist, including in the implementation of elements of the UNFCCC and the Paris Agreement as per the literature assessed, such as in relation to technology development and transfer, and finance (*high confidence*). International cooperation on innovation works best when tailored to specific institutional and capability contexts, when it benefits local value chains, when partners collaborate equitably and on voluntary and mutually agreed terms, when all relevant voices are heard, and when capacity building is an integral part of the effort (*medium confidence*). Support to strengthen technological innovation systems and innovation capabilities, including through financial support in developing countries would enhance engagement in and improve international cooperation on innovation (*high confidence*). {4.4, 14.2, 14.4, 16.3, 16.5, 16.6}

E.6.3 Transnational partnerships can stimulate policy development, low-emissions technology diffusion and emission reductions by linking sub-national and other actors, including cities, regions, non-governmental organisations and private sector entities, and by enhancing interactions between state and non-state actors. While this potential of transnational partnerships is evident, uncertainties remain over their costs, feasibility, and effectiveness. Transnational networks of city governments are leading to enhanced ambition and policy development and a growing exchange of experience and best practices (*medium confidence*). {8.5, 11.6, 14.5, 16.5, Cross-Chapter Box 12 in Chapter 16}

E.6.4 International environmental and sectoral agreements, institutions, and initiatives are helping, and in some cases may help, to stimulate low-GHG emissions investment and reduce emissions. Agreements addressing ozone depletion and transboundary air pollution are contributing to mitigation, and in other areas, such as atmospheric emissions of mercury, may contribute to mitigation (*high confidence*). Trade rules have the potential to stimulate international adoption of mitigation technologies and policies, but may also limit countries' ability to adopt trade-related climate policies (*medium confidence*). Current sectoral levels of ambition vary, with emission reduction aspirations in international aviation and shipping lower than in many other sectors (*medium confidence*). {14.5, 14.6}

SYNTHESIS REPORT
OF THE IPCC SIXTH ASSESSMENT REPORT (AR6)

Summary for Policymakers

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In the Summary for Policymakers, the references refer to the numbers of the Sections, figures, tables and boxes in the underlying Longer Report of the Synthesis Report, or to other sections of the SPM itself (in round brackets).

Other IPCC reports cited in this Synthesis Report:
AR5 Fifth Assessment Report

Introduction

This Synthesis Report (SYR) of the IPCC Sixth Assessment Report (AR6) summarises the state of knowledge of climate change, its widespread impacts and risks, and climate change mitigation and adaptation. It integrates the main findings of the Sixth Assessment Report (AR6) based on contributions from the three Working Groups[1], and the three Special Reports[2]. The summary for Policymakers (SPM) is structured in three parts: SPM.A Current Status and Trends, SPM.B Future Climate Change, Risks, and Long-Term Responses, and SPM.C Responses in the Near Term[3].

This report recognizes the interdependence of climate, ecosystems and biodiversity, and human societies; the value of diverse forms of knowledge; and the close linkages between climate change adaptation, mitigation, ecosystem health, human well-being and sustainable development, and reflects the increasing diversity of actors involved in climate action.

Based on scientific understanding, key findings can be formulated as statements of fact or associated with an assessed level of confidence using the IPCC calibrated language[4].

[1] The three Working Group contributions to AR6 are: AR6 Climate Change 2021: The Physical Science Basis; AR6 Climate Change 2022: Impacts, Adaptation and Vulnerability; and AR6 Climate Change 2022: Mitigation of Climate Change. Their assessments cover scientific literature accepted for publication respectively by 31 January 2021, 1 September 2021 and 11 October 2021.

[2] The three Special Reports are: Global Warming of 1.5°C (2018): an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (SR1.5); Climate Change and Land (2019): an IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL); and The Ocean and Cryosphere in a Changing Climate (2019) (SROCC). The Special Reports cover scientific literature accepted for publication respectively by 15 May 2018, 7 April 2019 and 15 May 2019.

[3] In this report, the near term is defined as the period until 2040. The long term is defined as the period beyond 2040.

[4] Each finding is grounded in an evaluation of underlying evidence and agreement. The IPCC calibrated language uses five qualifiers to express a level of confidence: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence*. The following terms are used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, more likely than not >50–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%; more likely than not >50–100%; and extremely unlikely 0–5%) are also used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*. This is consistent with AR5 and the other AR6 Reports.

A. Current Status and Trends

Observed Warming and its Causes

A.1 Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850–1900 in 2011–2020. Global greenhouse gas emissions have continued to increase, with unequal historical and ongoing contributions arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, between and within countries, and among individuals (*high confidence*). {2.1, Figure 2.1, Figure 2.2}

A.1.1 Global surface temperature was 1.09°C [0.95°C–1.20°C][5] higher in 2011–2020 than 1850–1900[6], with larger increases over land (1.59°C [1.34°C–1.83°C]) than over the ocean (0.88°C [0.68°C–1.01°C]). Global surface temperature in the first two decades of the 21st century (2001-2020) was 0.99 [0.84 to 1.10]°C higher than 1850-1900. Global surface temperature has increased faster since 1970 than in any other 50-year period over at least the last 2000 years (*high confidence*). {2.1.1, Figure 2.1}

A.1.2 The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019[7] is 0.8°C–1.3°C, with a best estimate of 1.07°C. Over this period, it is *likely* that well-mixed greenhouse gases (GHGs) contributed a warming of 1.0°C–2.0°C[8], and other human drivers (principally aerosols) contributed a cooling of 0.0°C–0.8°C, natural (solar and volcanic) drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. {2.1.1, Figure 2.1}

A.1.3 Observed increases in well-mixed GHG concentrations since around 1750 are unequivocally caused by GHG emissions from human activities over this period. Historical cumulative net CO_2 emissions from 1850 to 2019 were 2400±240 $GtCO_2$ of which more than half (58%) occurred between 1850 and 1989, and about 42% occurred between 1990 and 2019 (*high confidence*). In 2019, atmospheric CO_2 concentrations (410 parts per million) were higher than at any time in at least 2 million years (*high confidence*), and concentrations of methane (1866 parts per billion) and nitrous oxide (332 parts per billion) were higher than at any time in at least 800,000 years (*very high confidence*). {2.1.1, Figure 2.1}

A.1.4 Global net anthropogenic GHG emissions have been estimated to be 59±6.6 $GtCO_2$-eq[9] in 2019, about 12% (6.5 $GtCO_2$-eq) higher than in 2010 and 54% (21 $GtCO_2$-eq) higher than in 1990, with the largest share and growth in gross GHG emissions occurring in CO_2 from fossil fuels combustion and industrial processes (CO_2-FFI) followed by methane, whereas the highest relative growth occurred in fluorinated gases (F-gases), starting from low levels in 1990. Average annual GHG emissions during 2010-2019 were higher than in any previous decade on record, while the rate of growth between 2010 and 2019 (1.3% $year^{-1}$) was lower than that between 2000 and 2009 (2.1% $year^{-1}$). In 2019, approximately 79% of global GHG emissions came from the sectors of energy, industry, transport and buildings together and 22%[10] from agriculture, forestry and other land use (AFOLU). Emissions reductions in CO_2-FFI due to improvements in energy intensity of GDP and carbon intensity of energy, have been less than emissions increases from rising global activity levels in industry, energy supply, transport, agriculture and buildings. (*high confidence*) {2.1.1}

[5] Ranges given throughout the SPM represent *very likely* ranges (5–95% range) unless otherwise stated.

[6] The estimated increase in global surface temperature since AR5 is principally due to further warming since 2003–2012 (+0.19°C [0.16°C–0.22°C]). Additionally, methodological advances and new datasets have provided a more complete spatial representation of changes in surface temperature, including in the Arctic. These and other improvements have also increased the estimate of global surface temperature change by approximately 0.1°C, but this increase does not represent additional physical warming since AR5.

[7] The period distinction with A.1.1 arises because the attribution studies consider this slightly earlier period. The observed warming to 2010–2019 is 1.06°C [0.88°C–1.21°C].

[8] Contributions from emissions to the 2010-2019 warming relative to 1850-1900 assessed from radiative forcing studies are: CO_2 0.8 [0.5 to 1.2]°C; methane 0.5 [0.3 to 0.8]°C; nitrous oxide 0.1 [0.0 to 0.2]°C and fluorinated gases 0.1 [0.0 to 0.2]°C. {2.1.1}

[9] GHG emission metrics are used to express emissions of different greenhouse gases in a common unit. Aggregated GHG emissions in this report are stated in CO_2-equivalents (CO_2-eq) using the Global Warming Potential with a time horizon of 100 years (GWP100) with values based on the contribution of Working Group I to the AR6. The AR6 WGI and WGIII reports contain updated emission metric values, evaluations of different metrics with regard to mitigation objectives, and assess new approaches to aggregating gases. The choice of metric depends on the purpose of the analysis and all GHG emission metrics have limitations and uncertainties, given that they simplify the complexity of the physical climate system and its response to past and future GHG emissions. {2.1.1}

[10] GHG emission levels are rounded to two significant digits; as a consequence, small differences in sums due to rounding may occur. {2.1.1}

A.1.5 Historical contributions of CO_2 emissions vary substantially across regions in terms of total magnitude, but also in terms of contributions to CO_2-FFI and net CO_2 emissions from land use, land-use change and forestry (CO_2-LULUCF). In 2019, around 35% of the global population live in countries emitting more than 9 tCO_2-eq per capita[11] (excluding CO_2-LULUCF) while 41% live in countries emitting less than 3 tCO_2-eq per capita; of the latter a substantial share lacks access to modern energy services. Least developed countries (LDCs) and Small Island Developing States (SIDS) have much lower per capita emissions (1.7 tCO_2-eq and 4.6 tCO_2-eq, respectively) than the global average (6.9 tCO_2-eq), excluding CO_2-LULUCF. The 10% of households with the highest per capita emissions contribute 34–45% of global consumption-based household GHG emissions, while the bottom 50% contribute 13–15%. *(high confidence)* {2.1.1, Figure 2.2}

Observed Changes and Impacts

A.2 Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred. Human-caused climate change is already affecting many weather and climate extremes in every region across the globe. This has led to widespread adverse impacts and related losses and damages to nature and people (*high confidence*). Vulnerable communities who have historically contributed the least to current climate change are disproportionately affected (*high confidence*). {2.1, Table 2.1, Figure 2.2 and 2.3} (Figure SPM.1)

A.2.1 It is unequivocal that human influence has warmed the atmosphere, ocean and land. Global mean sea level increased by 0.20 [0.15–0.25] m between 1901 and 2018. The average rate of sea level rise was 1.3 [0.6 to 2.1]mm yr^{-1} between 1901 and 1971, increasing to 1.9 [0.8 to 2.9] mm yr^{-1} between 1971 and 2006, and further increasing to 3.7 [3.2 to 4.2] mm yr^{-1} between 2006 and 2018 (*high confidence*). Human influence was *very likely* the main driver of these increases since at least 1971. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has further strengthened since AR5. Human influence has *likely* increased the chance of compound extreme events since the 1950s, including increases in the frequency of concurrent heatwaves and droughts (*high confidence*). {2.1.2, Table 2.1, Figure 2.3, Figure 3.4} (Figure SPM.1)

A.2.2 Approximately 3.3–3.6 billion people live in contexts that are highly vulnerable to climate change. Human and ecosystem vulnerability are interdependent. Regions and people with considerable development constraints have high vulnerability to climatic hazards. Increasing weather and climate extreme events have exposed millions of people to acute food insecurity[12] and reduced water security, with the largest adverse impacts observed in many locations and/or communities in Africa, Asia, Central and South America, LDCs, Small Islands and the Arctic, and globally for Indigenous Peoples, small-scale food producers and low-income households. Between 2010 and 2020, human mortality from floods, droughts and storms was 15 times higher in highly vulnerable regions, compared to regions with very low vulnerability. (*high confidence*) {2.1.2, 4.4} (Figure SPM.1)

A.2.3 Climate change has caused substantial damages, and increasingly irreversible losses, in terrestrial, freshwater, cryospheric, and coastal and open ocean ecosystems (*high confidence*). Hundreds of local losses of species have been driven by increases in the magnitude of heat extremes (*high confidence*) with mass mortality events recorded on land and in the ocean (*very high confidence*). Impacts on some ecosystems are approaching irreversibility such as the impacts of hydrological changes resulting from the retreat of glaciers, or the changes in some mountain (*medium confidence*) and Arctic ecosystems driven by permafrost thaw (*high confidence*). {2.1.2, Figure 2.3} (Figure SPM.1)

A.2.4 Climate change has reduced food security and affected water security, hindering efforts to meet Sustainable Development Goals (*high confidence*). Although overall agricultural productivity has increased, climate change has slowed this growth over the past 50 years globally (*medium confidence*), with related negative impacts mainly in mid- and low latitude regions but positive impacts in some high latitude regions (*high confidence*). Ocean warming and ocean acidification have adversely affected food production from

[11] Territorial emissions.
[12] Acute food insecurity can occur at any time with a severity that threatens lives, livelihoods or both, regardless of the causes, context or duration, as a result of shocks risking determinants of food security and nutrition, and is used to assess the need for humanitarian action {2.1}.

fisheries and shellfish aquaculture in some oceanic regions (*high confidence*). Roughly half of the world's population currently experience severe water scarcity for at least part of the year due to a combination of climatic and non-climatic drivers (*medium confidence*). {2.1.2, Figure 2.3} (Figure SPM.1)

A.2.5 In all regions increases in extreme heat events have resulted in human mortality and morbidity (*very high confidence*). The occurrence of climate-related food-borne and water-borne diseases (*very high confidence*) and the incidence of vector-borne diseases (*high confidence*) have increased. In assessed regions, some mental health challenges are associated with increasing temperatures (*high confidence*), trauma from extreme events (*very high confidence*), and loss of livelihoods and culture (*high confidence*). Climate and weather extremes are increasingly driving displacement in Africa, Asia, North America (*high confidence*), and Central and South America (*medium confidence*), with small island states in the Caribbean and South Pacific being disproportionately affected relative to their small population size (*high confidence*). {2.1.2, Figure 2.3} (Figure SPM.1)

A.2.6 Climate change has caused widespread adverse impacts and related losses and damages[13] to nature and people that are unequally distributed across systems, regions and sectors. Economic damages from climate change have been detected in climate-exposed sectors, such as agriculture, forestry, fishery, energy, and tourism. Individual livelihoods have been affected through, for example, destruction of homes and infrastructure, and loss of property and income, human health and food security, with adverse effects on gender and social equity. (*high confidence*) {2.1.2} (Figure SPM.1)

A.2.7 In urban areas, observed climate change has caused adverse impacts on human health, livelihoods and key infrastructure. Hot extremes have intensified in cities. Urban infrastructure, including transportation, water, sanitation and energy systems have been compromised by extreme and slow-onset events[14], with resulting economic losses, disruptions of services and negative impacts to well-being. Observed adverse impacts are concentrated amongst economically and socially marginalised urban residents. (*high confidence*) {2.1.2}

[START FIGURE SPM.1 HERE]

[13] In this report, the term 'losses and damages' refer to adverse observed impacts and/or projected risks and can be economic and/or non-economic. (See Annex I: Glossary)

[14] Slow-onset events are described among the climatic-impact drivers of the WGI AR6 and refer to the risks and impacts associated with e.g., increasing temperature means, desertification, decreasing precipitation, loss of biodiversity, land and forest degradation, glacial retreat and related impacts, ocean acidification, sea level rise and salinization. {2.1.2}

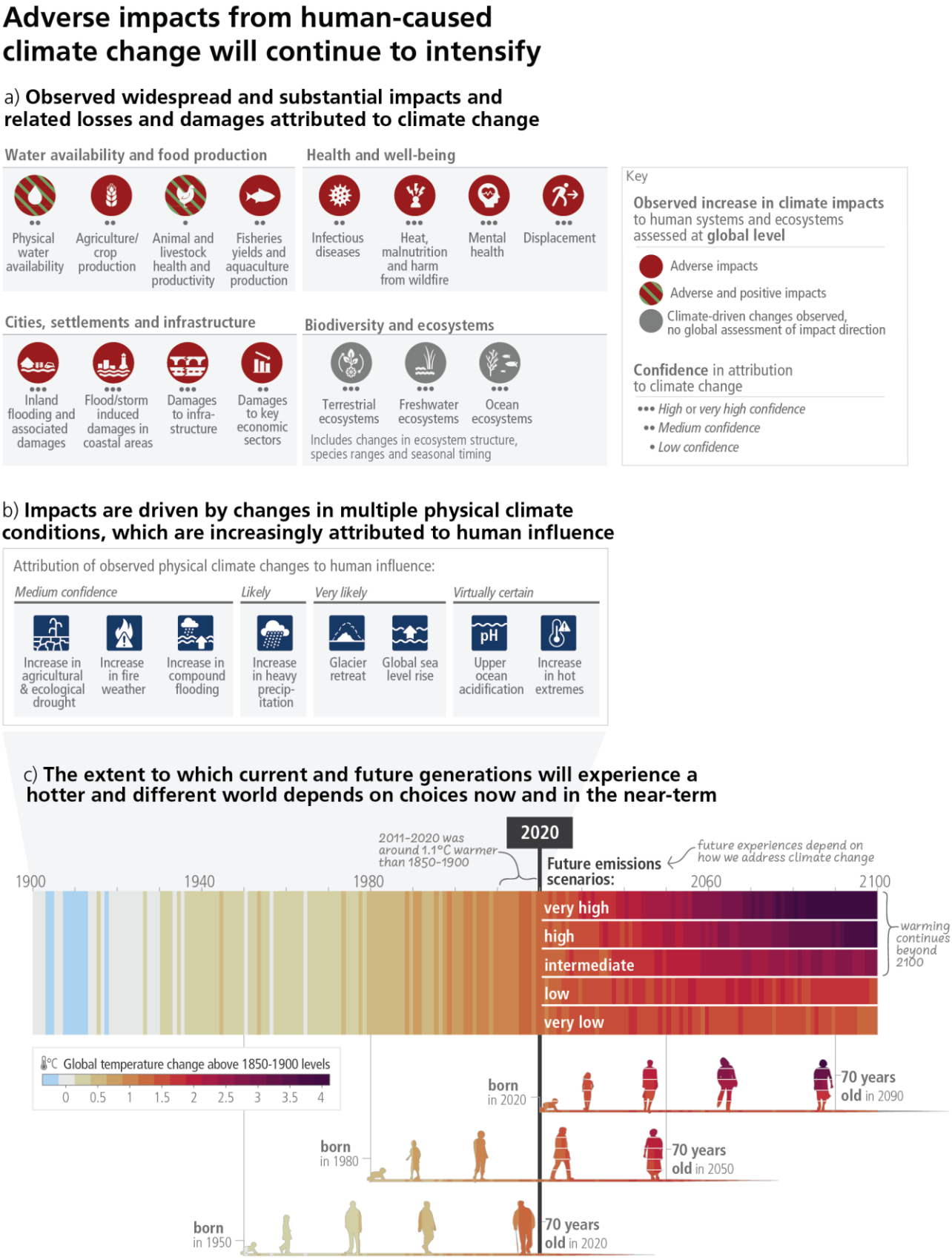

Figure SPM.1: (a) Climate change has already caused widespread impacts and related losses and damages on human systems and altered terrestrial, freshwater and ocean ecosystems worldwide. Physical water availability includes balance of water available from various sources including ground water, water quality and demand for water. Global mental health and displacement assessments reflect only assessed regions. Confidence levels reflect the assessment of attribution of the observed impact to climate change. **(b)** Observed impacts are connected to physical climate changes including many that have been attributed to human influence such as the selected climatic impact-drivers shown. Confidence and likelihood levels reflect the assessment of attribution

of the observed climatic impact-driver to human influence. **(c)** Observed (1900–2020) and projected (2021–2100) changes in global surface temperature (relative to 1850–1900), which are linked to changes in climate conditions and impacts, illustrate how the climate has already changed and will change along the lifespan of three representative generations (born in 1950, 1980 and 2020). Future projections (2021–2100) of changes in global surface temperature are shown for very low (SSP1-1.9), low (SSP1-2.6), intermediate (SSP2-4.5), high (SSP3-7.0) and very high (SSP5-8.5) GHG emissions scenarios. Changes in annual global surface temperatures are presented as 'climate stripes', with future projections showing the human-caused long-term trends and continuing modulation by natural variability (represented here using observed levels of past natural variability). Colours on the generational icons correspond to the global surface temperature stripes for each year, with segments on future icons differentiating possible future experiences. {2.1, 2.1.2, Figure 2.1, Table 2.1, Figure 2.3, Cross-Section Box.2, 3.1, Figure 3.3, 4.1, 4.3} (Box SPM.1)

[END FIGURE SPM.1 HERE]

Current Progress in Adaptation and Gaps and Challenges

A.3 Adaptation planning and implementation has progressed across all sectors and regions, with documented benefits and varying effectiveness. Despite progress, adaptation gaps exist, and will continue to grow at current rates of implementation. Hard and soft limits to adaptation have been reached in some ecosystems and regions. Maladaptation is happening in some sectors and regions. Current global financial flows for adaptation are insufficient for, and constrain implementation of, adaptation options, especially in developing countries (*high confidence*). {2.2, 2.3}

A.3.1 Progress in adaptation planning and implementation has been observed across all sectors and regions, generating multiple benefits (*very high confidence*). Growing public and political awareness of climate impacts and risks has resulted in at least 170 countries and many cities including adaptation in their climate policies and planning processes (*high confidence*). {2.2.3}

A.3.2 Effectiveness[15] of adaptation in reducing climate risks[16] is documented for specific contexts, sectors and regions (*high confidence*). Examples of effective adaptation options include: cultivar improvements, on-farm water management and storage, soil moisture conservation, irrigation, agroforestry, community-based adaptation, farm and landscape level diversification in agriculture, sustainable land management approaches, use of agroecological principles and practices and other approaches that work with natural processes (*high confidence*). Ecosystem-based adaptation[17] approaches such as urban greening, restoration of wetlands and upstream forest ecosystems have been effective in reducing flood risks and urban heat (*high confidence*). Combinations of non-structural measures like early warning systems and structural measures like levees have reduced loss of lives in case of inland flooding (*medium confidence*). Adaptation options such as disaster risk management, early warning systems, climate services and social safety nets have broad applicability across multiple sectors (*high confidence*). {2.2.3}

A.3.3 Most observed adaptation responses are fragmented, incremental[18], sector-specific and unequally distributed across regions. Despite progress, adaptation gaps exist across sectors and regions, and will continue to grow under current levels of implementation, with the largest adaptation gaps among lower income groups. (*high confidence*) {2.3.2}

A.3.4 There is increased evidence of maladaptation in various sectors and regions (*high confidence*). Maladaptation especially affects marginalised and vulnerable groups adversely (*high confidence*). {2.3.2}

A.3.5 Soft limits to adaptation are currently being experienced by small-scale farmers and households along some low-lying coastal areas (*medium confidence*) resulting from financial, governance, institutional and policy constraints (*high confidence*). Some tropical, coastal, polar and mountain ecosystems have reached hard

[15] Effectiveness refers here to the extent to which an adaptation option is anticipated or observed to reduce climate-related risk. {2.2.3}
[16] See Annex I: Glossary {2.2.3}
[17] Ecosystem based Adaptation (EbA) is recognized internationally under the Convention on Biological Diversity (CBD14/5). A related concept is Nature-based Solutions (NbS), see Annex I: Glossary.
[18] Incremental adaptations to change in climate are understood as extensions of actions and behaviours that already reduce the losses or enhance the benefits of natural variations in extreme weather/climate events. {2.3.2}

adaptation limits (*high confidence*). Adaptation does not prevent all losses and damages, even with effective adaptation and before reaching soft and hard limits (*high confidence*). {2.3.2}

A.3.6 Key barriers to adaptation are limited resources, lack of private sector and citizen engagement, insufficient mobilization of finance (including for research), low climate literacy, lack of political commitment, limited research and/or slow and low uptake of adaptation science, and low sense of urgency. There are widening disparities between the estimated costs of adaptation and the finance allocated to adaptation (*high confidence*). Adaptation finance has come predominantly from public sources, and a small proportion of global tracked climate finance was targeted to adaptation and an overwhelming majority to mitigation (*very high confidence*). Although global tracked climate finance has shown an upward trend since AR5, current global financial flows for adaptation, including from public and private finance sources, are insufficient and constrain implementation of adaptation options, especially in developing countries (*high confidence*). Adverse climate impacts can reduce the availability of financial resources by incurring losses and damages and through impeding national economic growth, thereby further increasing financial constraints for adaptation, particularly for developing and least developed countries (*medium confidence*). {2.3.2; 2.3.3}

[START BOX SPM.1 HERE]

Box SPM.1 The use of scenarios and modelled pathways in the AR6 Synthesis Report

Modelled scenarios and pathways[19] are used to explore future emissions, climate change, related impacts and risks, and possible mitigation and adaptation strategies and are based on a range of assumptions, including socio-economic variables and mitigation options. These are quantitative projections and are neither predictions nor forecasts. Global modelled emission pathways, including those based on cost effective approaches contain regionally differentiated assumptions and outcomes, and have to be assessed with the careful recognition of these assumptions. Most do not make explicit assumptions about global equity, environmental justice or intra-regional income distribution. IPCC is neutral with regard to the assumptions underlying the scenarios in the literature assessed in this report, which do not cover all possible futures.[20] {Cross-Section Box.2}

WGI assessed the climate response to five illustrative scenarios based on Shared Socio-economic Pathways (SSPs)[21] that cover the range of possible future development of anthropogenic drivers of climate change found in the literature. High and very high GHG emissions scenarios (SSP3-7.0 and SSP5-8.5[22]) have CO_2 emissions that roughly double from current levels by 2100 and 2050, respectively. The intermediate GHG emissions scenario (SSP2-4.5) has CO_2 emissions remaining around current levels until the middle of the century. The very low and low GHG emissions scenarios (SSP1-1.9 and SSP1-2.6) have CO_2 emissions declining to net zero around 2050 and 2070, respectively, followed by varying levels of net negative CO_2 emissions. In addition, Representative Concentration Pathways (RCPs)[23] were used by WGI and WGII to assess regional climate changes, impacts and risks. In WGIII, a large number of global modelled emissions pathways were assessed, of which 1202 pathways were categorised based on their assessed global warming over the 21st century; categories range from pathways that limit warming to 1.5°C with more than 50% likelihood (noted >50% in this report) with no or limited overshoot (C1) to pathways that exceed 4°C (C8). (Box SPM.1, Table 1). {Cross-Section Box.2}

[19] In the literature, the terms pathways and scenarios are used interchangeably, with the former more frequently used in relation to climate goals. WGI primarily used the term scenarios and WGIII mostly used the term modelled emission and mitigation pathways. The SYR primarily uses scenarios when referring to WGI and modelled emission and mitigation pathways when referring to WGIII.

[20] Around half of all modelled global emission pathways assume cost-effective approaches that rely on least-cost mitigation/abatement options globally. The other half looks at existing policies and regionally and sectorally differentiated actions.

[21] SSP-based scenarios are referred to as SSPx-y, where 'SSPx' refers to the Shared Socioeconomic Pathway describing the socioeconomic trends underlying the scenarios, and 'y' refers to the level of radiative forcing (in watts per square metre, or Wm^{-2}) resulting from the scenario in the year 2100. {Cross-Section Box.2}

[22] Very high emissions scenarios have become less likely but cannot be ruled out. Warming levels >4°C may result from very high emissions scenarios, but can also occur from lower emission scenarios if climate sensitivity or carbon cycle feedbacks are higher than the best estimate. {3.1.1}

[23] RCP-based scenarios are referred to as RCPy, where 'y' refers to the level of radiative forcing (in watts per square metre, or Wm^{-2}) resulting from the scenario in the year 2100. The SSP scenarios cover a broader range of greenhouse gas and air pollutant futures than the RCPs. They are similar but not identical, with differences in concentration trajectories. The overall effective radiative forcing tends to be higher for the SSPs compared to the RCPs with the same label (*medium confidence*). {Cross-Section Box.2}

Global warming levels (GWLs) relative to 1850–1900 are used to integrate the assessment of climate change and related impacts and risks since patterns of changes for many variables at a given GWL are common to all scenarios considered and independent of timing when that level is reached. {Cross-Section Box.2}

[START BOX SPM.1, TABLE 1 HERE]

Box SPM.1, Table 1: Description and relationship of scenarios and modelled pathways considered across AR6 Working Group reports. {Cross-Section Box.2, Figure 1}

Category in WGIII	Category description	GHG emissions scenarios (SSPx-y*) in WGI & WGII	RCPy** in WGI & WGII
C1	limit warming to 1.5°C (>50%) with no or limited overshoot***	Very low (SSP1-1.9)	
C2	return warming to 1.5°C (>50%) after a high overshoot***		
C3	limit warming to 2°C (>67%)	Low (SSP1-2.6)	RCP2.6
C4	limit warming to 2°C (>50%)		
C5	limit warming to 2.5°C (>50%)		
C6	limit warming to 3°C (>50%)	Intermediate (SSP2-4.5)	RCP 4.5
C7	limit warming to 4°C (>50%)	High (SSP3-7.0)	
C8	exceed warming of 4°C (>50%)	Very high (SSP5-8.5)	RCP 8.5

* See footnote 27 for the SSPx-y terminology.
** See footnote 28 for the RCPy terminology.
*** Limited overshoot refers to exceeding 1.5°C global warming by up to about 0.1°C, high overshoot by 0.1°C-0.3°C, in both cases for up to several decades.

[END BOX SPM.1, TABLE 1 HERE]

[END BOX SPM.1 HERE]

Current Mitigation Progress, Gaps and Challenges

A.4 Policies and laws addressing mitigation have consistently expanded since AR5. Global GHG emissions in 2030 implied by nationally determined contributions (NDCs) announced by October 2021 make it *likely* that warming will exceed 1.5°C during the 21st century and make it harder to limit warming below 2°C. There are gaps between projected emissions from implemented policies and those from NDCs and finance flows fall short of the levels needed to meet climate goals across all sectors and regions. (*high confidence*) {2.2, 2.3, Figure 2.5, Table 2.2}

A.4.1 The UNFCCC, Kyoto Protocol, and the Paris Agreement are supporting rising levels of national ambition. The Paris Agreement, adopted under the UNFCCC, with near universal participation, has led to policy development and target-setting at national and sub-national levels, in particular in relation to mitigation, as well as enhanced transparency of climate action and support (*medium confidence*). Many regulatory and economic instruments have already been deployed successfully (*high confidence*). In many countries, policies have enhanced energy efficiency, reduced rates of deforestation and accelerated technology deployment, leading to avoided and in some cases reduced or removed emissions (*high confidence*). Multiple lines of evidence suggest that mitigation policies have led to several[24] Gt CO_2-eq yr^{-1} of avoided global emissions *(medium confidence)*. At least 18 countries have sustained absolute production-based GHG and consumption-based CO_2 reductions[25] for longer than 10 years. These reductions have only partly offset global emissions growth (*high confidence*). {2.2.1, 2.2.2}

[24] At least 1.8 $GtCO_2$-eq yr^{-1} can be accounted for by aggregating separate estimates for the effects of economic and regulatory instruments. Growing numbers of laws and executive orders have impacted global emissions and were estimated to result in 5.9 $GtCO_2$-eq yr^{-1} less emissions in 2016 than they otherwise would have been. (*medium confidence*) {2.2.2}

[25] Reductions were linked to energy supply decarbonisation, energy efficiency gains, and energy demand reduction, which resulted from both policies and changes in economic structure (*high confidence*). {2.2.2}

A.4.2 Several mitigation options, notably solar energy, wind energy, electrification of urban systems, urban green infrastructure, energy efficiency, demand-side management, improved forest- and crop/grassland management, and reduced food waste and loss, are technically viable, are becoming increasingly cost effective and are generally supported by the public. From 2010– 2019 there have been sustained decreases in the unit costs of solar energy (85%), wind energy (55%), and lithium ion batteries (85%), and large increases in their deployment, e.g., >10x for solar and >100x for electric vehicles (EVs), varying widely across regions. The mix of policy instruments that reduced costs and stimulated adoption includes public R&D, funding for demonstration and pilot projects, and demand pull instruments such as deployment subsidies to attain scale. Maintaining emission-intensive systems may, in some regions and sectors, be more expensive than transitioning to low emission systems. (*high confidence*) {2.2.2, Figure 2.4}

A.4.3 A substantial 'emissions gap' exists between global GHG emissions in 2030 associated with the implementation of NDCs announced prior to COP26[26] and those associated with modelled mitigation pathways that limit warming to 1.5°C (>50%) with no or limited overshoot or limit warming to 2°C (>67%) assuming immediate action (*high confidence*). This would make it *likely* that warming will exceed 1.5°C during the 21st century (*high confidence*). Global modelled mitigation pathways that limit warming to 1.5°C (>50%) with no or limited overshoot or limit warming to 2°C (>67%) assuming immediate action imply deep global GHG emissions reductions this decade (*high confidence*) (see SPM Box 1, Table 1, B.6)[27]. Modelled pathways that are consistent with NDCs announced prior to COP26 until 2030 and assume no increase in ambition thereafter have higher emissions, leading to a median global warming of 2.8 [2.1–3.4]°C by 2100 (*medium confidence*). Many countries have signalled an intention to achieve net-zero GHG or net-zero CO_2 by around mid-century but pledges differ across countries in terms of scope and specificity, and limited policies are to date in place to deliver on them. {2.3.1, Table 2.2, Figure 2.5; Table 3.1; 4.1}

A.4.4 Policy coverage is uneven across sectors (*high confidence*). Policies implemented by the end of 2020 are projected to result in higher global GHG emissions in 2030 than emissions implied by NDCs, indicating an 'implementation gap' (*high confidence*). Without a strengthening of policies, global warming of 3.2 [2.2–3.5]°C is projected by 2100 (*medium confidence*). {2.2.2, 2.3.1, 3.1.1, Figure 2.5} (Box SPM.1, Figure SPM.5)

A.4.5 The adoption of low-emission technologies lags in most developing countries, particularly least developed ones, due in part to limited finance, technology development and transfer, and capacity (*medium confidenc*e). The magnitude of climate finance flows has increased over the last decade and financing channels have broadened but growth has slowed since 2018 *(high confidence).* Financial flows have developed heterogeneously across regions and sectors (*high confidence*). Public and private finance flows for fossil fuels are still greater than those for climate adaptation and mitigation (*high confidence*). The overwhelming majority of tracked climate finance is directed towards mitigation, but nevertheless falls short of the levels needed to limit warming to below 2°C or to 1.5°C across all sectors and regions (see C7.2) (*very high confidence*). In 2018, public and publicly mobilised private climate finance flows from developed to developing countries were below the collective goal under the UNFCCC and Paris Agreement to mobilise USD100 billion per year by 2020 in the context of meaningful mitigation action and transparency on implementation (*medium confidence*). {2.2.2, 2.3.1, 2.3.3}

[26] Due to the literature cutoff date of WGIII, the additional NDCs submitted after 11 October 2021 are not assessed here. {Footnote 32 in Longer Report}

[27] Projected 2030 GHG emissions are 50 (47–55) $GtCO_2$-eq if all conditional NDC elements are taken into account. Without conditional elements, the global emissions are projected to be approximately similar to modelled 2019 levels at 53 (50–57) $GtCO_2$-eq. {2.3.1, Table 2.2}

B. Future Climate Change, Risks, and Long-Term Responses

Future Climate Change

B.1 Continued greenhouse gas emissions will lead to increasing global warming, with the best estimate of reaching 1.5°C in the near term in considered scenarios and modelled pathways. Every increment of global warming will intensify multiple and concurrent hazards (*high confidence*). Deep, rapid, and sustained reductions in greenhouse gas emissions would lead to a discernible slowdown in global warming within around two decades, and also to discernible changes in atmospheric composition within a few years (*high confidence*). {Cross-Section Boxes 1 and 2, 3.1, 3.3, Table 3.1, Figure 3.1, 4.3} (Figure SPM.2, Box SPM.1)

B.1.1 Global warming[28] will continue to increase in the near term (2021-2040) mainly due to increased cumulative CO_2 emissions in nearly all considered scenarios and modelled pathways. In the near term, global warming is *more likely than not* to reach 1.5°C even under the very low GHG emission scenario (SSP1-1.9) and *likely* or *very likely* to exceed 1.5°C under higher emissions scenarios. In the considered scenarios and modelled pathways, the best estimates of the time when the level of global warming of 1.5°C is reached lie in the near term[29]. Global warming declines back to below 1.5°C by the end of the 21st century in some scenarios and modelled pathways (see B.7). The assessed climate response to GHG emissions scenarios results in a best estimate of warming for 2081–2100 that spans a range from 1.4°C for a very low GHG emissions scenario (SSP1-1.9) to 2.7°C for an intermediate GHG emissions scenario (SSP2-4.5) and 4.4°C for a very high GHG emissions scenario (SSP5-8.5)[30], with narrower uncertainty ranges[31] than for corresponding scenarios in AR5. {Cross-Section Boxes 1 and 2, 3.1.1, 3.3.4, Table 3.1, 4.3} (Box SPM.1)

B.1.2 Discernible differences in trends of global surface temperature between contrasting GHG emissions scenarios (SSP1-1.9 and SSP1-2.6 vs. SSP3-7.0 and SSP5-8.5) would begin to emerge from natural variability[32] within around 20 years. Under these contrasting scenarios, discernible effects would emerge within years for GHG concentrations, and sooner for air quality improvements, due to the combined targeted air pollution controls and strong and sustained methane emissions reductions. Targeted reductions of air pollutant emissions lead to more rapid improvements in air quality within years compared to reductions in GHG emissions only, but in the long term, further improvements are projected in scenarios that combine efforts to reduce air pollutants as well as GHG emissions[33]. (*high confidence*) {3.1.1} (Box SPM.1)

B.1.3 Continued emissions will further affect all major climate system components. With every additional increment of global warming, changes in extremes continue to become larger. Continued global warming is projected to further intensify the global water cycle, including its variability, global monsoon precipitation, and very wet and very dry weather and climate events and seasons (*high confidence*). In scenarios with increasing CO_2 emissions, natural land and ocean carbon sinks are projected to take up a decreasing proportion of these emissions (*high confidence*). Other projected changes include further reduced extents and/or volumes of almost

[28] Global warming (see Annex I: Glossary) is here reported as running 20-year averages, unless stated otherwise, relative to 1850–1900. Global surface temperature in any single year can vary above or below the long-term human-caused trend, due to natural variability. The internal variability of global surface temperature in a single year is estimated to be about ±0.25°C (5–95% range, *high confidence*). The occurrence of individual years with global surface temperature change above a certain level does not imply that this global warming level has been reached. {4.3, Cross-Section Box.2}

[29] Median five-year interval at which a 1.5°C global warming level is reached (50% probability) in categories of modelled pathways considered in WGIII is 2030-2035. By 2030, global surface temperature in any individual year could exceed 1.5°C relative to 1850-1900 with a probability between 40% and 60%, across the five scenarios assessed in WGI (*medium confidence*). In all scenarios considered in WGI except the very high emissions scenario (SSP5-8.5), the midpoint of the first 20-year running average period during which the assessed average global surface temperature change reaches 1.5°C lies in the first half of the 2030s. In the very high GHG emissions scenario, the midpoint is in the late 2020s. {3.1.1, 3.3.1, 4.3} (Box SPM.1)

[30] The best estimates [and *very likely* ranges] for the different scenarios are: 1.4°C [1.0°C–1.8°C] (SSP1-1.9); 1.8°C [1.3°C–2.4°C] (SSP1-2.6); 2.7°C [2.1°C–3.5°C] (SSP2-4.5)); 3.6°C [2.8°C–4.6°C] (SSP3-7.0); and 4.4°C [3.3°C–5.7°C] (SSP5-8.5). {3.1.1} (Box SPM.1)

[31] Assessed future changes in global surface temperature have been constructed, for the first time, by combining multi-model projections with observational constraints and the assessed equilibrium climate sensitivity and transient climate response. The uncertainty range is narrower than in the AR5 thanks to improved knowledge of climate processes, paleoclimate evidence and model-based emergent constraints. {3.1.1}

[32] See Annex I: Glossary. Natural variability includes natural drivers and internal variability. The main internal variability phenomena include El Niño-Southern Oscillation, Pacific Decadal Variability and Atlantic Multi-decadal Variability. {4.3}

[33] Based on additional scenarios.

all cryospheric elements[34] (*high confidence*), further global mean sea level rise (*virtually certain*), and increased ocean acidification (*virtually certain*) and deoxygenation (*high confidence*). {3.1.1, 3.3.1, Figure 3.4} (Figure SPM.2)

B.1.4 With further warming, every region is projected to increasingly experience concurrent and multiple changes in climatic impact-drivers. Compound heatwaves and droughts are projected to become more frequent, including concurrent events across multiple locations (*high confidence*). Due to relative sea level rise, current 1-in-100 year extreme sea level events are projected to occur at least annually in more than half of all tide gauge locations by 2100 under all considered scenarios (*high confidence*). Other projected regional changes include intensification of tropical cyclones and/or extratropical storms (*medium confidence*), and increases in aridity and fire weather (*medium* to *high confidence*) {3.1.1, 3.1.3}

B.1.5 Natural variability will continue to modulate human-caused climate changes, either attenuating or amplifying projected changes, with little effect on centennial-scale global warming (*high confidence*). These modulations are important to consider in adaptation planning, especially at the regional scale and in the near term. If a large explosive volcanic eruption were to occur[35], it would temporarily and partially mask human-caused climate change by reducing global surface temperature and precipitation for one to three years (*medium confidence*). {4.3}

[START FIGURE SPM.2 HERE]

[34] Permafrost, seasonal snow cover, glaciers, the Greenland and Antarctic Ice Sheets, and Arctic Sea ice.

[35] Based on 2500-year reconstructions, eruptions with a radiative forcing more negative than -1 Wm-2, related to the radiative effect of volcanic stratospheric aerosols in the literature assessed in this report, occur on average twice per century. {4.3}

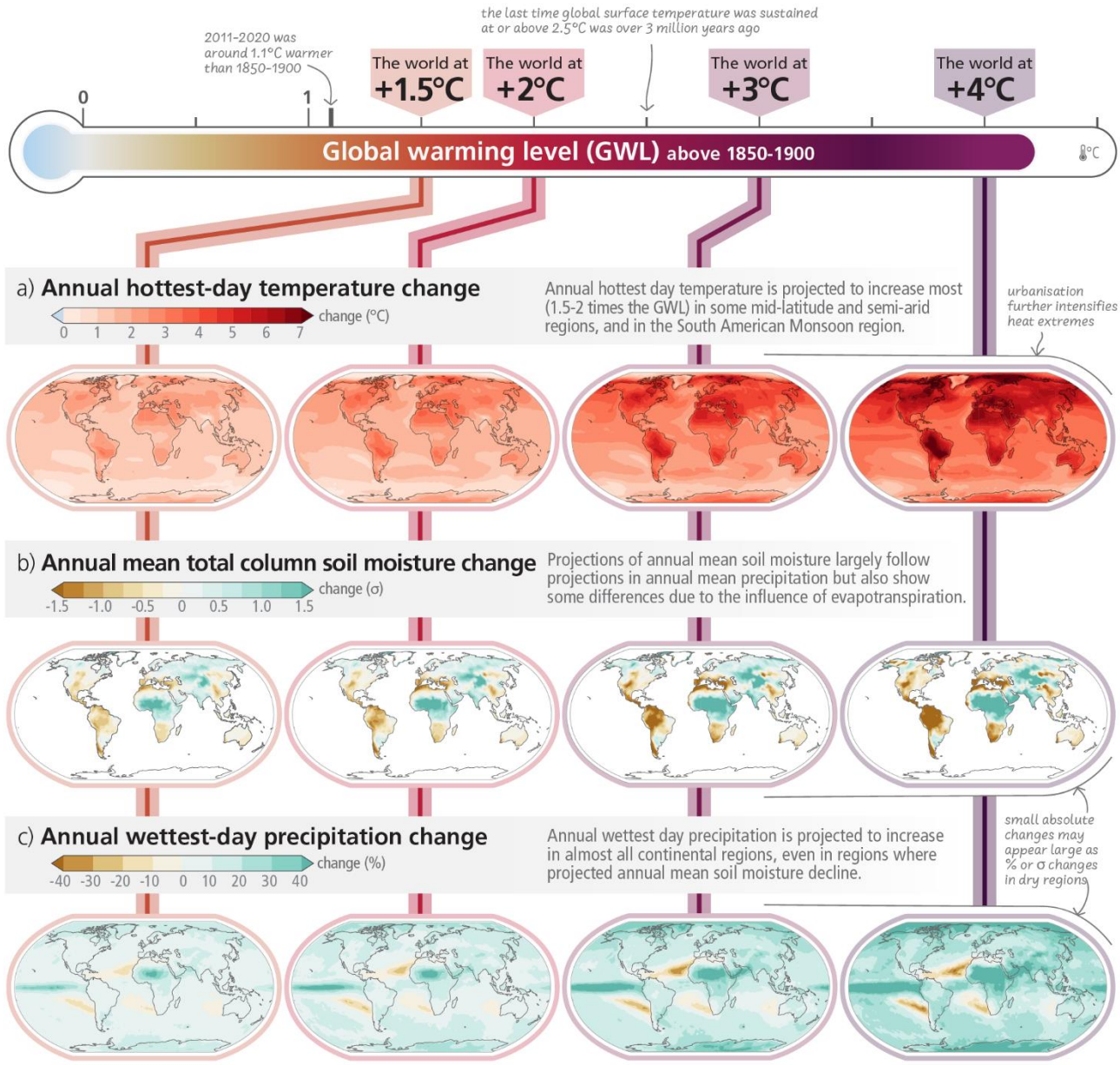

Figure SPM.2: Projected changes of annual maximum daily maximum temperature, annual mean total column soil moisture and annual maximum 1-day precipitation at global warming levels of 1.5°C, 2°C, 3°C, and 4°C relative to 1850–1900. Projected **(a)** annual maximum daily temperature change (°C), **(b)** annual mean total column soil moisture (standard deviation), **(c)** annual maximum 1-day precipitation change (%). The panels show CMIP6 multi-model median changes. In panels (b) and (c), large positive relative changes in dry regions may correspond to small absolute changes. In panel (b), the unit is the standard deviation of interannual variability in soil moisture during 1850–1900. Standard deviation is a widely used metric in characterising drought severity. A projected reduction in mean soil moisture by one standard deviation corresponds to soil moisture conditions typical of droughts that occurred about once every six years during 1850–1900. The WGI Interactive Atlas (https://interactive-atlas.ipcc.ch/) can be used to explore additional changes in the climate system across the range of global warming levels presented in this figure. {Figure 3.1, Cross-Section Box.2}

[END FIGURE SPM.2 HERE]

Climate Change Impacts and Climate-Related Risks

B.2 For any given future warming level, many climate-related risks are higher than assessed in AR5, and projected long-term impacts are up to multiple times higher than currently observed (*high confidence*). Risks and projected adverse impacts and related losses and damages from climate change escalate with every increment of global warming (*very high confidence*). Climatic and non-climatic risks will increasingly interact, creating compound and cascading risks that are more complex and difficult to manage (*high confidence*). {Cross-Section Box.2, 3.1, 4.3, Figure 3.3, Figure 4.3} (Figure SPM.3, Figure SPM.4)

B.2.1 In the near term, every region in the world is projected to face further increases in climate hazards (*medium to high confidence*, depending on region and hazard), increasing multiple risks to ecosystems and humans (*very high confidence*). Hazards and associated risks expected in the near-term include an increase in heat-related human mortality and morbidity (*high confidence*), food-borne, water-borne, and vector-borne diseases (*high confidence*), and mental health challenges[36] (*very high confidence*), flooding in coastal and other low-lying cities and regions (*high confidence*), biodiversity loss in land, freshwater and ocean ecosystems (*medium to very high confidence*, depending on ecosystem), and a decrease in food production in some regions (*high confidence*). Cryosphere-related changes in floods, landslides, and water availability have the potential to lead to severe consequences for people, infrastructure and the economy in most mountain regions (*high confidence*). The projected increase in frequency and intensity of heavy precipitation (*high confidence*) will increase rain-generated local flooding (*medium confidence*). {Figure 3.2, Figure 3.3, 4.3, Figure 4.3} (Figure SPM.3, Figure SPM.4)

B.2.2 Risks and projected adverse impacts and related losses and damages from climate change will escalate with every increment of global warming (*very high confidence*). They are higher for global warming of 1.5°C than at present, and even higher at 2°C (*high confidence*). Compared to the AR5, global aggregated risk levels[37] (Reasons for Concern[38]) are assessed to become high to very high at lower levels of global warming due to recent evidence of observed impacts, improved process understanding, and new knowledge on exposure and vulnerability of human and natural systems, including limits to adaptation (*high confidence*). Due to unavoidable sea level rise (see also B.3), risks for coastal ecosystems, people and infrastructure will continue to increase beyond 2100 (*high confidence*). {3.1.2, 3.1.3, Figure 3.4, Figure 4.3} (Figures SPM.3, Figure SPM.4)

B.2.3 With further warming, climate change risks will become increasingly complex and more difficult to manage. Multiple climatic and non-climatic risk drivers will interact, resulting in compounding overall risk and risks cascading across sectors and regions. Climate-driven food insecurity and supply instability, for example, are projected to increase with increasing global warming, interacting with non-climatic risk drivers such as competition for land between urban expansion and food production, pandemics and conflict. (*high confidence*) {3.1.2, 4.3, Figure 4.3}

B.2.4 For any given warming level, the level of risk will also depend on trends in vulnerability and exposure of humans and ecosystems. Future exposure to climatic hazards is increasing globally due to socio-economic development trends including migration, growing inequality and urbanisation. Human vulnerability will concentrate in informal settlements and rapidly growing smaller settlements. In rural areas vulnerability will be heightened by high reliance on climate-sensitive livelihoods. Vulnerability of ecosystems will be strongly influenced by past, present, and future patterns of unsustainable consumption and production, increasing

[36] In all assessed regions.

[37] Undetectable risk level indicates no associated impacts are detectable and attributable to climate change; moderate risk indicates associated impacts are both detectable and attributable to climate change with at least *medium confidence*, also accounting for the other specific criteria for key risks; high risk indicates severe and widespread impacts that are judged to be high on one or more criteria for assessing key risks; and very high risk level indicates very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks. {3.1.2}

[38] The Reasons for Concern (RFC) framework communicates scientific understanding about accrual of risk for five broad categories. RFC1: Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties. RFC2: Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events. RFC3: Distribution of impacts: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. RFC4: Global aggregate impacts: impacts to socio-ecological systems that can be aggregated globally into a single metric. RFC5: Large-scale singular events: relatively large, abrupt and sometimes irreversible changes in systems caused by global warming. See also Annex I: Glossary. {3.1.2, Cross-Section Box.2}

demographic pressures, and persistent unsustainable use and management of land, ocean, and water. Loss of ecosystems and their services has cascading and long-term impacts on people globally, especially for Indigenous Peoples and local communities who are directly dependent on ecosystems, to meet basic needs. (*high confidence*) {Cross-Section Box.2, Figure 1c, 3.1.2, 4.3}

[START FIGURE SPM.3 HERE]

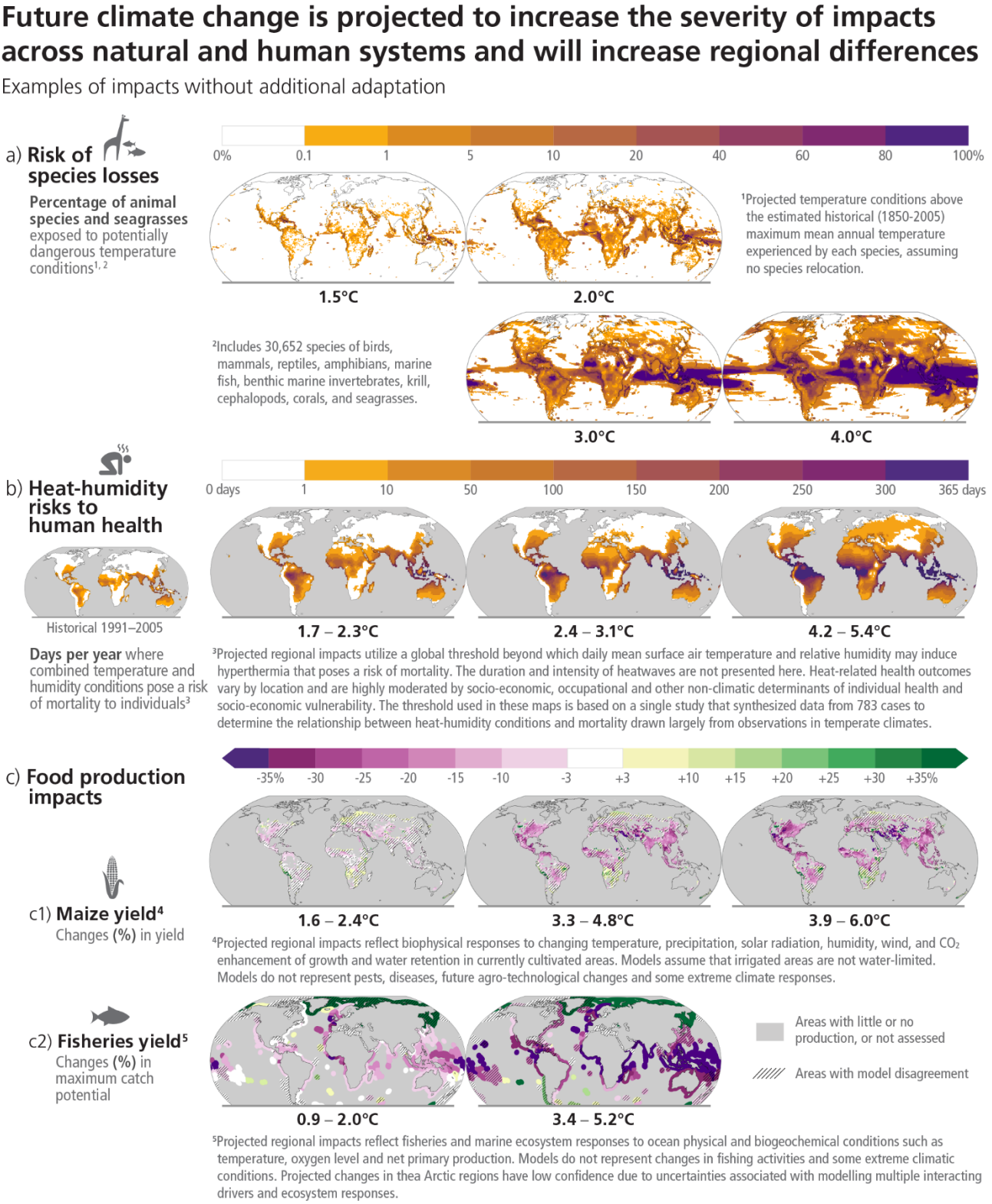

Figure SPM.3: Projected risks and impacts of climate change on natural and human systems at different global warming levels (GWLs) relative to 1850-1900 levels. Projected risks and impacts shown on the maps are based on outputs from different subsets of Earth system and impact models that were used to project each impact indicator without additional adaptation. WGII provides further assessment of the impacts on human and natural systems using these projections and

additional lines of evidence. **(a)** Risks of species losses as indicated by the percentage of assessed species exposed to potentially dangerous temperature conditions, as defined by conditions beyond the estimated historical (1850-2005) maximum mean annual temperature experienced by each species, at GWLs of 1.5ºC, 2ºC,3ºC and 4ºC. Underpinning projections of temperature are from 21 Earth system models and do not consider extreme events impacting ecosystems such as the Arctic. **(b)** Risks to human health as indicated by the days per year of population exposure to hyperthermic conditions that pose a risk of mortality from surface air temperature and humidity conditions for historical period (1991-2005) and at GWLs of 1.7°C–2.3°C (mean = 1.9°C; 13 climate models), 2.4°C–3.1°C (2.7°C; 16 climate models) and 4.2°C–5.4°C (4.7°C; 15 climate models). Interquartile ranges of GWLs by 2081–2100 under RCP2.6, RCP4.5 and RCP8.5. The presented index is consistent with common features found in many indices included within WGI and WGII assessments **(c)** Impacts on food production: (c1) Changes in maize yield by 2080–2099 relative to 1986–2005 at projected GWLs of 1.6°C–2.4ºC (2.0°C), 3.3°C–4.8ºC (4.1°C) and 3.9°C–6.0ºC (4.9°C). Median yield changes from an ensemble of 12 crop models, each driven by bias-adjusted outputs from 5 Earth system models, from the Agricultural Model Intercomparison and Improvement Project (AgMIP) and the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP). Maps depict 2080–2099 compared to 1986–2005 for current growing regions (>10 ha), with the corresponding range of future global warming levels shown under SSP1-2.6, SSP3-7.0 and SSP5-8.5, respectively. Hatching indicates areas where <70% of the climate-crop model combinations agree on the sign of impact. (c2) Change in maximum fisheries catch potential by 2081–2099 relative to 1986–2005 at projected GWLs of 0.9°C–2.0°C (1.5°C) and 3.4°C–5.2°C (4.3°C). GWLs by 2081–2100 under RCP2.6 and RCP8.5. Hatching indicates where the two climate-fisheries models disagree in the direction of change. Large relative changes in low yielding regions may correspond to small absolute changes. Biodiversity and fisheries in Antarctica were not analysed due to data limitations. Food security is also affected by crop and fishery failures not presented here.{3.1.2, Figure 3.2, Cross-Section Box.2} (Box SPM.1)

[END FIGURE SPM.3 HERE]

[START FIGURE SPM.4 HERE]

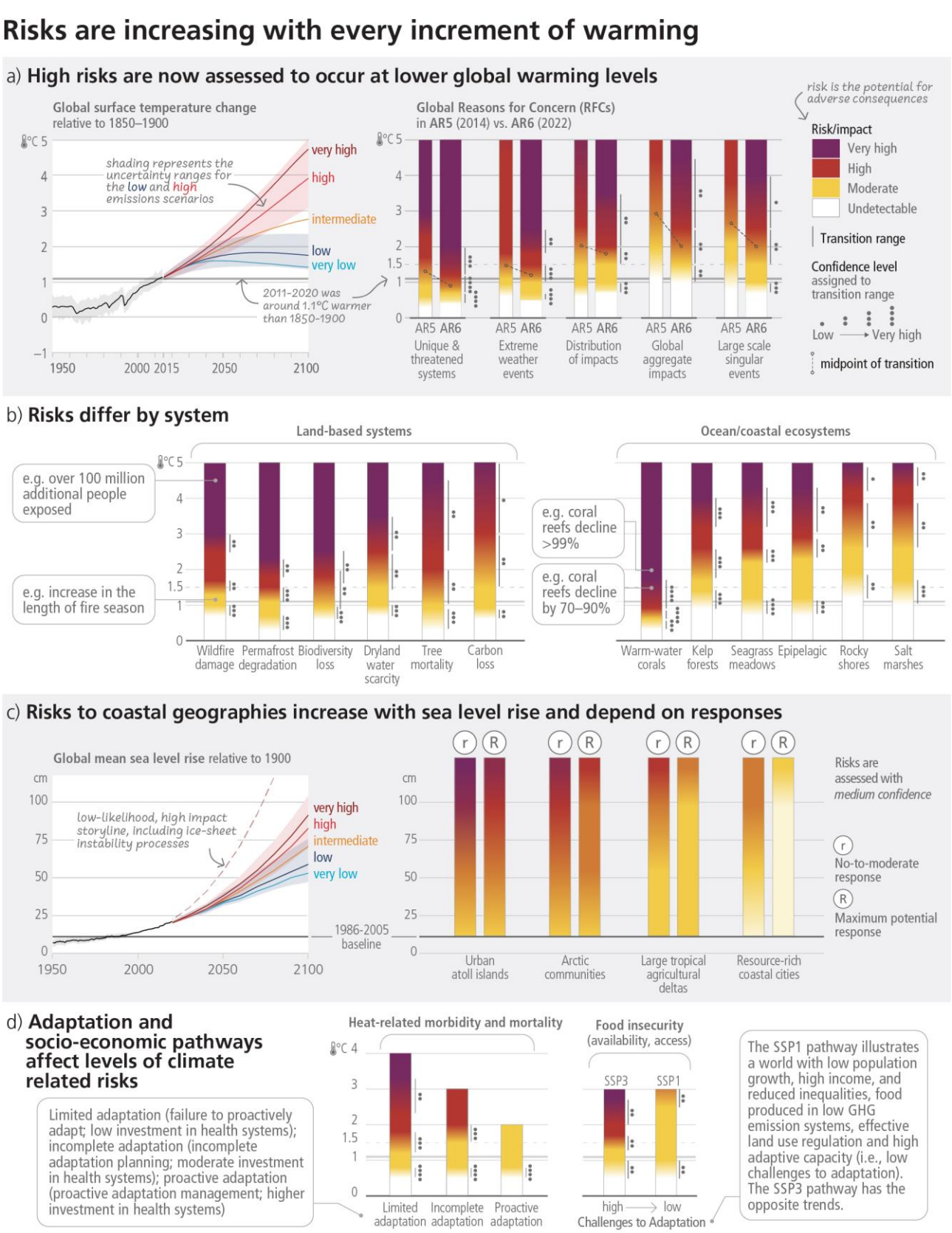

Figure SPM.4: Subset of assessed climate outcomes and associated global and regional climate risks. The burning embers result from a literature based expert elicitation. **Panel (a): Left** – Global surface temperature changes in °C relative to 1850–1900. These changes were obtained by combining CMIP6 model simulations with observational constraints based on past simulated warming, as well as an updated assessment of equilibrium climate sensitivity. *Very likely* ranges are shown for the low and high GHG emissions scenarios (SSP1-2.6 and SSP3-7.0) (Cross-Section Box 2); **Right** – Global Reasons for Concern (RFC), comparing AR6 (thick embers) and AR5 (thin embers) assessments. Risk transitions have generally shifted towards lower temperatures with updated scientific understanding. Diagrams are shown for each RFC, assuming low to no adaptation. Lines connect the midpoints of the transitions from moderate to high risk across AR5 and AR6. **Panel (b)**: Selected global risks for land and ocean ecosystems, illustrating general increase of risk with global warming levels with low to no adaptation. **Panel (c)**: **Left -** Global mean sea level change in centimetres, relative to 1900.

The historical changes (black) are observed by tide gauges before 1992 and altimeters afterwards. The future changes to 2100 (coloured lines and shading) are assessed consistently with observational constraints based on emulation of CMIP, ice-sheet, and glacier models, and *likely* ranges are shown for SSP1-2.6 and SSP3-7.0. **Right** - Assessment of the combined risk of coastal flooding, erosion and salinization for four illustrative coastal geographies in 2100, due to changing mean and extreme sea levels, under two response scenarios, with respect to the SROCC baseline period (1986-2005). The assessment does not account for changes in extreme sea level beyond those directly induced by mean sea level rise; risk levels could increase if other changes in extreme sea levels were considered (e.g., due to changes in cyclone intensity). "No-to-moderate response" describes efforts as of today (i.e. no further significant action or new types of actions). "Maximum potential response" represent a combination of responses implemented to their full extent and thus significant additional efforts compared to today, assuming minimal financial, social and political barriers. (In this context, 'today' refers to 2019.) The assessment criteria include exposure and vulnerability, coastal hazards, in-situ responses and planned relocation. Planned relocation refers to managed retreat or resettlements. The term response is used here instead of adaptation because some responses, such as retreat, may or may not be considered to be adaptation. **Panel (d):** Selected risks under different socio-economic pathways, illustrating how development strategies and challenges to adaptation influence risk. **Left** - Heat-sensitive human health outcomes under three scenarios of adaptation effectiveness. The diagrams are truncated at the nearest whole ºC within the range of temperature change in 2100 under three SSP scenarios. **Right** - Risks associated with food security due to climate change and patterns of socio-economic development. Risks to food security include availability and access to food, including population at risk of hunger, food price increases and increases in disability adjusted life years attributable to childhood underweight. Risks are assessed for two contrasted socio-economic pathways (SSP1 and SSP3) excluding the effects of targeted mitigation and adaptation policies. {Figure 3.3} (Box SPM.1)

[END FIGURE SPM.4 HERE]

Likelihood and Risks of Unavoidable, Irreversible or Abrupt Changes

B.3 Some future changes are unavoidable and/or irreversible but can be limited by deep, rapid and sustained global greenhouse gas emissions reduction. The likelihood of abrupt and/or irreversible changes increases with higher global warming levels. Similarly, the probability of low-likelihood outcomes associated with potentially very large adverse impacts increases with higher global warming levels. (*high confidence*) {3.1}

B.3.1 Limiting global surface temperature does not prevent continued changes in climate system components that have multi-decadal or longer timescales of response (*high confidence*). Sea level rise is unavoidable for centuries to millennia due to continuing deep ocean warming and ice sheet melt, and sea levels will remain elevated for thousands of years (*high confidence*). However, deep, rapid and sustained GHG emissions reductions would limit further sea level rise acceleration and projected long-term sea level rise commitment. Relative to 1995–2014, the *likely* global mean sea level rise under the SSP1-1.9 GHG emissions scenario is 0.15–0.23 m by 2050 and 0.28–0.55 m by 2100; while for the SSP5-8.5 GHG emissions scenario it is 0.20–0.29 m by 2050 and 0.63–1.01 m by 2100 (*medium confidence*). Over the next 2000 years, global mean sea level will rise by about 2–3 m if warming is limited to 1.5°C and 2–6 m if limited to 2°C (*low confidence*). {3.1.3, Figure 3.4} (Box SPM.1)

B.3.2 The likelihood and impacts of abrupt and/or irreversible changes in the climate system, including changes triggered when tipping points are reached, increase with further global warming (*high confidence*). As warming levels increase, so do the risks of species extinction or irreversible loss of biodiversity in ecosystems including forests (*medium confidence*), coral reefs (*very high confidence*) and in Arctic regions (*high confidence*). At sustained warming levels between 2°C and 3°C, the Greenland and West Antarctic ice sheets will be lost almost completely and irreversibly over multiple millennia, causing several metres of sea level rise (*limited evidence*). The probability and rate of ice mass loss increase with higher global surface temperatures (*high confidence*). {3.1.2, 3.1.3}

B.3.3 The probability of low-likelihood outcomes associated with potentially very large impacts increases with higher global warming levels (*high confidence*). Due to deep uncertainty linked to ice-sheet processes, global mean sea level rise above the *likely* range – approaching 2 m by 2100 and in excess of 15 m by 2300 under the very high GHG emissions scenario (SSP5-8.5) (*low confidence*) – cannot be excluded. There is *medium confidence* that the Atlantic Meridional Overturning Circulation will not collapse abruptly before 2100, but if it

were to occur, it would *very likely* cause abrupt shifts in regional weather patterns, and large impacts on ecosystems and human activities. {3.1.3} (Box SPM.1)

Adaptation Options and their Limits in a Warmer World

B.4 Adaptation options that are feasible and effective today will become constrained and less effective with increasing global warming. With increasing global warming, losses and damages will increase and additional human and natural systems will reach adaptation limits. Maladaptation can be avoided by flexible, multi-sectoral, inclusive, long-term planning and implementation of adaptation actions, with co-benefits to many sectors and systems. (*high confidence*) {3.2, 4.1, 4.2, 4.3}

B.4.1 The effectiveness of adaptation, including ecosystem-based and most water-related options, will decrease with increasing warming. The feasibility and effectiveness of options increase with integrated, multi-sectoral solutions that differentiate responses based on climate risk, cut across systems and address social inequities. As adaptation options often have long implementation times, long-term planning increases their efficiency. (*high confidence*) {3.2, Figure 3.4, 4.1, 4.2}

B.4.2 With additional global warming, limits to adaptation and losses and damages, strongly concentrated among vulnerable populations, will become increasingly difficult to avoid (*high confidence*). Above 1.5°C of global warming, limited freshwater resources pose potential hard adaptation limits for small islands and for regions dependent on glacier and snow melt (*medium confidence*). Above that level, ecosystems such as some warm-water coral reefs, coastal wetlands, rainforests, and polar and mountain ecosystems will have reached or surpassed hard adaptation limits and as a consequence, some Ecosystem-based Adaptation measures will also lose their effectiveness (*high confidence*). {2.3.2, 3.2, 4.3}

B.4.3 Actions that focus on sectors and risks in isolation and on short-term gains often lead to maladaptation over the long-term, creating lock-ins of vulnerability, exposure and risks that are difficult to change. For example, seawalls effectively reduce impacts to people and assets in the short-term but can also result in lock-ins and increase exposure to climate risks in the long-term unless they are integrated into a long-term adaptive plan. Maladaptive responses can worsen existing inequities especially for Indigenous Peoples and marginalised groups and decrease ecosystem and biodiversity resilience. Maladaptation can be avoided by flexible, multi-sectoral, inclusive, long-term planning and implementation of adaptation actions, with co-benefits to many sectors and systems. (*high confidence*) {2.3.2, 3.2}

Carbon Budgets and Net Zero Emissions

B.5 Limiting human-caused global warming requires net zero CO_2 emissions. Cumulative carbon emissions until the time of reaching net-zero CO_2 emissions and the level of greenhouse gas emission reductions this decade largely determine whether warming can be limited to 1.5°C or 2°C (*high confidence*). Projected CO_2 emissions from existing fossil fuel infrastructure without additional abatement would exceed the remaining carbon budget for 1.5°C (50%) (*high confidence*). {2.3, 3.1, 3.3, Table 3.1}

B.5.1 From a physical science perspective, limiting human-caused global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions. Reaching net zero GHG emissions primarily requires deep reductions in CO_2, methane, and other GHG emissions, and implies net-negative CO_2 emissions[39]. Carbon dioxide removal (CDR) will be necessary to achieve net-negative CO2 emissions (see B.6). Net zero GHG emissions, if sustained, are projected to result in a gradual decline in global surface temperatures after an earlier peak. (*high confidence*) {3.1.1, 3.3.1, 3.3.2, 3.3.3, Table 3.1, Cross-Section Box 1}

B.5.2 For every 1000 $GtCO_2$ emitted by human activity, global surface temperature rises by 0.45°C (best estimate, with a *likely* range from 0.27 to 0.63°C). The best estimates of the remaining carbon budgetsfrom the

[39] Net zero GHG emissions defined by the 100-year global warming potential. See footnote 9.

beginning of 2020 are 500 $GtCO_2$ for a 50% likelihood of limiting global warming to 1.5°C and 1150 $GtCO_2$ for a 67% likelihood of limiting warming to 2°C[40]. The stronger the reductions in non-CO_2 emissions the lower the resulting temperatures are for a given remaining carbon budget or the larger remaining carbon budget for the same level of temperature change[41]. {3.3.1}

B.5.3 If the annual CO_2 emissions between 2020–2030 stayed, on average, at the same level as 2019, the resulting cumulative emissions would almost exhaust the remaining carbon budget for 1.5°C (50%), and deplete more than a third of the remaining carbon budget for 2°C (67%). Estimates of future CO_2 emissions from existing fossil fuel infrastructures without additional abatement[42] already exceed the remaining carbon budget for limiting warming to 1.5°C (50%) (*high confidence*). Projected cumulative future CO_2 emissions over the lifetime of existing and planned fossil fuel infrastructure, if historical operating patterns are maintained and without additional abatement[43], are approximately equal to the remaining carbon budget for limiting warming to 2°C with a likelihood of 83%[44] (*high confidence*). {2.3.1, 3.3.1, Figure 3.5}

B.5.4 Based on central estimates only, historical cumulative net CO_2 emissions between 1850 and 2019 amount to about four-fifths[45] of the total carbon budget for a 50% probability of limiting global warming to 1.5°C (central estimate about 2900 $GtCO_2$), and to about two thirds[46] of the total carbon budget for a 67% probability to limit global warming to 2°C (central estimate about 3550 $GtCO_2$). {3.3.1, Figure 3.5}

Mitigation Pathways

B.6 All global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and those that limit warming to 2°C (>67%), involve rapid and deep and, in most cases, immediate greenhouse gas emissions reductions in all sectors this decade. Global net zero CO_2 emissions are reached for these pathway categories, in the early 2050s and around the early 2070s, respectively. (*high confidence*) {3.3, 3.4, 4.1, 4.5, Table 3.1} (Figure SPM.5, Box SPM.1)

B.6.1 Global modelled pathways provide information on limiting warming to different levels; these pathways, particularly their sectoral and regional aspects, depend on the assumptions described in Box SPM.1. Global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot or limit warming to 2°C (>67%) are characterized by deep, rapid and, in most cases, immediate GHG emissions reductions. Pathways that limit warming to 1.5C (>50%) with no or limited overshoot reach net zero CO_2 in the early 2050s, followed by net negative CO_2 emissions. Those pathways that reach net zero GHG emissions do so around the 2070s. Pathways that limit warming to 2C (>67%) reach net zero CO2 emissions in the early 2070s. Global GHG emissions are projected to peak between 2020 and at the latest before 2025 in global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot and in those that limit warming to 2°C (>67%) and assume immediate action. (*high confidence*) {3.3.2, 3.3.4, 4.1, Table 3.1, Figure 3.6} (Table XX)

[START TABLE XX]

[40] Global databases make different choices about which emissions and removals occurring on land are considered anthropogenic. Most countries report their anthropogenic land CO_2 fluxes including fluxes due to human-caused environmental change (e.g., CO_2 fertilisation) on 'managed' land in their national GHG inventories. Using emissions estimates based on these inventories, the remaining carbon budgets must be correspondingly reduced. {3.3.1}

[41] For example, remaining carbon budgets could be 300 or 600 $GtCO_2$ for 1.5°C (50%), respectively for high and low non-CO_2 emissions, compared to 500 $GtCO_2$ in the central case. {3.3.1}

[42] Abatement here refers to human interventions that reduce the amount of greenhouse gases that are released from fossil fuel infrastructure to the atmosphere.

[43] Ibid.

[44] WGI provides carbon budgets that are in line with limiting global warming to temperature limits with different likelihoods, such as 50%, 67% or 83%. {3.3.1}

[45] Uncertainties for total carbon budgets have not been assessed and could affect the specific calculated fractions.

[46] Ibid.

Table XX: Greenhouse gas and CO_2 emission reductions from 2019, median and 5-95 percentiles {3.3.1; 4.1; Table 3.1; Figure 2.5; Box SPM1}

		Reductions from 2019 emission levels (%)			
		2030	2035	2040	2050
Limit warming to1.5°C (>50%) with no or limited overshoot	GHG	43 [34-60]	60 [49-77]	69 [58-90]	84 [73-98]
	CO_2	48 [36-69]	65 [50-96]	80 [61-109]	99 [79-119]
Limit warming to 2°C (>67%)	GHG	21 [1-42]	35 [22-55]	46 [34-63]	64 [53-77]
	CO_2	22 [1-44]	37 [21-59]	51 [36-70]	73 [55-90]

[END TABLE XX]

B.6.2 Reaching net zero CO_2 or GHG emissions primarily requires deep and rapid reductions in gross emissions of CO_2, as well as substantial reductions of non-CO_2 GHG emissions (*high confidence*). For example, in modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, global methane emissions are reduced by 34 [21–57]% by 2030 relative to 2019. However, some hard-to-abate residual GHG emissions (e.g., some emissions from agriculture, aviation, shipping, and industrial processes) remain and would need to be counterbalanced by deployment of carbon dioxide removal (CDR) methods to achieve net zero CO_2 or GHG emissions (*high confidence*). As a result, net zero CO_2 is reached earlier than net zero GHGs (*high confidence*). {3.3.2, 3.3.3, Table 3.1, Figure 3.5} (Figure SPM.5)

B.6.3 Global modelled mitigation pathways reaching net zero CO_2 and GHG emissions include transitioning from fossil fuels without carbon capture and storage (CCS) to very low- or zero-carbon energy sources, such as renewables or fossil fuels with CCS, demand-side measures and improving efficiency, reducing non-CO_2 GHG emissions, and CDR[47]. In most global modelled pathways, land-use change and forestry (via reforestation and reduced deforestation) and the energy supply sector reach net zero CO_2 emissions earlier than the buildings, industry and transport sectors. (*high confidence*) {3.3.3, 4.1, 4.5, Figure 4.1} (Figure SPM.5, Box SPM.1)

B.6.4 Mitigation options often have synergies with other aspects of sustainable development, but some options can also have trade-offs. There are potential synergies between sustainable development and, for instance, energy efficiency and renewable energy. Similarly, depending on the context[48], biological CDR methods like reforestation, improved forest management, soil carbon sequestration, peatland restoration and coastal blue carbon management can enhance biodiversity and ecosystem functions, employment and local livelihoods. However, afforestation or production of biomass crops can have adverse socio-economic and environmental impacts, including on biodiversity, food and water security, local livelihoods and the rights of Indigenous Peoples, especially if implemented at large scales and where land tenure is insecure. Modelled pathways that assume using resources more efficiently or that shift global development towards sustainability include fewer challenges, such as less dependence on CDR and pressure on land and biodiversity. (*high confidence*) {3.4.1}

[START FIGURE SPM.5 HERE]

[47] CCS is an option to reduce emissions from large-scale fossil-based energy and industry sources provided geological storage is available. When CO_2 is captured directly from the atmosphere (DACCS), or from biomass (BECCS), CCS provides the storage component of these CDR methods. CO_2 capture and subsurface injection is a mature technology for gas processing and enhanced oil recovery. In contrast to the oil and gas sector, CCS is less mature in the power sector, as well as in cement and chemicals production, where it is a critical mitigation option. The technical geological storage capacity is estimated to be on the order of 1000 $GtCO_2$, which is more than the CO_2 storage requirements through 2100 to limit global warming to 1.5°C, although the regional availability of geological storage could be a limiting factor. If the geological storage site is appropriately selected and managed, it is estimated that the CO_2 can be permanently isolated from the atmosphere. Implementation of CCS currently faces technological, economic, institutional, ecological-environmental and socio-cultural barriers. Currently, global rates of CCS deployment are far below those in modelled pathways limiting global warming to 1.5°C to 2°C. Enabling conditions such as policy instruments, greater public support and technological innovation could reduce these barriers. (*high confidence*) {3.3.3}

[48] The impacts, risks, and co-benefits of CDR deployment for ecosystems, biodiversity and people will be highly variable depending on the method, site-specific context, implementation and scale (*high confidence*).

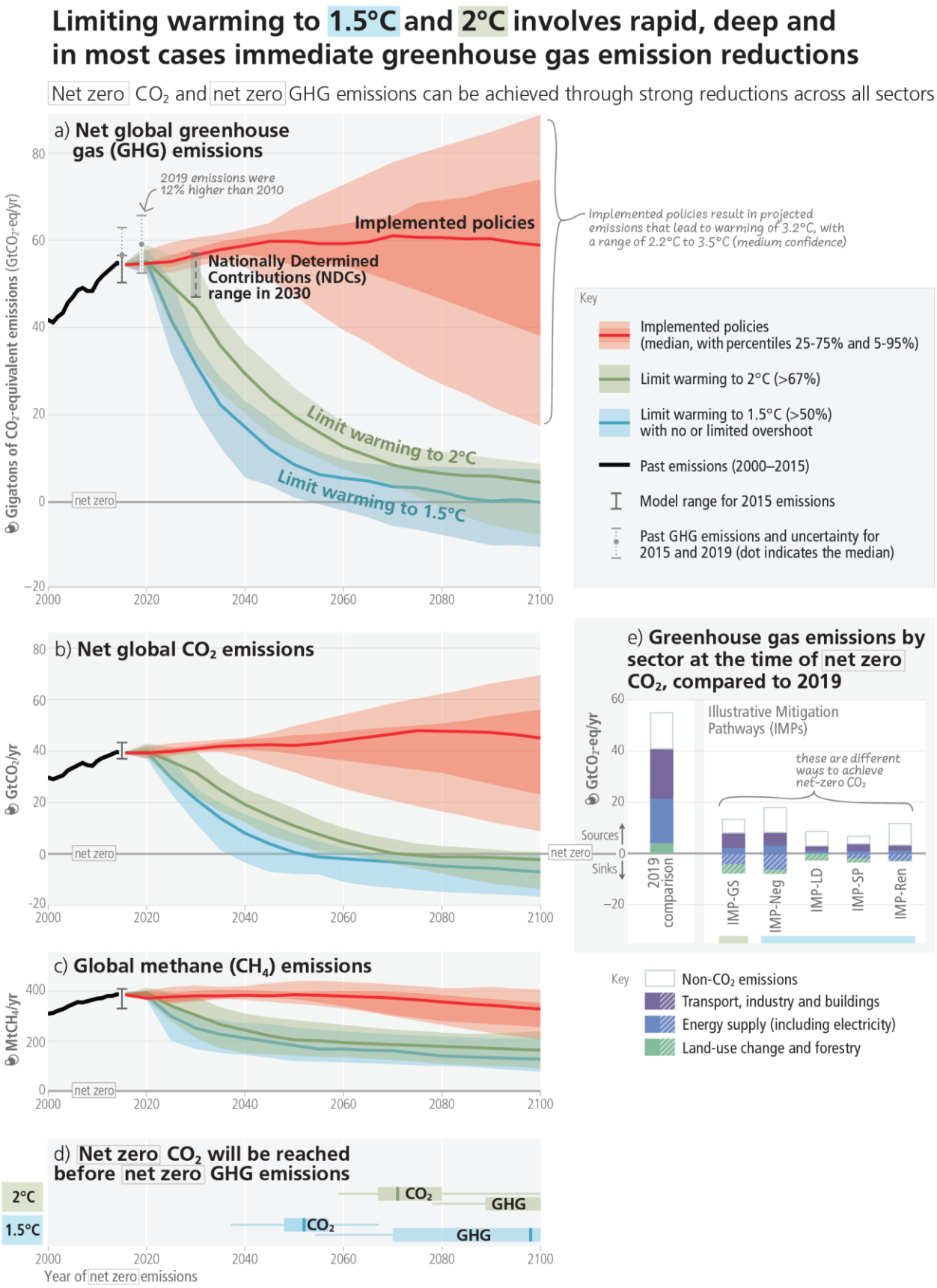

Figure SPM.5: Global emissions pathways consistent with implemented policies and mitigation strategies. Panel (a), (b) and **(c)** show the development of global GHG, CO_2 and methane emissions in modelled pathways, while **panel (d)** shows the associated timing of when GHG and CO_2 emissions reach net zero. Coloured ranges denote the 5th to 95th percentile across the global modelled pathways falling within a given category as described in Box SPM.1. The red ranges depict emissions pathways assuming policies that were implemented by the end of 2020. Ranges of modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot are shown in light blue (category C1) and pathways that

limit warming to 2°C (>67%) are shown in green (category C3). Global emission pathways that would limit warming to 1.5°C (>50%) with no or limited overshoot and also reach net zero GHG in the second half of the century do so between 2070-2075. **Panel (e)** shows the sectoral contributions of CO_2 and non-CO_2 emissions sources and sinks at the time when net zero CO_2 emissions are reached in illustrative mitigation pathways (IMPs) consistent with limiting warming to 1.5°C with a high reliance on net negative emissions (IMP-Neg) ("high overshoot"), high resource efficiency (IMP-LD), a focus on sustainable development (IMP-SP), renewables (IMP-Ren) and limiting warming to 2°C with less rapid mitigation initially followed by a gradual strengthening (IMP-GS). Positive and negative emissions for different IMPs are compared to GHG emissions from the year 2019. Energy supply (including electricity) includes bioenergy with carbon dioxide capture and storage and direct air carbon dioxide capture and storage. CO_2 emissions from land-use change and forestry can only be shown as a net number as many models do not report emissions and sinks of this category separately. {Figure 3.6, 4.1} (Box SPM.1)

[END FIGURE SPM.5 HERE]

Overshoot: Exceeding a Warming Level and Returning

B.7 If warming exceeds a specified level such as 1.5°C, it could gradually be reduced again by achieving and sustaining net negative global CO_2 emissions. This would require additional deployment of carbon dioxide removal, compared to pathways without overshoot, leading to greater feasibility and sustainability concerns. Overshoot entails adverse impacts, some irreversible, and additional risks for human and natural systems, all growing with the magnitude and duration of overshoot. (*high confidence*) {3.1, 3.3, 3.4, Table 3.1, Figure 3.6}

B.7.1 Only a small number of the most ambitious global modelled pathways limit global warming to 1.5°C (>50%) by 2100 without exceeding this level temporarily. Achieving and sustaining net negative global CO_2 emissions, with annual rates of CDR greater than residual CO_2 emissions, would gradually reduce the warming level again (*high confidence*). Adverse impacts that occur during this period of overshoot and cause additional warming via feedback mechanisms, such as increased wildfires, mass mortality of trees, drying of peatlands, and permafrost thawing, weakening natural land carbon sinks and increasing releases of GHGs would make the return more challenging (*medium confidence*). {3.3.2, 3.3.4, Table 3.1, Figure 3.6} (Box SPM.1)

B.7.2 The higher the magnitude and the longer the duration of overshoot, the more ecosystems and societies are exposed to greater and more widespread changes in climatic impact-drivers, increasing risks for many natural and human systems. Compared to pathways without overshoot, societies would face higher risks to infrastructure, low-lying coastal settlements, and associated livelihoods. Overshooting 1.5°C will result in irreversible adverse impacts on certain ecosystems with low resilience, such as polar, mountain, and coastal ecosystems, impacted by ice-sheet, glacier melt, or by accelerating and higher committed sea level rise. (*high confidence*) {3.1.2, 3.3.4}

B.7.3 The larger the overshoot, the more net negative CO_2 emissions would be needed to return to 1.5°C by 2100. Transitioning towards net zero CO_2 emissions faster and reducing non-CO_2 emissions such as methane more rapidly would limit peak warming levels and reduce the requirement for net negative CO_2 emissions, thereby reducing feasibility and sustainability concerns, and social and environmental risks associated with CDR deployment at large scales. (*high confidence*) {3.3.3, 3.3.4, 3.4.1, Table 3.1}

C. Responses in the Near Term

Urgency of Near-Term Integrated Climate Action

C.1 Climate change is a threat to human well-being and planetary health (*very high confidence*). There is a rapidly closing window of opportunity to secure a liveable and sustainable future for all (*very high confidence*). Climate resilient development integrates adaptation and mitigation to advance sustainable development for all, and is enabled by increased international cooperation including improved access to adequate financial resources, particularly for vulnerable regions, sectors and groups, and inclusive governance and coordinated policies (*high confidence*). The choices and actions implemented in this decade will have impacts now and for thousands of years (*high confidence*). {3.1, 3.3, 4.1, 4.2, 4.3, 4.4, 4.7, 4.8, 4.9, Figure 3.1, Figure 3.3, Figure 4.2} (Figure SPM.1; Figure SPM.6)

C.1.1 Evidence of observed adverse impacts and related losses and damages, projected risks, levels and trends in vulnerability and adaptation limits, demonstrate that worldwide climate resilient development action is more urgent than previously assessed in AR5. Climate resilient development integrates adaptation and GHG mitigation to advance sustainable development for all. Climate resilient development pathways have been constrained by past development, emissions and climate change and are progressively constrained by every increment of warming, in particular beyond 1.5°C. (*very high confidence*) {3.4; 3.4.2; 4.1}

C.1.2 Government actions at sub-national, national and international levels**,** with civil society and the private sector, play a crucial role in enabling and accelerating shifts in development pathways towards sustainability and climate resilient development (*very high confidence*). Climate resilient development is enabled when governments, civil society and the private sector make inclusive development choices that prioritize risk reduction, equity and justice, and when decision-making processes, finance and actions are integrated across governance levels, sectors, and timeframes (*very high confidence*). Enabling conditions are differentiated by national, regional and local circumstances and geographies, according to capabilities, and include: political commitment and follow-through, coordinated policies, social and international cooperation, ecosystem stewardship, inclusive governance, knowledge diversity, technological innovation, monitoring and evaluation, and improved access to adequate financial resources, especially for vulnerable regions, sectors and communities (*high confidence*). {3.4; 4.2, 4.4, 4.5, 4.7, 4.8} (Figure SPM.6)

C.1.3 Continued emissions will further affect all major climate system components, and many changes will be irreversible on centennial to millennial time scales and become larger with increasing global warming. Without urgent, effective, and equitable mitigation and adaptation actions, climate change increasingly threatens ecosystems, biodiversity, and the livelihoods, health and wellbeing of current and future generations. (*high confidence*) {3.1.3; 3.3.3; 3.4.1, Figure 3.4; 4.1, 4.2, 4.3, 4.4} (Figure SPM.1, Figure SPM.6).

[START FIGURE SPM.6 HERE]

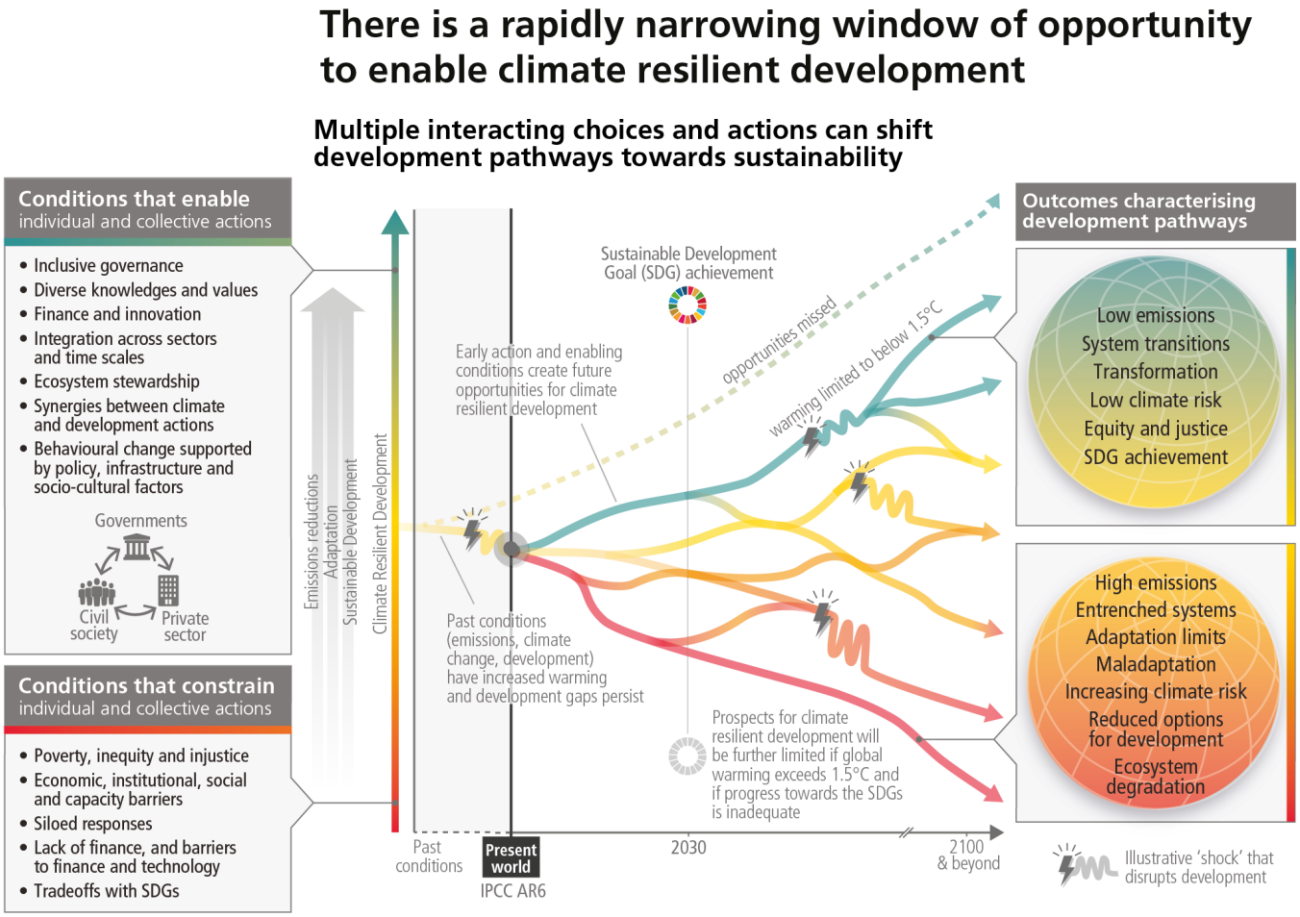

Figure SPM.6: The illustrative development pathways (red to green) and associated outcomes (right panel) show that there is a rapidly narrowing window of opportunity to secure a liveable and sustainable future for all. Climate resilient development is the process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development. Diverging pathways illustrate that interacting choices and actions made by diverse government, private sector and civil society actors can advance climate resilient development, shift pathways towards sustainability, and enable lower emissions and adaptation. Diverse knowledge and values include cultural values, Indigenous Knowledge, local knowledge, and scientific knowledge. Climatic and non-climatic events, such as droughts, floods or pandemics, pose more severe shocks to pathways with lower climate resilient development (red to yellow) than to pathways with higher climate resilient development (green). There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5°C, and with every increment of warming, losses and damages will increase. The development pathways taken by countries at all stages of economic development impact GHG emissions and mitigation challenges and opportunities, which vary across countries and regions. Pathways and opportunities for action are shaped by previous actions (or inactions and opportunities missed; dashed pathway) and enabling and constraining conditions (left panel), and take place in the context of climate risks, adaptation limits and development gaps. The longer emissions reductions are delayed, the fewer effective adaptation options. {Figure 4.2; 3.1; 3.2; 3.4; 4.2; 4.4; 4.5; 4.6; 4.9}

[END FIGURE SPM.6 HERE]

The Benefits of Near-Term Action

C.2 Deep, rapid and sustained mitigation and accelerated implementation of adaptation actions in this decade would reduce projected losses and damages for humans and ecosystems (*very high confidence*), and deliver many co-benefits, especially for air quality and health (*high confidence*). Delayed mitigation and adaptation action would lock-in high-emissions infrastructure, raise risks of stranded assets and cost-escalation, reduce feasibility, and increase losses and damages (*high confidence*). Near-term actions involve high up-front investments and potentially disruptive changes that can be lessened by a range of enabling policies (*high confidence*). {2.1, 2.2, 3.1, 3.2, 3.3, 3.4, 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8}

C.2.1 Deep, rapid, and sustained mitigation and accelerated implementation of adaptation actions in this decade would reduce future losses and damages related to climate change for humans and ecosystems (*very high confidence*). As adaptation options often have long implementation times, accelerated implementation of adaptation in this decade is important to close adaptation gaps (*high confidence*). Comprehensive, effective, and innovative responses integrating adaptation and mitigation can harness synergies and reduce trade-offs between adaptation and mitigation (*high confidence*). {4.1, 4.2, 4.3}.

C.2.2 Delayed mitigation action will further increase global warming and losses and damages will rise and additional human and natural systems will reach adaptation limits (*high confidence*). Challenges from delayed adaptation and mitigation actions include the risk of cost escalation, lock-in of infrastructure, stranded assets, and reduced feasibility and effectiveness of adaptation and mitigation options (*high confidence*). Without rapid, deep and sustained mitigation and accelerated adaptation actions, losses and damages will continue to increase, including projected adverse impacts in Africa, LDCs, SIDS, Central and South America[49], Asia and the Arctic, and will disproportionately affect the most vulnerable populations (*high confidence*). {2.1.2; 3.1.2, 3.2, 3.3.1, 3.3.3; 4.1, 4.2, 4.3} (Figure SPM.3, Figure SPM.4)

C.2.3 Accelerated climate action can also provide co-benefits (see also C.4). Many mitigation actions would have benefits for health through lower air pollution, active mobility (e.g., walking, cycling), and shifts to sustainable healthy diets. Strong, rapid and sustained reductions in methane emissions can limit near-term warming and improve air quality by reducing global surface ozone. (*high confidence*) Adaptation can generate multiple additional benefits such as improving agricultural productivity, innovation, health and wellbeing, food security, livelihood, and biodiversity conservation (*very high confidence*). {4.2, 4.5.4, 4.5.5, 4.6}

C.2.4 Cost-benefit analysis remains limited in its ability to represent all avoided damages from climate change (*high confidence*). The economic benefits for human health from air quality improvement arising from mitigation action can be of the same order of magnitude as mitigation costs, and potentially even larger (*medium confidence*). Even without accounting for all the benefits of avoiding potential damages the global economic and social benefit of limiting global warming to 2°C exceeds the cost of mitigation in most of the assessed literature (*medium confidence*).[50] More rapid climate change mitigation, with emissions peaking earlier, increases co-benefits and reduces feasibility risks and costs in the long-term, but requires higher up-front investments (*high confidence*). {3.4.1, 4.2}

C.2.5 Ambitious mitigation pathways imply large and sometimes disruptive changes in existing economic structures, with significant distributional consequences within and between countries. To accelerate climate action, the adverse consequences of these changes can be moderated by fiscal, financial, institutional and regulatory reforms and by integrating climate actions with macroeconomic policies through (i) economy-wide packages, consistent with national circumstances, supporting sustainable low-emission growth paths; (ii) climate resilient safety nets and social protection; and (iii) improved access to finance for low-emissions infrastructure and technologies, especially in developing countries. (*high confidence*) {4.2, 4.4, 4.7, 4.8.1}

[49] The southern part of Mexico is included in the climactic subregion South Central America (SCA) for WGI. Mexico is assessed as part of North America for WGII. The climate change literature for the SCA region occasionally includes Mexico, and in those cases WGII assessment makes reference to Latin America. Mexico is considered part of Latin America and the Caribbean for WGIII.

[50] The evidence is too limited to make a similar robust conclusion for limiting warming to 1.5°C. Limiting global warming to 1.5°C instead of 2°C would increase the costs of mitigation, but also increase the benefits in terms of reduced impacts and related risks, and reduced adaptation needs (*high confidence*).

[START FIGURE SPM.7 HERE]

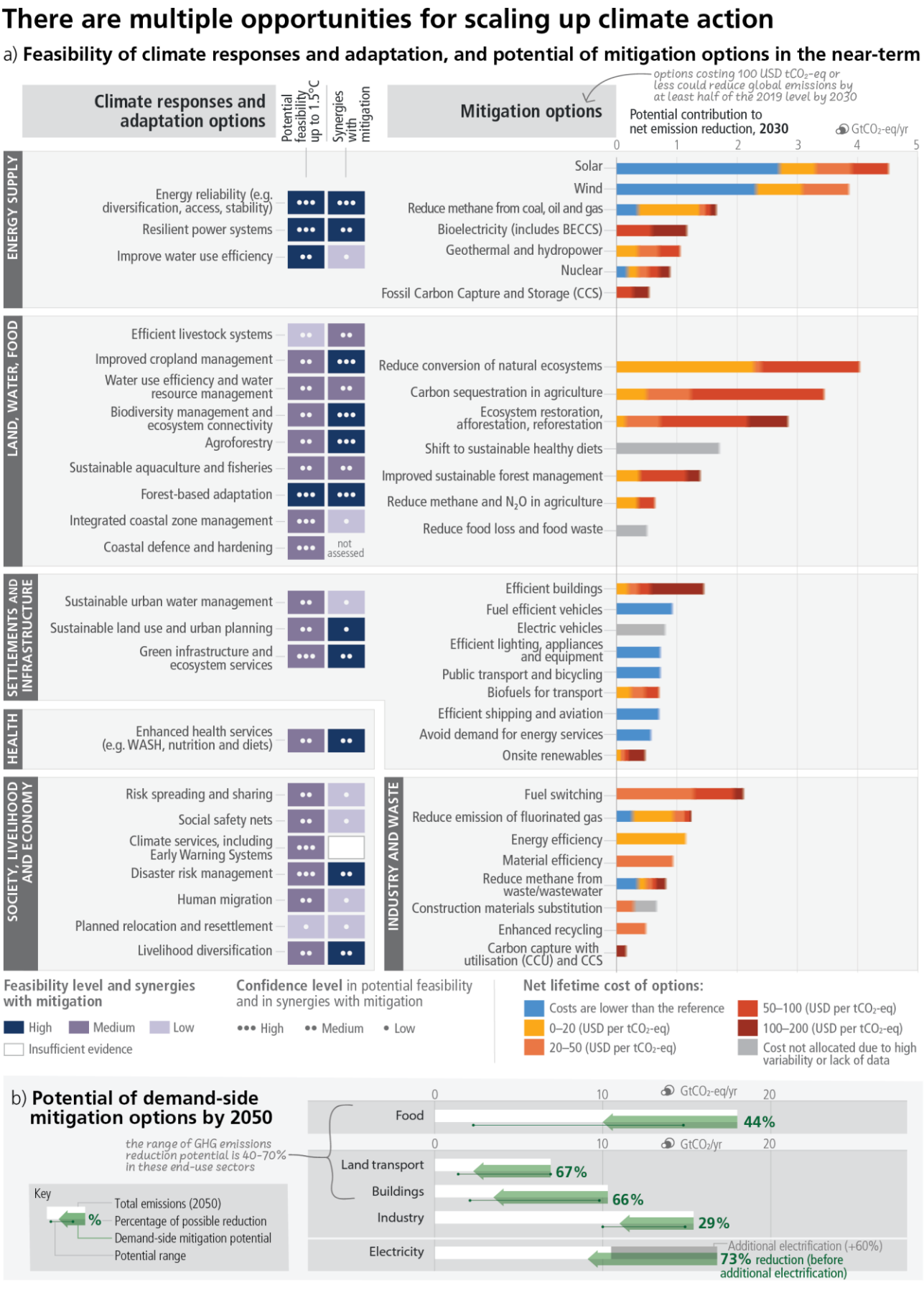

Figure SPM.7: Multiple Opportunities for scaling up climate action. **Panel (a)** presents selected mitigation and adaptation options across different systems. The left hand side of panel a shows climate responses and adaptation options assessed for their multidimensional feasibility at global scale, in the near term and up to 1.5°C global warming. As literature above 1.5°C is limited, feasibility at higher levels of warming may change, which is currently not possible to assess robustly. The term response is used here in addition to adaptation because some responses, such as migration, relocation and resettlement may or may not be considered to be adaptation. Forest based adaptation includes sustainable forest management, forest conservation and restoration, reforestation and afforestation. WASH refers to water, sanitation and hygiene. Six feasibility dimensions (economic, technological, institutional, social, environmental and geophysical) were used to calculate the potential feasibility of climate responses and adaptation options, along with their synergies with mitigation. For potential feasibility and feasibility dimensions, the figure shows high, medium, or low feasibility. Synergies with mitigation are identified as high, medium, and low.

The right hand side of Panel a provides an overview of selected mitigation options and their estimated costs and potentials in 2030. Costs are net lifetime discounted monetary costs of avoided GHG emissions calculated relative to a reference technology. Relative potentials and costs will vary by place, context and time and in the longer term compared to 2030. The potential (horizontal axis) is the net GHG emission reduction (sum of reduced emissions and/or enhanced sinks) broken down into cost categories (coloured bar segments) relative to an emission baseline consisting of current policy (around 2019) reference scenarios from the AR6 scenarios database. The potentials are assessed independently for each option and are not additive. Health system mitigation options are included mostly in settlement and infrastructure (e.g., efficient healthcare buildings) and cannot be identified separately. Fuel switching in industry refers to switching to electricity, hydrogen, bioenergy and natural gas. Gradual colour transitions indicate uncertain breakdown into cost categories due to uncertainty or heavy context dependency. The uncertainty in the total potential is typically 25–50%.

Panel (b) displays the indicative potential of demand-side mitigation options for 2050. Potentials are estimated based on approximately 500 bottom-up studies representing all global regions. The baseline (white bar) is provided by the sectoral mean GHG emissions in 2050 of the two scenarios (IEA-STEPS and IP_ModAct) consistent with policies announced by national governments until 2020. The green arrow represents the demand-side emissions reductions potentials. The range in potential is shown by a line connecting dots displaying the highest and the lowest potentials reported in the literature. Food shows demand-side potential of socio-cultural factors and infrastructure use, and changes in land-use patterns enabled by change in food demand. Demand-side measures and new ways of end-use service provision can reduce global GHG emissions in end-use sectors (buildings, land transport, food) by 40–70% by 2050 compared to baseline scenarios, while some regions and socioeconomic groups require additional energy and resources. The last row shows how demand-side mitigation options in other sectors can influence overall electricity demand. The dark grey bar shows the projected increase in electricity demand above the 2050 baseline due to increasing electrification in the other sectors. Based on a bottom-up assessment, this projected increase in electricity demand can be avoided through demand-side mitigation options in the domains of infrastructure use and socio-cultural factors that influence electricity usage in industry, land transport, and buildings (green arrow). {Figure 4.4}

[END FIGURE SPM.7 HERE]

Mitigation and Adaptation Options across Systems

C.3 Rapid and far-reaching transitions across all sectors and systems are necessary to achieve deep and sustained emissions reductions and secure a liveable and sustainable future for all. These system transitions involve a significant upscaling of a wide portfolio of mitigation and adaptation options. Feasible, effective, and low-cost options for mitigation and adaptation are already available, with differences across systems and regions. (*high confidence*) {4.1, 4.5, 4.6} (Figure SPM.7)

C.3.1 The systemic change required to achieve rapid and deep emissions reductions and transformative adaptation to climate change is unprecedented in terms of scale, but not necessarily in terms of speed (*medium confidence*). Systems transitions include: deployment of low- or zero-emission technologies; reducing and changing demand through infrastructure design and access, socio-cultural and behavioural changes, and increased technological efficiency and adoption; social protection, climate services or other services; and protecting and restoring ecosystems (*high confidence*). Feasible, effective, and low-cost options for mitigation and adaptation are already available (*high confidence*). The availability, feasibility and potential of mitigation and adaptation options in the near-term differs across systems and regions (*very high confidence*). {4.1, 4.5.1–4.5.6}(Figure SPM.7)

Energy Systems

C.3.2 Net zero CO_2 energy systems entail: a substantial reduction in overall fossil fuel use, minimal use of unabated fossil fuels[51], and use of carbon capture and storage in the remaining fossil fuel systems; electricity systems that emit no net CO_2; widespread electrification; alternative energy carriers in applications less amenable to electrification; energy conservation and efficiency; and greater integration across the energy system (*high confidence*). Large contributions to emissions reductions with costs less than USD 20 $tCO_2\text{-}eq^{-1}$ come from solar and wind energy, energy efficiency improvements, and methane emissions reductions (coal mining, oil and gas, waste) (*medium confidence*). There are feasible adaptation options that support infrastructure resilience, reliable power systems and efficient water use for existing and new energy generation systems (*very high confidence*). Energy generation diversification (e.g., via wind, solar, small scale hydropower) and demand side management (e.g., storage and energy efficiency improvements) can increase energy reliability and reduce vulnerabilities to climate change (*high confidence*). Climate responsive energy markets, updated design standards on energy assets according to current and projected climate change, smart-grid technologies, robust transmission systems and improved capacity to respond to supply deficits have high feasibility in the medium- to long-term, with mitigation co-benefits (*very high confidence*). {4.5.1} (Figure SPM.7)

Industry and Transport

C.3.3 Reducing industry GHG emissions entails coordinated action throughout value chains to promote all mitigation options, including demand management, energy and materials efficiency, circular material flows, as well as abatement technologies and transformational changes in production processes (*high confidence*). In transport, sustainable biofuels, low-emissions hydrogen, and derivatives (including ammonia and synthetic fuels) can support mitigation of CO_2 emissions from shipping, aviation, and heavy-duty land transport but require production process improvements and cost reductions (*medium confidence*). Sustainable biofuels can offer additional mitigation benefits in land-based transport in the short and medium term (*medium confidence*). Electric vehicles powered by low-GHG emissions electricity have large potential to reduce land-based transport GHG emissions, on a life cycle basis (*high confidence*). Advances in battery technologies could facilitate the electrification of heavy-duty trucks and compliment conventional electric rail systems (*medium confidence*). The environmental footprint of battery production and growing concerns about critical minerals can be addressed by material and supply diversification strategies, energy and material efficiency improvements, and circular material flows (*medium confidence*). 4.5.2, 4.5.3} (Figure SPM.7)

[51] In this context, 'unabated fossil fuels' refers to fossil fuels produced and used without interventions that substantially reduce the amount of GHG emitted throughout the life cycle; for example, capturing 90% or more CO2 from power plants, or 50–80% of fugitive methane emissions from energy supply.

Cities, Settlements and Infrastructure

C.3.4 Urban systems are critical for achieving deep emissions reductions and advancing climate resilient development (*high confidence*). Key adaptation and mitigation elements in cities include considering climate change impacts and risks (e.g. through climate services) in the design and planning of settlements and infrastructure; land use planning to achieve compact urban form, co-location of jobs and housing; supporting public transport and active mobility (e.g., walking and cycling); the efficient design, construction, retrofit, and use of buildings; reducing and changing energy and material consumption; sufficiency[52]; material substitution; and electrification in combination with low emissions sources (*high confidence*). Urban transitions that offer benefits for mitigation, adaptation, human health and well-being, ecosystem services, and vulnerability reduction for low-income communities are fostered by inclusive long-term planning that takes an integrated approach to physical, natural and social infrastructure (*high confidence*). Green/natural and blue infrastructure supports carbon uptake and storage and either singly or when combined with grey infrastructure can reduce energy use and risk from extreme events such as heatwaves, flooding, heavy precipitation and droughts, while generating co-benefits for health, well-being and livelihoods (*medium confidence*). {4.5.3}

Land, Ocean, Food, and Water

C.3.5 Many agriculture, forestry, and other land use (AFOLU) options provide adaptation and mitigation benefits that could be upscaled in the near-term across most regions. Conservation, improved management, and restoration of forests and other ecosystems offer the largest share of economic mitigation potential, with reduced deforestation in tropical regions having the highest total mitigation potential. Ecosystem restoration, reforestation, and afforestation can lead to trade-offs due to competing demands on land. Minimizing trade-offs requires integrated approaches to meet multiple objectives including food security. Demand-side measures (shifting to sustainable healthy diets[53] and reducing food loss/waste) and sustainable agricultural intensification can reduce ecosystem conversion, and methane and nitrous oxide emissions, and free up land for reforestation and ecosystem restoration. Sustainably sourced agricultural and forest products, including long-lived wood products, can be used instead of more GHG-intensive products in other sectors. Effective adaptation options include cultivar improvements, agroforestry, community-based adaptation, farm and landscape diversification, and urban agriculture. These AFOLU response options require integration of biophysical, socioeconomic and other enabling factors. Some options, such as conservation of high-carbon ecosystems (e.g., peatlands, wetlands, rangelands, mangroves and forests), deliver immediate benefits, while others, such as restoration of high-carbon ecosystems, take decades to deliver measurable results. {4.5.4} (Figure SPM.7)

C.3.6 Maintaining the resilience of biodiversity and ecosystem services at a global scale depends on effective and equitable conservation of approximately 30% to 50% of Earth's land, freshwater and ocean areas, including currently near-natural ecosystems (*high confidence*). Conservation, protection and restoration of terrestrial, freshwater, coastal and ocean ecosystems, together with targeted management to adapt to unavoidable impacts of climate change reduces the vulnerability of biodiversity and ecosystem services to climate change (*high confidence*), reduces coastal erosion and flooding (*high confidence*), and could increase carbon uptake and storage if global warming is limited (*medium confidence*). Rebuilding overexploited or depleted fisheries reduces negative climate change impacts on fisheries (*medium confidence*) and supports food security, biodiversity, human health and well-being (*high confidence*). Land restoration contributes to climate change mitigation and adaptation with synergies via enhanced ecosystem services and with economically positive returns and co-benefits for poverty reduction and improved livelihoods (*high confidence*). Cooperation, and inclusive decision making, with Indigenous Peoples and local communities, as well as recognition of inherent rights of Indigenous Peoples, is integral to successful adaptation and mitigation across forests and other ecosystems (*high confidence*). {4.5.4, 4.6} (Figure SPM.7)

[52] A set of measures and daily practices that avoid demand for energy, materials, land, and water while delivering human well-being for all within planetary boundaries {4.5.3}

[53] 'Sustainable healthy diets' promote all dimensions of individuals' health and well-being; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable, as described in FAO and WHO. The related concept of 'balanced diets' refers to diets that feature plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, and animal-sourced food produced in resilient, sustainable and low-GHG emission systems, as described in SRCCL.

Health and Nutrition

C.3.7 Human health will benefit from integrated mitigation and adaptation options that mainstream health into food, infrastructure, social protection, and water policies (*very high confidence*). Effective adaptation options exist to help protect human health and wellbeing, including: strengthening public health programs related to climate-sensitive diseases, increasing health systems resilience, improving ecosystem health, improving access to potable water, reducing exposure of water and sanitation systems to flooding, improving surveillance and early warning systems, vaccine development (*very high confidence*), improving access to mental healthcare, and Heat Health Action Plans that include early warning and response systems (*high confidence*). Adaptation strategies which reduce food loss and waste or support balanced, sustainable healthy diets contribute to nutrition, health, biodiversity and other environmental benefits (*high confidence*). {4.5.5} (Figure SPM.7)

Society, Livelihoods, and Economies

C.3.8 Policy mixes that include weather and health insurance, social protection and adaptive social safety nets, contingent finance and reserve funds, and universal access to early warning systems combined with effective contingency plans, can reduce vulnerability and exposure of human systems. Disaster risk management, early warning systems, climate services and risk spreading and sharing approaches have broad applicability across sectors. Increasing education including capacity building, climate literacy, and information provided through climate services and community approaches can facilitate heightened risk perception and accelerate behavioural changes and planning. (*high confidence*) {4.5.6}

Synergies and Trade-Offs with Sustainable Development

C.4 Accelerated and equitable action in mitigating and adapting to climate change impacts is critical to sustainable development. Mitigation and adaptation actions have more synergies than trade-offs with Sustainable Development Goals. Synergies and trade-offs depend on context and scale of implementation. (*high confidence*) {3.4, 4.2, 4.4, 4.5, 4.6, 4.9, Figure 4.5}

C.4.1 Mitigation efforts embedded within the wider development context can increase the pace, depth and breadth of emission reductions (*medium confidence*). Countries at all stages of economic development seek to improve the well-being of people, and their development priorities reflect different starting points and contexts. Different contexts include but are not limited to social, economic, environmental, cultural, political circumstances, resource endowment, capabilities, international environment, and prior development (*high confidence*). In regions with high dependency on fossil fuels for, among other things, revenue and employment generation, mitigating risk for sustainable development requires policies that promote economic and energy sector diversification and considerations of just transitions principles, processes and practices (*high confidence*). Eradicating extreme poverty, energy poverty, and providing decent living standards in low-emitting countries / regions in the context of achieving sustainable development objectives, in the near term, can be achieved without significant global emissions growth (*high confidence*). {4.4, 4.6, Annex I: Glossary}

C.4.2 Many mitigation and adaptation actions have multiple synergies with Sustainable Development Goals (SDGs) and sustainable development generally, but some actions can also have trade-offs. Potential synergies with SDGs exceed potential trade-offs; synergies and trade-offs depend on the pace and magnitude of change and the development context including inequalities with consideration of climate justice. Trade-offs can be evaluated and minimised by giving emphasis to capacity building, finance, governance, technology transfer, investments, development, context specific gender-based and other social equity considerations with meaningful participation of Indigenous Peoples, local communities and vulnerable populations. (*high confidence*) {3.4.1, 4.6, Figure 4.5, 4.9}

C.4.3 Implementing both mitigation and adaptation actions together and taking trade-offs into account supports co-benefits and synergies for human health and well-being. For example, improved access to clean energy sources and technologies generate health benefits especially for women and children; electrification combined with low-GHG energy, and shifts to active mobility and public transport can enhance air quality, health, employment, and can elicit energy security and deliver equity. (*high confidence*) {4.2, 4.5.3, 4.5.5, 4.6, 4.9}

Equity and Inclusion

C.5 Prioritising equity, climate justice, social justice, inclusion and just transition processes can enable adaptation and ambitious mitigation actions and climate resilient development. Adaptation outcomes are enhanced by increased support to regions and people with the highest vulnerability to climatic hazards. Integrating climate adaptation into social protection programs improves resilience. Many options are available for reducing emission-intensive consumption, including through behavioural and lifestyle changes, with co-benefits for societal well-being. (*high confidence*) {4.4, 4.5}

C.5.1 Equity remains a central element in the UN climate regime, notwithstanding shifts in differentiation between states over time and challenges in assessing fair shares. Ambitious mitigation pathways imply large and sometimes disruptive changes in economic structure, with significant distributional consequences, within and between countries. Distributional consequences within and between countries include shifting of income and employment during the transition from high- to low-emissions activities. (*high confidence*) {4.4}

C.5.2 Adaptation and mitigation actions, that prioritise equity, social justice, climate justice, rights-based approaches, and inclusivity, lead to more sustainable outcomes, reduce trade-offs, support transformative change and advance climate resilient development. Redistributive policies across sectors and regions that shield the poor and vulnerable, social safety nets, equity, inclusion and just transitions, at all scales can enable deeper societal ambitions and resolve trade-offs with sustainable development goals. Attention to equity and broad and meaningful participation of all relevant actors in decision making at all scales can build social trust which builds on equitable sharing of benefits and burdens of mitigation that deepen and widen support for transformative changes. (*high confidence*) {4.4}

C.5.3 Regions and people (3.3 to 3.6 billion in number) with considerable development constraints have high vulnerability to climatic hazards (see A.2.2). Adaptation outcomes for the most vulnerable within and across countries and regions are enhanced through approaches focusing on equity, inclusivity and rights-based approaches. Vulnerability is exacerbated by inequity and marginalisation linked to e.g., gender, ethnicity, low incomes, informal settlements, disability, age, and historical and ongoing patterns of inequity such as colonialism, especially for many Indigenous Peoples and local communities. Integrating climate adaptation into social protection programs, including cash transfers and public works programs, is highly feasible and increases resilience to climate change, especially when supported by basic services and infrastructure. The greatest gains in well-being in urban areas can be achieved by prioritising access to finance to reduce climate risk for low-income and marginalised communities including people living in informal settlements. (*high confidence*). {4.4, 4.5.3, 4.5.5, 4.5.6}

C.5.4 The design of regulatory instruments and economic instruments and consumption-based approaches, can advance equity. Individuals with high socio-economic status contribute disproportionately to emissions, and have the highest potential for emissions reductions. Many options are available for reducing emission-intensive consumption while improving societal well-being. Socio-cultural options, behaviour and lifestyle changes supported by policies, infrastructure, and technology can help end-users shift to low-emissions-intensive consumption, with multiple co-benefits. A substantial share of the population in low-emitting countries lack access to modern energy services. Technology development, transfer, capacity building and financing can support developing countries/ regions leapfrogging or transitioning to low-emissions transport systems thereby providing multiple co-benefits. Climate resilient development is advanced when actors work in equitable, just and inclusive ways to reconcile divergent interests, values and worldviews, toward equitable and just outcomes. (*high confidence*) {2.1, 4.4}

Governance and Policies

C.6 Effective climate action is enabled by political commitment, well-aligned multilevel governance, institutional frameworks, laws, policies and strategies and enhanced access to finance and technology. Clear goals, coordination across multiple policy domains, and inclusive governance processes facilitate effective climate action. Regulatory and economic instruments can support deep emissions reductions and climate resilience if scaled up and applied widely. Climate resilient development benefits from drawing on diverse knowledge. (*high confidence*) {2.2, 4.4, 4.5, 4.7}

C.6.1 Effective climate governance enables mitigation and adaptation. Effective governance provides overall direction on setting targets and priorities and mainstreaming climate action across policy domains and levels, based on national circumstances and in the context of international cooperation. It enhances monitoring and evaluation and regulatory certainty, prioritising inclusive, transparent and equitable decision-making, and improves access to finance and technology (see C.7). (*high confidence)* {2.2.2, 4.7}

C.6.2 Effective local, municipal, national and subnational institutions build consensus for climate action among diverse interests, enable coordination and inform strategy setting but require adequate institutional capacity. Policy support is influenced by actors in civil society, including businesses, youth, women, labour, media, Indigenous Peoples, and local communities. Effectiveness is enhanced by political commitment and partnerships between different groups in society. (*high confidence*) {2.2; 4.7}

C.6.3 Effective multilevel governance for mitigation, adaptation, risk management, and climate resilient development is enabled by inclusive decision processes that prioritise equity and justice in planning and implementation, allocation of appropriate resources, institutional review, and monitoring and evaluation. Vulnerabilities and climate risks are often reduced through carefully designed and implemented laws, policies, participatory processes, and interventions that address context specific inequities such as those based on gender, ethnicity, disability, age, location and income. (*high confidence*) {4.4, 4.7}

C.6.4 Regulatory and economic instruments could support deep emissions reductions if scaled up and applied more widely (*high confidence*). Scaling up and enhancing the use of regulatory instruments can improve mitigation outcomes in sectoral applications, consistent with national circumstances (*high confidence*). Where implemented, carbon pricing instruments have incentivized low-cost emissions reduction measures but have been less effective, on their own and at prevailing prices during the assessment period, to promote higher-cost measures necessary for further reductions (*medium confidence*). Equity and distributional impacts of such carbon pricing instruments, e.g., carbon taxes and emissions trading, can be addressed by using revenue to support low-income households, among other approaches. Removing fossil fuel subsidies would reduce emissions[54] and yield benefits such as improved public revenue, macroeconomic and sustainability performance; subsidy removal can have adverse distributional impacts, especially on the most economically vulnerable groups which, in some cases can be mitigated by measures such as redistributing revenue saved, all of which depend on national circumstances (*high confidence*). Economy-wide policy packages, such as public spending commitments, pricing reforms, can meet short-term economic goals while reducing emissions and shifting development pathways towards sustainability (*medium confidence*). Effective policy packages would be comprehensive, consistent, balanced across objectives, and tailored to national circumstances *(high confidence).* {2.2.2, 4.7}

C.6.5 Drawing on diverse knowledges and cultural values, meaningful participation and inclusive engagement processes—including Indigenous Knowledge, local knowledge, and scientific knowledge—facilitates climate resilient development, builds capacity and allows locally appropriate and socially acceptable solutions. (*high confidence*) {4.4, 4.5.6, 4.7}

[54] Fossil fuel subsidy removal is projected by various studies to reduce global CO_2 emission by 1-4%, and GHG emissions by up to 10% by 2030, varying across regions (*medium confidence*).

Finance, Technology and International Cooperation

C.7 Finance, technology and international cooperation are critical enablers for accelerated climate action. If climate goals are to be achieved, both adaptation and mitigation financing would need to increase many-fold. There is sufficient global capital to close the global investment gaps but there are barriers to redirect capital to climate action. Enhancing technology innovation systems is key to accelerate the widespread adoption of technologies and practices. Enhancing international cooperation is possible through multiple channels. *(high confidence*) {2.3, 4.8}

C.7.1 Improved availability of and access to finance[55] would enable accelerated climate action (*very high confidence*). Addressing needs and gaps and broadening equitable access to domestic and international finance, when combined with other supportive actions, can act as a catalyst for accelerating adaptation and mitigation, and enabling climate resilient development *(high confidence).* If climate goals are to be achieved, and to address rising risks and accelerate investments in emissions reductions, both adaptation and mitigation finance would need to increase many-fold (*high confidence).* {4.8.1}

C.7.2 Increased access to finance can build capacity and address soft limits to adaptation and avert rising risks, especially for developing countries, vulnerable groups, regions and sectors (*high confidence*). Public finance is an important enabler of adaptation and mitigation, and can also leverage private finance *(high confidence)*. Average annual modelled mitigation investment requirements for 2020 to 2030 in scenarios that limit warming to 2°C or 1.5°C are a factor of three to six greater than current levels[56], and total mitigation investments (public, private, domestic and international) would need to increase across all sectors and regions (*medium confidence*). Even if extensive global mitigation efforts are implemented, there will be a need for financial, technical, and human resources for adaptation *(high confidence*). {4.3, 4.8.1}

C.7.3 There is sufficient global capital and liquidity to close global investment gaps, given the size of the global financial system, but there are barriers to redirect capital to climate action both within and outside the global financial sector and in the context of economic vulnerabilities and indebtedness facing developing countries. Reducing financing barriers for scaling up financial flows would require clear signalling and support by governments, including a stronger alignment of public finances in order to lower real and perceived regulatory, cost and market barriers and risks and improving the risk-return profile of investments. At the same time, depending on national contexts, financial actors, including investors, financial intermediaries, central banks and financial regulators can shift the systemic underpricing of climate-related risks, and reduce sectoral and regional mismatches between available capital and investment needs. (*high confidence*) {4.8.1}

C.7.4 Tracked financial flows fall short of the levels needed for adaptation and to achieve mitigation goals across all sectors and regions. These gaps create many opportunities and the challenge of closing gaps is largest in developing countries. Accelerated financial support for developing countries from developed countries and other sources is a critical enabler to enhance adaptation and mitigation actions and address inequities in access to finance, including its costs, terms and conditions, and economic vulnerability to climate change for developing countries. Scaled-up public grants for mitigation and adaptation funding for vulnerable regions, especially in Sub-Saharan Africa, would be cost-effective and have high social returns in terms of access to basic energy. Options for scaling up mitigation in developing countries include: increased levels of public finance and publicly mobilised private finance flows from developed to developing countries in the context of the USD 100 billion-a-year goal; increased use of public guarantees to reduce risks and leverage private flows at lower cost; local capital markets development; and building greater trust in international cooperation processes. A coordinated effort to make the post-pandemic recovery sustainable over the longer-term can accelerate climate action, including in developing regions and countries facing high debt costs, debt distress and macroeconomic uncertainty. (*high confidence*) {4.8.1}

[55] Finance originates from diverse sources: public or private, local, national or international, bilateral or multilateral, and alternative sources. It can take the form of grants, technical assistance, loans (concessional and non-concessional), bonds, equity, risk insurance and financial guarantees (of different types).
[56] These estimates rely on scenario assumptions.

C.7.5 Enhancing technology innovation systems can provide opportunities to lower emissions growth, create social and environmental co-benefits, and achieve other SDGs. Policy packages tailored to national contexts and technological characteristics have been effective in supporting low-emission innovation and technology diffusion. Public policies can support training and R&D, complemented by both regulatory and market-based instruments that create incentives and market opportunities. Technological innovation can have trade-offs such as new and greater environmental impacts, social inequalities, overdependence on foreign knowledge and providers, distributional impacts and rebound effects[57], requiring appropriate governance and policies to enhance potential and reduce trade-offs. Innovation and adoption of low-emission technologies lags in most developing countries, particularly least developed ones, due in part to weaker enabling conditions, including limited finance, technology development and transfer, and capacity building. (*high confidence*) {4.8.3}

C.7.6 International cooperation is a critical enabler for achieving ambitious climate change mitigation, adaptation, and climate resilient development (*high confidence*). Climate resilient development is enabled by increased international cooperation including mobilising and enhancing access to finance, particularly for developing countries, vulnerable regions, sectors and groups and aligning finance flows for climate action to be consistent with ambition levels and funding needs (*high confidence*). Enhancing international cooperation on finance, technology and capacity building can enable greater ambition and can act as a catalyst for accelerating mitigation and adaptation, and shifting development pathways towards sustainability (*high confidence*). This includes support to NDCs and accelerating technology development and deployment (*high confidence*). Transnational partnerships can stimulate policy development, technology diffusion, adaptation and mitigation, though uncertainties remain over their costs, feasibility and effectiveness (*medium confidence*). International environmental and sectoral agreements, institutions and initiatives are helping, and in some cases may help, to stimulate low GHG emissions investments and reduce emissions (*medium confidence*). {2.2.2, 4.8.2}

[57] Leading to lower net emission reductions or even emission increases.