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INTERGOVERNMENTAL PANEL ON climate change

Climate Change 2022

Mitigation of Climate Change

Summary for Policymakers, Technical Summary, Frequently Asked Questions and Glossary

WGIII

Working Group III contribution to the
Sixth Assessment Report of the
Intergovernmental Panel on Climate Change

WMO UNEP

Front cover photograph: Matt Bridgestock, Director and Architect at John Gilbert Architects

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Electronic copies of this Summary for Policymakers are available from the IPCC website www.ipcc.ch
ISBN 978-92-9169-165-4

Climate Change 2022
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Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change

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Foreword and Preface

Foreword

Climate Change 2022: Mitigation of Climate Change is the third part of the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) and was prepared by its Working Group III. The volume provides an updated global assessment of current and projected emissions from all sources and sectors, mitigation options that reduce emissions or remove greenhouse gases from the atmosphere, and progress towards meeting climate ambitions. It assesses what is required to achieve net zero emissions as pledged by many countries.

This report shows that greenhouse gas emissions over the last decade are at the highest levels in human history. It shows that urgent action is needed. Unless there are immediate and deep emissions reductions across all sectors, limiting global warming to 1.5°C will be beyond reach. Global greenhouse gas emissions implied by Nationally Determined Contributions announced prior to COP26 make it likely that warming will exceed 1.5°C and will also make it harder to limit warming to below 2°C.

But there are positive signs and increased evidence of climate action. Options are available now in every sector that can at least halve emissions by 2030. Some countries have already achieved a steady decrease in emissions consistent with limiting warming to 2°C. Costs for some forms of renewable energy have fallen, use of renewables continues to rise and, in some countries and regions, electricity systems are already predominantly powered by renewables.

This IPCC report highlights for the first time the social and demand-side aspects of climate mitigation. As long as the necessary policies, infrastructure and technologies are in place, changes to lifestyles and behaviour have the potential for large reductions in global greenhouse gas emissions and, at the same time, lead to improved wellbeing.

The report calls attention to the deep links between climate mitigation and sustainable development. It draws attention to the way that climate action is intimately connected to addressing the nature crisis. Attention to equity and just transitions can support deeper ambition for accelerated climate action.

The findings in this report have considerably enhanced our understanding of available mitigation pathways. The timing of this report is critical. It provides crucial information that informs the first Global Stocktake under the Paris Agreement. It demands the urgent attention of policymakers and the general public.

As an intergovernmental body jointly established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), the IPCC has successfully provided policymakers with the most authoritative and objective scientific and technical assessments, which are policy relevant without being policy prescriptive. Beginning in 1990, this series of IPCC Assessment Reports, Special Reports, Technical Papers, Methodology Reports and other products have become standard works of reference.

This Working Group III assessment was made possible thanks to the commitment and dedication of many hundreds of experts, representing a wide range of regions and scientific disciplines. WMO and UNEP are proud that so many of the experts belong to their communities and networks.

We express our deep gratitude to all authors, review editors and expert reviewers for devoting their knowledge, expertise and time. We note the particular challenges presented by the COVID-19 pandemic and the burdens placed on experts. We would like to thank the staff of the Working Group III Technical Support Unit and the IPCC Secretariat for their dedication.

We are also thankful to the governments that supported their scientists' participation in developing this report and that contributed to the IPCC Trust Fund to provide for the essential participation of experts from developing countries and countries with economies in transition.

We would like to express our appreciation to the government of Ethiopia for hosting the scoping meeting for the IPCC's Sixth Assessment Report, to the governments of the United Kingdom of Great Britain and Northern Ireland, India, Ecuador and Italy for hosting drafting sessions for the Working Group III contribution. The latter two meetings were held in a virtual format due to the COVID-19 pandemic. We also express our thanks to the government of the United Kingdom for hosting the Fourteenth Session of Working Group III for approval of the Working Group III Report. The generous financial support by the government of the United Kingdom, and the hosting of the Working Group III Technical Support Unit by Imperial College London (United Kingdom) and Ahmedabad University (India), is gratefully acknowledged.

We would particularly like to thank Dr. Hoesung Lee, Chairman of the IPCC, for his direction and guidance of the IPCC and we express our deep gratitude to Professor Priyadarshi R. Shukla and Professor Jim Skea, the Co-Chairs of Working Group III, for their tireless leadership throughout the development and production of this report.

Petteri Taalas
Secretary-General
World Meteorological Organization

Inger Andersen
Executive Director
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Preface

The Working Group III (WG III) contribution to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) provides a comprehensive and transparent assessment of the scientific literature on climate change mitigation. It builds upon the WG III contribution to the IPCC's Fifth Assessment Report (AR5) in 2014, the WG I and WG II contributions to the AR6, and the three AR6 Special Reports: *Global Warming of 1.5°C*; *Climate Change and Land*; and *The Ocean and Cryosphere in a Changing Climate*.

The report assesses progress in climate change mitigation and options for reducing emissions and enhancing sinks. It evaluates the societal implications of mitigation actions, without recommending any specific options.

Scope of the Report

The scoping of the WG III contribution to AR6 was driven by three guiding principles: to achieve a better synthesis between higher-level whole system and grounded bottom-up insights into technologies and other approaches for reducing emissions; to make wider use of social science disciplines, especially for gaining insight into issues related to lifestyle, behaviour, consumption and socio-technical transitions; and to link climate change mitigation better to other agreed policy goals both nationally and internationally.

The core of the report remains, as in AR5, a set of chapters devoted to different sectors, broadly aligned with the categorisation used in the IPCC Guidelines for National Greenhouse Gas Inventories. These chapters cover emission trends and drivers, mitigation costs and potentials, regional specificities, and sector specific barriers, policies, financing and enabling conditions. A systems level perspective was followed where appropriate. A cross-sectoral perspectives chapter integrates findings from the sectoral chapters and assesses approaches falling outside the scope of individual sectors.

As in the AR5, there is a chapter on recent trends and drivers, with the scope expanded to cover historic emissions and recent policy developments. Following the pattern established in the WG III AR5 report, and the Special Report on Global Warming of 1.5°C, this report assesses published emission scenarios with a 21st century perspective. Modelled emission scenarios are categorised according to climate outcomes, allowing a handshake with the WG I assessment. To meet the goal of linking top-down and bottom-up insights, the report includes an additional pathways chapter that provides a mid-century perspective, focussing on national and regional scales and the alignment between development pathways and mitigation actions.

As in the AR5, this report addresses mitigation enablers such as international cooperation, finance and investment, and policies and institutions, with a greater emphasis placed on the role of institutions than in the AR5. A new chapter is dedicated to the assessment of innovation systems, technology development and technology transfer. A further novelty is a chapter that assesses the literature on human behaviour, lifestyle and culture, and its implications for mitigation action. This chapter touches on patterns of development and human well-being, and circular and sharing economy concepts. It brings a wide range of disciplines, notably from the social sciences, within the scope of the WG III assessment.

Linkages with development and specifically the Sustainable Development Goals (SDGs) permeate the WG III report. This framing is set up in Chapter 1, and the threads are drawn together in the final chapter where linkages between mitigation and the SDGs are systematically assessed.

The AR6 has benefited from close and unprecedented collaboration between the three IPCC WGs: with WG I on scenarios and with WG II on urban systems, land use and development pathways. This collaboration is manifested in a number of Cross-Working Group boxes covering topics such as the economic benefits from avoided impacts along mitigation pathways, climate change and urban areas, mitigation and adaptation through the bioeconomy, and solar radiation modification.

Structure of the Report

This report consists of a Summary for Policymakers, a Technical Summary, 17 Chapters, six Annexes, and Index, as well as online Supplementary Material to chapters.

Chapters 1 (Introduction and framing) and 17 (Accelerating the transition in the context of sustainable development), the first and final chapters of the report, set climate change mitigation in the context of sustainable development. Chapter 1 sets out the evolving policy landscape for climate mitigation, provides the reader with the framing of, and context for, the report, and highlights key concepts. Chapter 17 adopts an integrative perspective on sustainable development and climate change responses, identifying synergies and trade-offs, and explores joint responses to climate change and sustainable development challenges.

Chapters 2–4 take a high-level view of trends and future pathways using three different time frames. Chapter 2 (Emissions trends and drivers) covers historic and current emission trends and socio-economic and demographic drivers of emissions. It also maps developments in technologies and policies since the AR5. Chapter 3 (Mitigation pathways compatible with long-term goals) assesses modelled emission pathways compatible with the Paris Agreement and higher warming levels. It addresses socio-cultural-techno-economic assumptions, technological and behavioural aspects of mitigation pathways, and links to adaptation and sustainable development. Chapter 4 (Mitigation and development pathways in the near- to mid-term) takes a mid-century perspective, considering national, regional and international scales and the implications of mitigation for national development objectives including employment, competitiveness, poverty eradication and the SDGs. Annex III (Scenarios and modelling methods) provides methodological background to Chapters 3 and 4.

Chapter 5 (Demand, services and social aspects of mitigation), a new chapter in AR6, explores how mitigation interacts with meeting human needs and access to services. It explores, *inter alia*: sustainable production and consumption; patterns of development and indicators of wellbeing; the role of culture, social norms, practices and behaviour changes; the sharing economy and circular economy; and policies facilitating behavioural and lifestyle change.

Chapters 6–12 (Energy systems; Agriculture, Forestry, and Other Land Uses (AFOLU); Urban systems and other settlements; Buildings; Transport; Industry; Cross-sectoral perspectives) assess the potential for emissions reductions in specific systems and sectors, taking into account trends in emissions and their key drivers, global and regional costs and potentials, links to climate adaptation and associated risks and co-benefits, and sector specific barriers, policies, financing and enabling conditions. Specificities include fugitive emissions and carbon capture and storage (Energy), provision of food, feed, fibre, wood, biomass for energy and other ecosystem services (AFOLU), demographic changes and urban form (Urban systems and other settlements), mitigation strategies including efficiency, sufficiency and renewables (Buildings), access to mobility (Transport), and resource efficiency (Industry). Chapter 12 (Cross-sectoral perspectives) synthesises costs and potentials, and co-benefits and trade-offs, across sectors; it also addresses cross-cutting approaches such as carbon dioxide removal and mitigation opportunities in the food system.

Chapters 13–16 address enabling conditions for mitigation action. Chapter 13 (National and sub-national policies and institutions) provides insights from national and subnational plans and strategies, including trends in legislation and institutions. Chapter 14 (International cooperation) assesses international cooperation and institutions, including linkages with non-climate organisations and processes, international sectoral agreements, and institutions for finance and investment and capacity building. Chapter 15 (Investment and finance) assesses scenarios of, and needs for, mitigation investment and financial flows, and the means of mobilising climate finance at the national and sub-national levels. Chapter 16 (Innovation, technology development and transfer) examines the role of innovation, technology development, diffusion and transfer in contributing to sustainable development and the aims of the Paris Agreement. It addresses specific challenges in emerging economies and least developed countries.

The Assessment Process

This WG III contribution to the AR6 has been prepared in accordance with IPCC rules and procedures. A scoping meeting was held in May 2017 and the outlines for the contributions of the three WGs were approved at the 46th Session of the Panel in September 2017.

Governments and IPCC observer organisations nominated experts for the author teams. The team of 199 Coordinating Lead Authors and Lead Authors, plus 38 Review Editors, selected by the WG III Bureau, was accepted at the 55th Session of the IPCC Bureau in January 2018. More than 350 Contributing Authors provided text for the author teams.

Drafts were subject to two rounds of formal review and revision followed by a final round of government comments on the Summary for Policymakers. More than 59,000 written comments were submitted by more than 1,600 expert reviewers and 42 governments. For each chapter, the review process was monitored by Review Editors to ensure that all comments received appropriate consideration.

During the review periods and in the run-up to the approval session, webinars were held with governments and two of the UNFCCC non-governmental organisation (NGO) constituencies, the Business and Industry NGOs (BINGOs), and the Environmental NGOs (ENGOs). These informal webinars offered an opportunity for authors to present draft material to IPCC audiences and to receive additional feedback.

The Report was accepted by the Panel at its 56th Session. The Summary for Policymakers was approved line-by-line and the underlying chapters were accepted at the 14th Session of IPCC WG III from 21 March – 4 April 2022, hosted virtually by the United Kingdom of Great Britain and Northern Ireland (UK).

Acknowledgements

The report was made possible thanks to the expertise, hard work and commitment to excellence shown by Coordinating Lead Authors and Lead Authors, with inputs from many Contributing Authors. Their efforts and stamina are particularly commendable given the additional demands and stresses imposed by virtual working as a consequence of the COVID pandemic.

We gratefully acknowledge the support of the Chapter Scientists, who worked tirelessly alongside the authors to deliver their chapters to the highest possible standards. Their time, dedication and hard work is greatly appreciated.

We would like to express our appreciation to the Government and Expert Reviewers for the time and energy they invested to provide constructive and useful comments on the draft reports. Our Review Editors were also critical in the AR6 process, helping author teams to process comments, and assuring an objective discussion of relevant issues.

We wish to thank the governments and other institutions for generous support which enabled the authors, Review Editors and Government and Expert Reviewers to participate.

We would like to thank the Vice-Chairs of the WG III Bureau, who provided invaluable scientific input and thoughtful advice throughout the AR6 process: Amjad Abdulla, Carlo Carraro, Diriba Korecha Dadi, Ramón Pichs-Madruga, Nagmeldin G.E. Mahmoud, Andy Reisinger and Diana Ürge-Vorsatz. Specific thanks are due to Andy Reisinger, who together with the Co-Chairs acted as an editor of the Summary for Policymakers, and to Ramón Pichs-Madruga and Diana Ürge-Vorsatz, who took on roles of editors of the Technical Summary.

We thank the Integrated Assessment Modelling Consortium (IAMC) and the International Institute for Applied Systems Analysis (IIASA) for facilitating the development, and hosting, of the AR6 Scenario Explorer and Database. Particular thanks are due to Edward Byers and Keywan Riahi of IIASA who led this initiative. We thank the International Energy Agency (IEA), in particular Roberta Quadrelli and her team, for providing us with access to their data products. We also thank Monica Crippa and her team at the Joint Research Centre of the European Commission for access to the EDGAR (Emissions Database for Global Atmospheric Research), and William Lamb and Jan Minx who led the assessment of emissions data across the report.

We acknowledge support from countries hosting WG III Lead Author Meetings (LAMs): the UK for hosting the first LAM in Edinburgh (March 2019); India for hosting the second LAM in New Delhi (September 2019); Ecuador for hosting the third LAM virtually (April 2020); and Italy for hosting the fourth LAM, also held virtually (April 2021). We thank the government of Ethiopia for hosting the Scoping Meeting for the report in Addis Ababa (May 2017).

We are especially grateful for the support of the UK government, in particular the Department of Business, Energy and Industrial Strategy (BEIS) and the Engineering and Physical Sciences Research Council (EPSRC), for funding the WG III Technical Support Unit (TSU). Jolene Cook, Eleanor Webster, Rhian Rees-Owen, Sarah Honour, Cathy Johnson, Julie Maclean, Alice Montgomery, Caroline Prescott, and Andrew Russell at BEIS, and Jim Fleming, Kathryn Magnay, Strachan McCormick, Kate Bowman and Jasmine Cain at EPSRC were always ready to dedicate time and energy to the needs of the team. BEIS also organised the venue hosting the core team for the 14th Session of IPCC WG III.

We are grateful for the close collaboration with authors, Bureau members and members of the Technical Support Units from WGs I and II, and Task Force on National Greenhouse Gas Inventories (TFI).. We especially thank WG I Co-Chairs Valérie Masson-Delmotte and Panmao Zhai, WG II Co-Chairs Hans-Otto Portner and Debra Roberts, and the Co-Chairs of the Task Force on Greenhouse Gas Inventories, Eduardo Calvo Buendía and Kiyoto Tanabe, for their collegial spirit and mutual support during the assessment. We extend our gratitude to the IPCC leadership. The Executive Committee, notably Vice-Chairs Ko Barrett, Thelma Krug, Youba Sokona, strengthened the work of all three WGs. We thank IPCC Chair, Hoesung Lee, for his leadership.

We would like to thank the Secretary of the IPCC, Abdalah Mokssit, and Deputy Secretaries, Ermira Fida and Kerstin Stendahl, and their colleagues Mudathir Abdallah, Jesbin Baidya, Laura Biagioni, Annie Courtin, Oksana Ekzarkho, Judith Ewa, Joelle Fernandez, Emelie Larrode, Jennifer Lew Schneider, Jonathan Lynn, Andrej Mahecic, Nina Peeva, Sophie Schlingemann, Mxolisi Shongwe, Melissa Walsh, and Werani Zabula, for their guidance in implementing IPCC processes, their logistical support, their close collaboration on communications, and for enabling the participation of experts from developing countries through the IPCC Trust Fund.

We wish to thank Sue Escott of Escott-Hunt and staff at the UN Foundation for their insight and hard work to ensure the effective communication of the messages in the report. Thanks are expressed to John Schwartz and his team at Soapbox Communications Ltd for graphics design support and for typesetting the final report, in particular Ian Blenkinsop, Margherita Cardoso, Autumn Forecast, Žiga Kropivšek, Sharon Mah, Jenny McCarten, Polly O'Hara, Francesca Romano and Alice Woodward, to Georgie Bowden for her careful compilation of the report index, and to Matt Lloyd, Jenny van der Meijden, and the team at Cambridge University Press for final publication of the report.

We are grateful to the members of the core team at the 14th Session of WG III, especially the IPCC Vice Chairs, WG I and II Vice-Chairs Greg Flato, Jan Fuglestvedt and Mark Howden, WG I, II and SYR TSU members, in particular Nada Caud, Sarah Connors, Melissa Gomis, Tijama Kerscher, Katherine Leitzell, Noëmie Leprince-Ringuet, Sina Löschke, Tom Maycock, Katja Mintenbeck, Komila Nabiyeva, Clotilde Péan, Anna Pirani, Elvira Poloczanska, Jussi Savolainen, and Melinda Tignor, as well as Sophie Berger, Kiane de Kleijne, and Chloe Ludden.

It is a pleasure to acknowledge the tireless work, resilience and good humour of the staff of the WG III TSU throughout the many challenges faced during the assessment cycle. Our thanks go to Raphael Slade, Roger Fradera, Minal Pathak, Alaa Al Khourdajie, Malek Belkacemi, Renée van Diemen, Apoorva Hasija, Géninha Lisboa, Sigourney Luz, Juliette Malley, David McCollum, Shreya Some, and Purvi Vyas, and also to past team members: Elizabeth Huntley, Katie Kissick, Suvadip Neogi and Joanna Portugal-Pereira. Your professionalism, creativity and indomitable spirit has been exemplary and continually inspiring. Finally, on behalf of all participants, we thank colleagues, family and friends for their understanding and support throughout the production of this report, which has taken place during unprecedented times.

Sincerely,

Jim Skea
Co-Chair Working Group III

Priyadarshi R. Shukla
Co-Chair Working Group III

In memoriam

Cristóbal Díaz Morejón

(1949–2021)

Lead Author of Chapter 17 on Accelerating the transition in the context of sustainable development

Cristóbal Díaz Morejón was an internationally renowned expert across a range of environmental disciplines. Over the course of a busy and successful career he led projects on the salinity of soils, water resource management, environmental strategy, desertification and droughts, and energy efficiency, amongst others. He represented Cuba in many international meetings on water resources and sustainable development. In 1994 he was awarded a Medal by the Academy of Sciences of Cuba on its 30th Anniversary, and in 2004, the "Juan Tomas Roig" Medal for 25 years dedicated to research. A contributor to IPCC reports since 2004, he was an intelligent, knowledgeable, dedicated and kind colleague, and will be sorely missed.

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Summary for Policymakers

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This Summary for Policymakers should be cited as:
IPCC, 2022: Summary for Policymakers [P.R. Shukla, J. Skea, A. Reisinger, R. Slade, R. Fradera, M. Pathak, A. Al Khourdajie, M. Belkacemi, R. van Diemen, A. Hasija, G. Lisboa, S. Luz, J. Malley, D. McCollum, S. Some, P. Vyas, (eds.)]. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.001

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

[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}

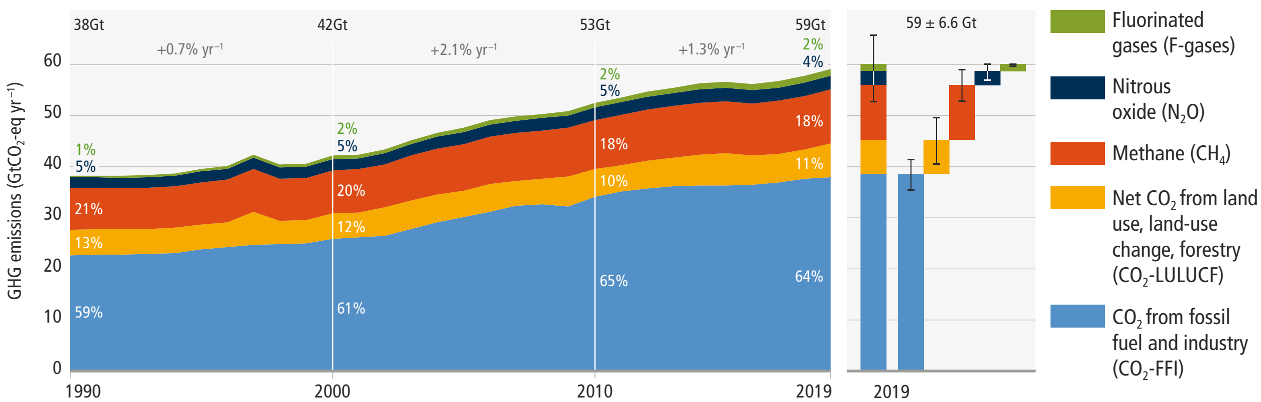
[10] For consistency with WGI, historical cumulative CO_2 emissions from 1850 to 2019 are reported using 68% confidence intervals.

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}

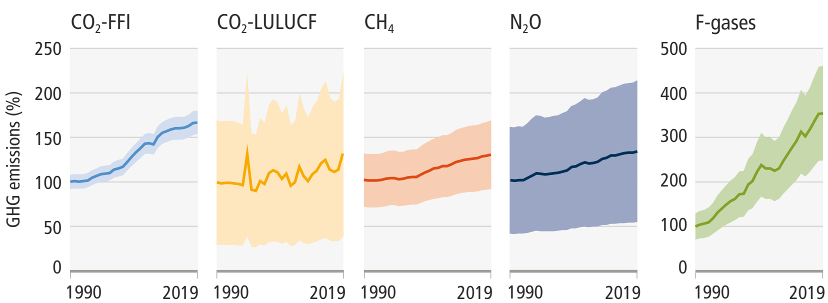
B.1.4 Emissions of CO_2-FFI dropped temporarily in the first half of 2020 due to responses to the COVID-19 pandemic (*high confidence*), but rebounded by the end of the year (*medium confidence*). The annual average CO_2-FFI emissions reduction in 2020 relative to 2019 was about 5.8% [5.1–6.3%], or 2.2 [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.

a. Global net anthropogenic GHG emissions 1990–2019 [(5)]



b. Global anthropogenic GHG emissions and uncertainties by gas – relative to 1990



	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

The solid line indicates central estimate of emissions trends. The shaded area indicates the uncertainty range.

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}

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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}

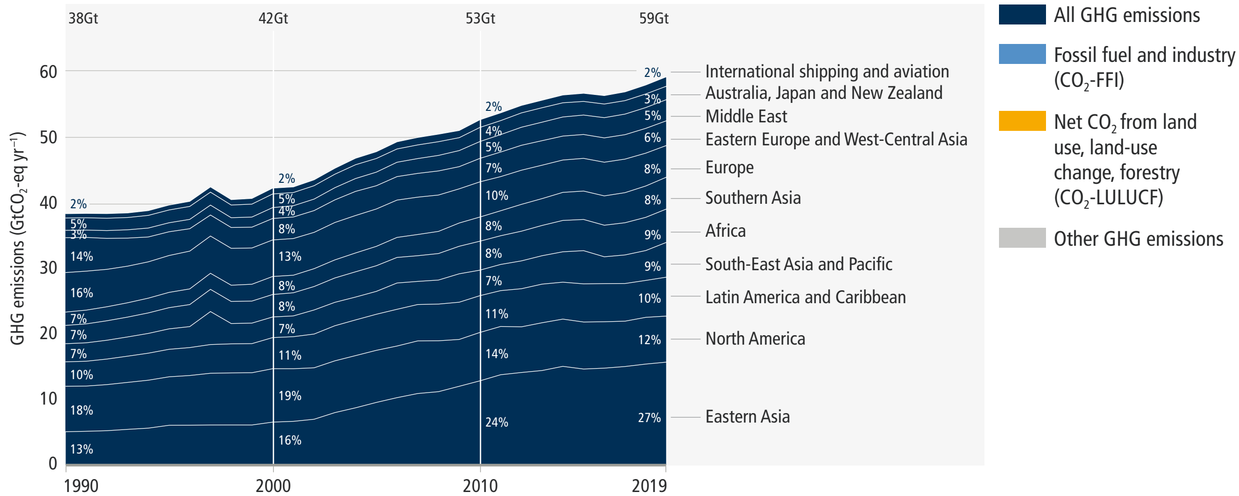
19 In this report, access to modern energy services is defined as access to clean, reliable and affordable energy services for cooking and heating, lighting, communications, and productive uses. {Annex I: Glossary}

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}

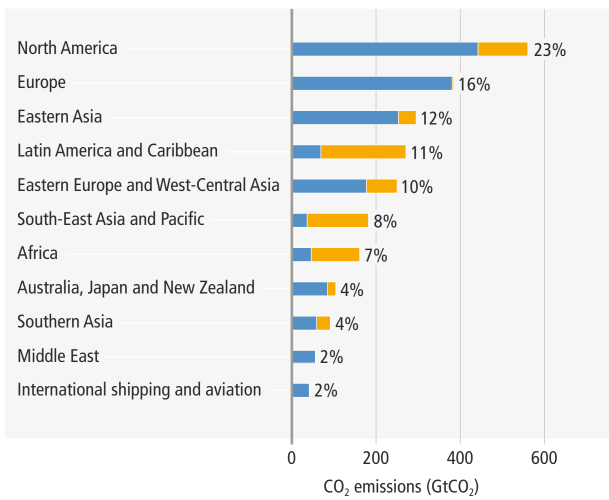
21 Consumption-based emissions refer to emissions released to the atmosphere to generate the goods and services consumed by a certain entity (e.g., a person, firm, country, or region). The bottom 50% of emitters spend less than USD3 PPP (purchasing power parity) per capita per day. The top 10% of emitters (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.

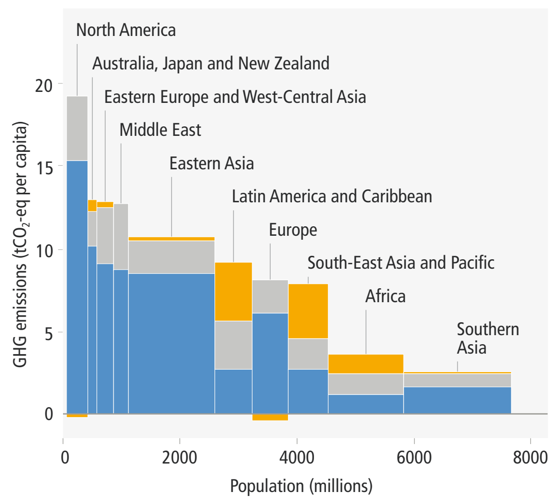
a. Global net anthropogenic GHG emissions by region (1990–2019)



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}

SPM

The unit costs of some forms of renewable energy and of batteries for passenger EVs have fallen, and their use continues to rise.

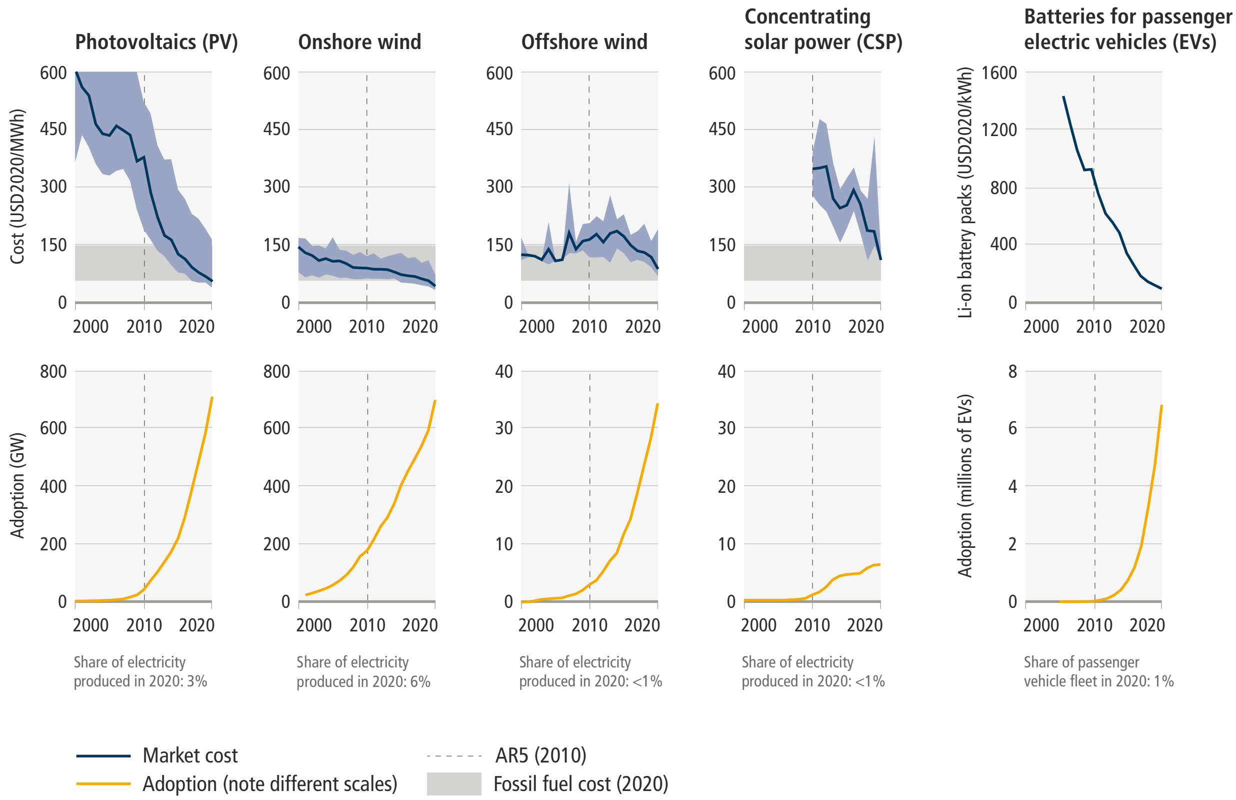


Figure SPM.3 | Unit cost reductions and use in some rapidly changing mitigation technologies. The **top panel** shows global costs per unit of energy (USD per MWh) for some rapidly changing mitigation technologies. Solid blue lines indicate average unit cost in each year. Light blue shaded areas show 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}

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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.

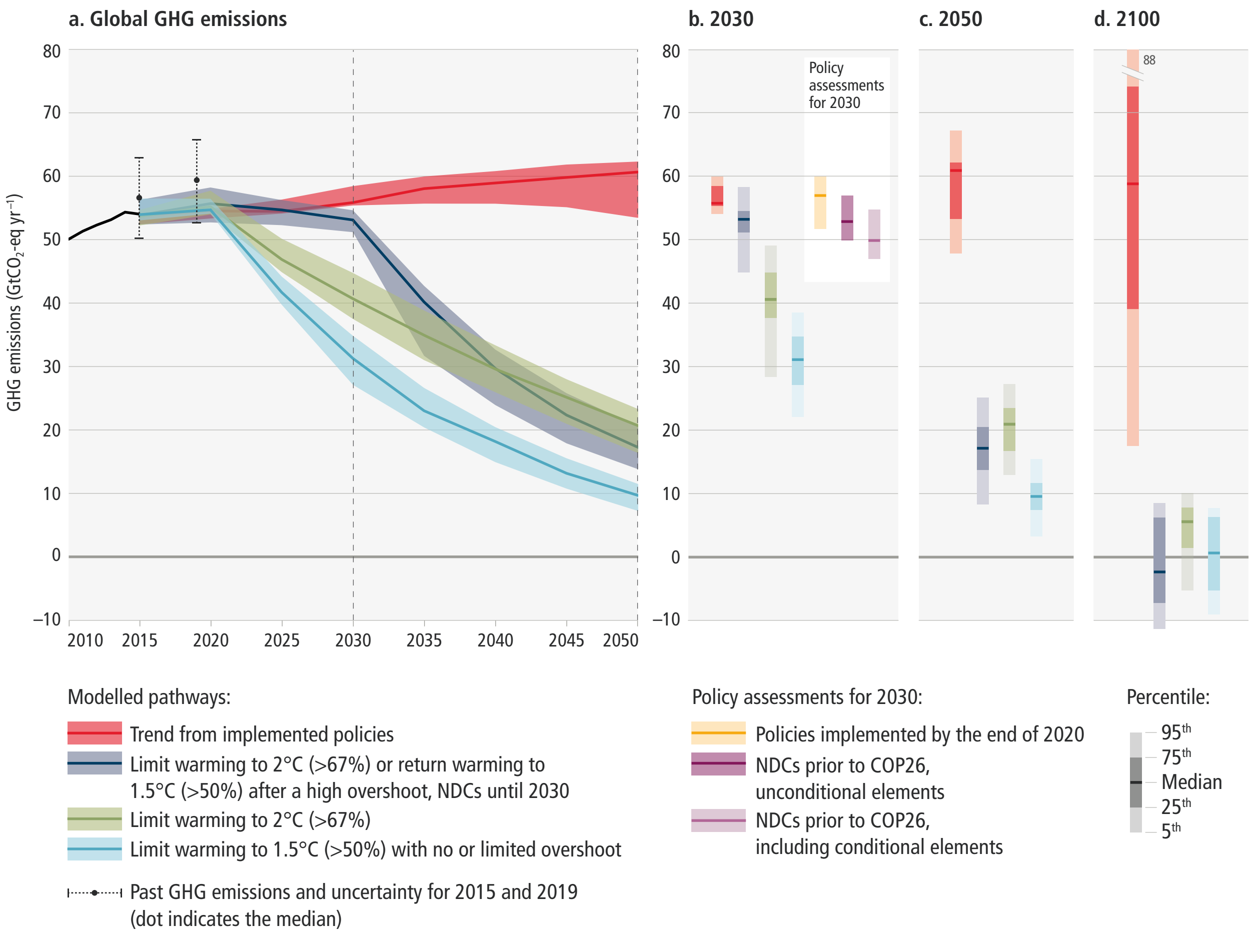

Figure SPM.4 | Global GHG emissions of modelled pathways (funnels in Panel a, and associated bars in Panels b, c, d) and projected emission outcomes from near-term policy assessments for 2030 (Panel b).

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]	2020–2025 (100%) [2020–2030]		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]	2020–2025 (100%) [2020–2030]		…–… (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%) [2020–2090]	2020–2025 (97%)	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%) [2040–…]	2090–2095 (56%)	no net zero		no net zero	4220 [3160–5000]	no net zero	temperature does not peak by 2100	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–…]		no net zero		no net zero	5600 [4910–7450]	no net zero	temperature does not peak by 2100	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%.

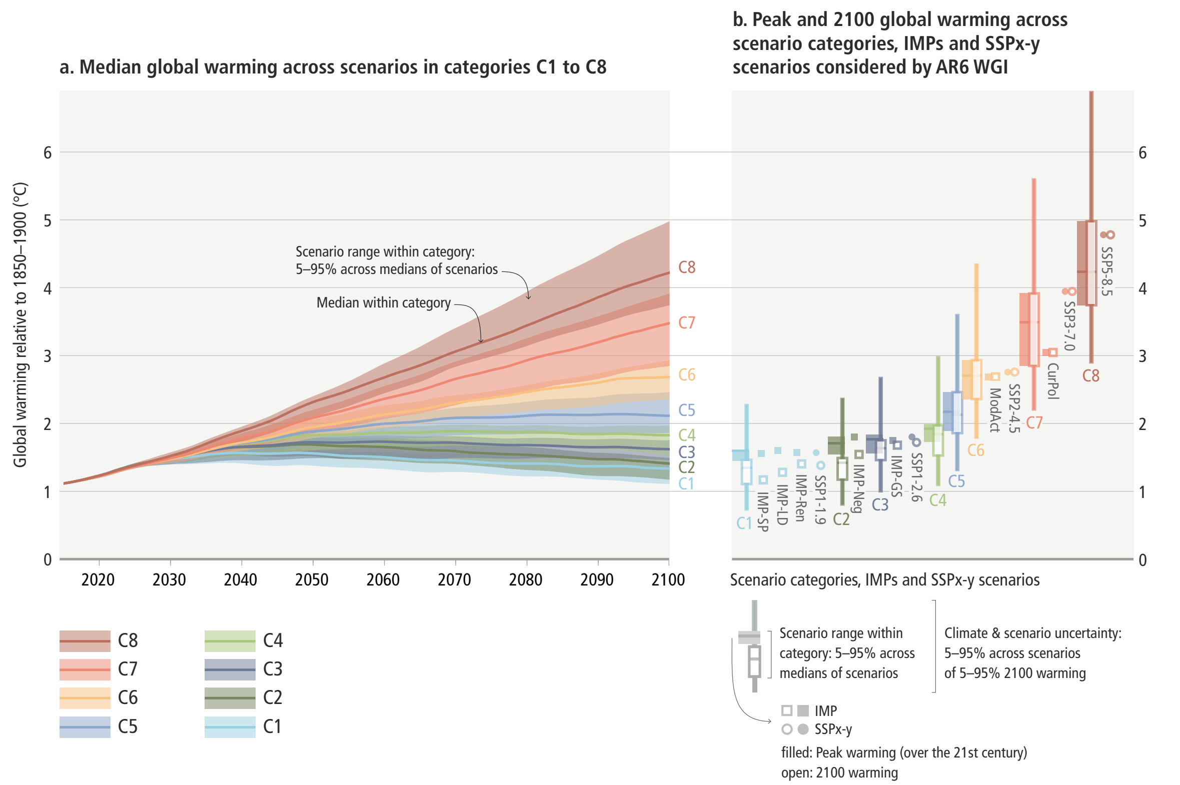
Box SPM.1 (continued)

- 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}

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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.

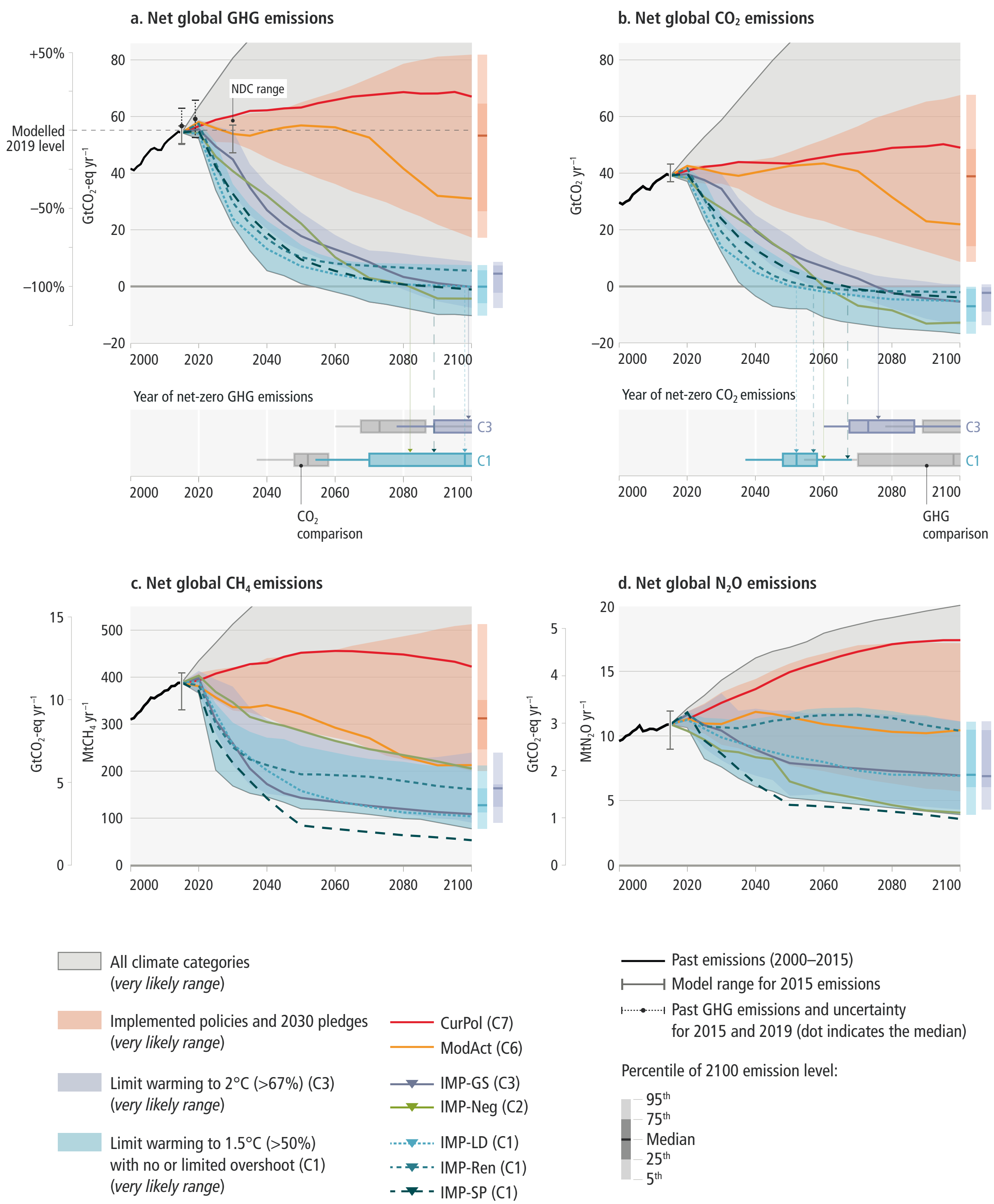

Figure SPM.5 | Illustrative Mitigation Pathways (IMPs) and net zero CO_2 and GHG emissions strategies.

Net zero CO_2 and net zero GHG emissionsare possible through different modelled mitigation pathways.

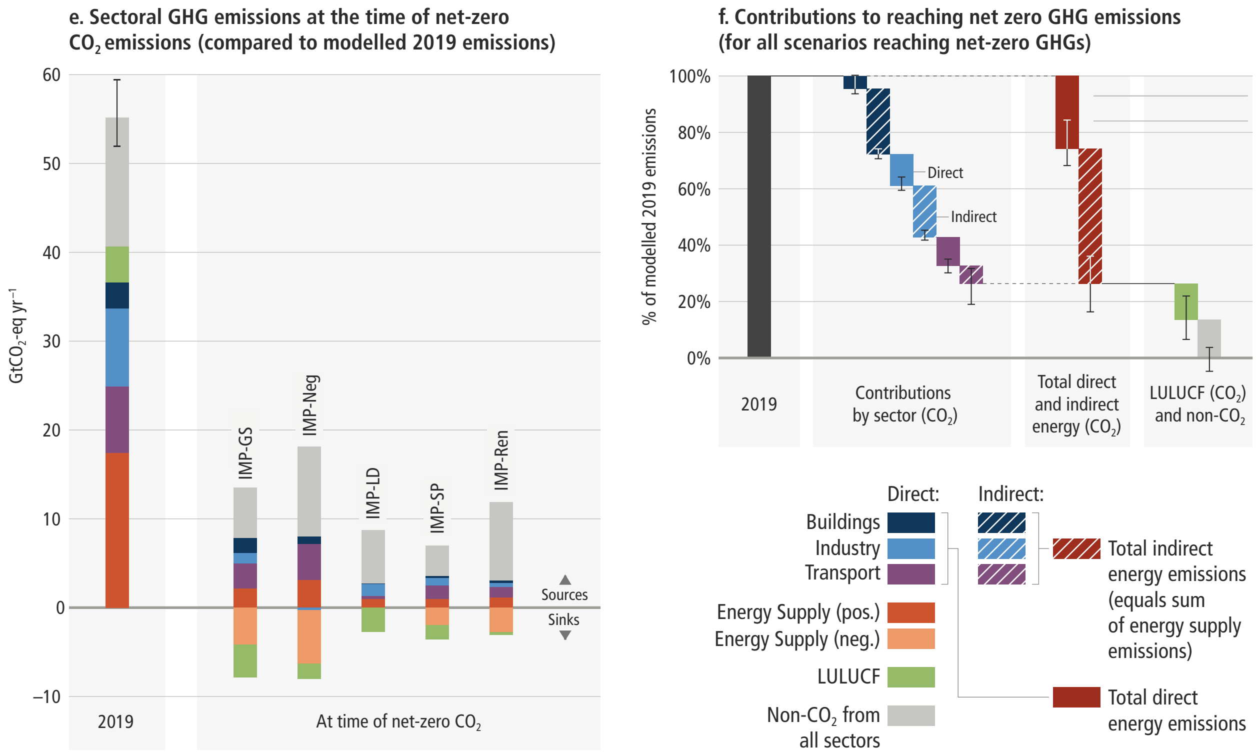

Figure SPM.5 (continued): Illustrative Mitigation Pathways (IMPs) and net zero CO_2 and GHG emissions strategies. Panels a and b show the development of global GHG and CO_2 emissions in modelled global pathways (upper sub-panels) and the associated timing of when GHG and CO_2 emissions reach net zero (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}

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[55] Primary metals refers to virgin metals produced from ore.

SPM

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.

SPM

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

[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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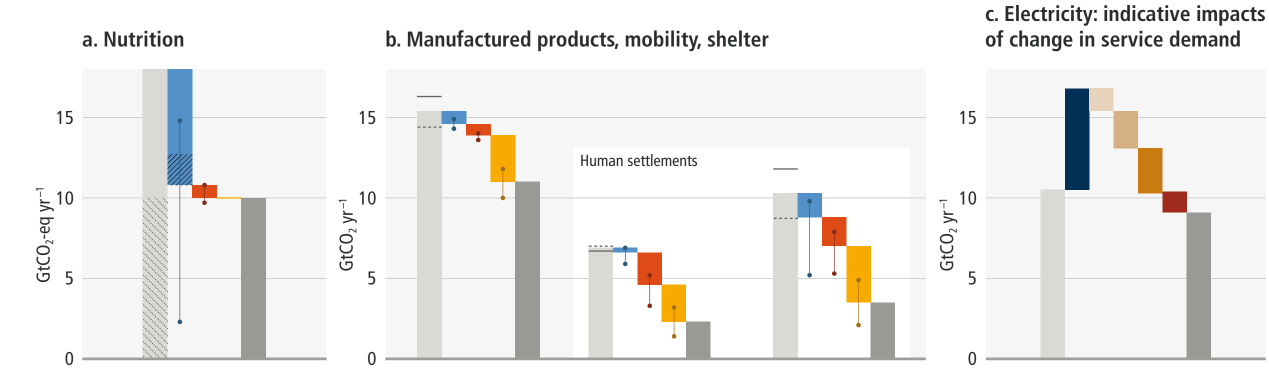
62 'Choice architecture' describes the presentation of choices to consumers, and the impact that presentation has on consumer decision-making.

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.



End-use sectors	Food	Industry	Land transport	Buildings	Electricity
Services for well-being	Nutrition	Manufactured products	Mobility	Shelter	
	Socio-cultural factors	Socio-cultural factors			Additional electrification (+60%)
	Dietary shift (shifting to balanced, sustainable healthy diets), avoidance of food waste and over-consumption	Shift in demand towards sustainable consumption, such as intensive use of longer-lived repairable products	Teleworking or telecommuting; active mobility through walking and cycling	Social practices resulting in energy saving; lifestyle and behavioural changes	Additional emissions from increased electricity generation to enable the end-use sectors' substitution of electricity for fossil fuels, e.g. via heat pumps and electric cars {Table SM5.3; 6.6}
	Infrastructure use	Infrastructure use			Industry; Land transport; Buildings; Load management[2] — Demand-side measures −73%
	Choice architecture[1] and information to guide dietary choices; financial incentives; waste management; recycling infrastructure	Networks established for recycling, repurposing, remanufacturing and reuse of metals, plastics and glass; labelling low-emissions materials and products	Public transport; shared mobility; compact cities; spatial planning	Compact cities; rationalisation of living floor space; architectural design; urban planning (e.g., green roof, cool roof, urban green spaces etc.)	Reduced emissions through demand-side mitigation options (in end-use sectors: buildings, industry and land transport) which has potential to reduce electricity demand[3]
	End-use technology adoption	End-use technology adoption			
	Currently estimates are not available (for lab-based meat and similar options – no quantitative literature available, overall potential considered in socio-cultural factors)	Green procurement to access material-efficient products and services; access to energy-efficient and CO_2 neutral materials	Electric vehicles; shift to more efficient vehicles	Energy efficient building envelopes and appliances; shift to renewables	

Total emissions 2050: Mean ---- IEA-STEPS —— IP_ModAct

- AFOLU
- Direct reduction of food related emissions, excluding reforestation of freed up land
- Total emissions 2050
- Socio-cultural factors
- Infrastructure use
- End-use technology adoption
- Emissions that cannot be avoided or reduced through demand-side options are assumed to be addressed by supply-side options
- Add. electrification
- Industry
- Land transport
- Buildings
- Load management

[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.

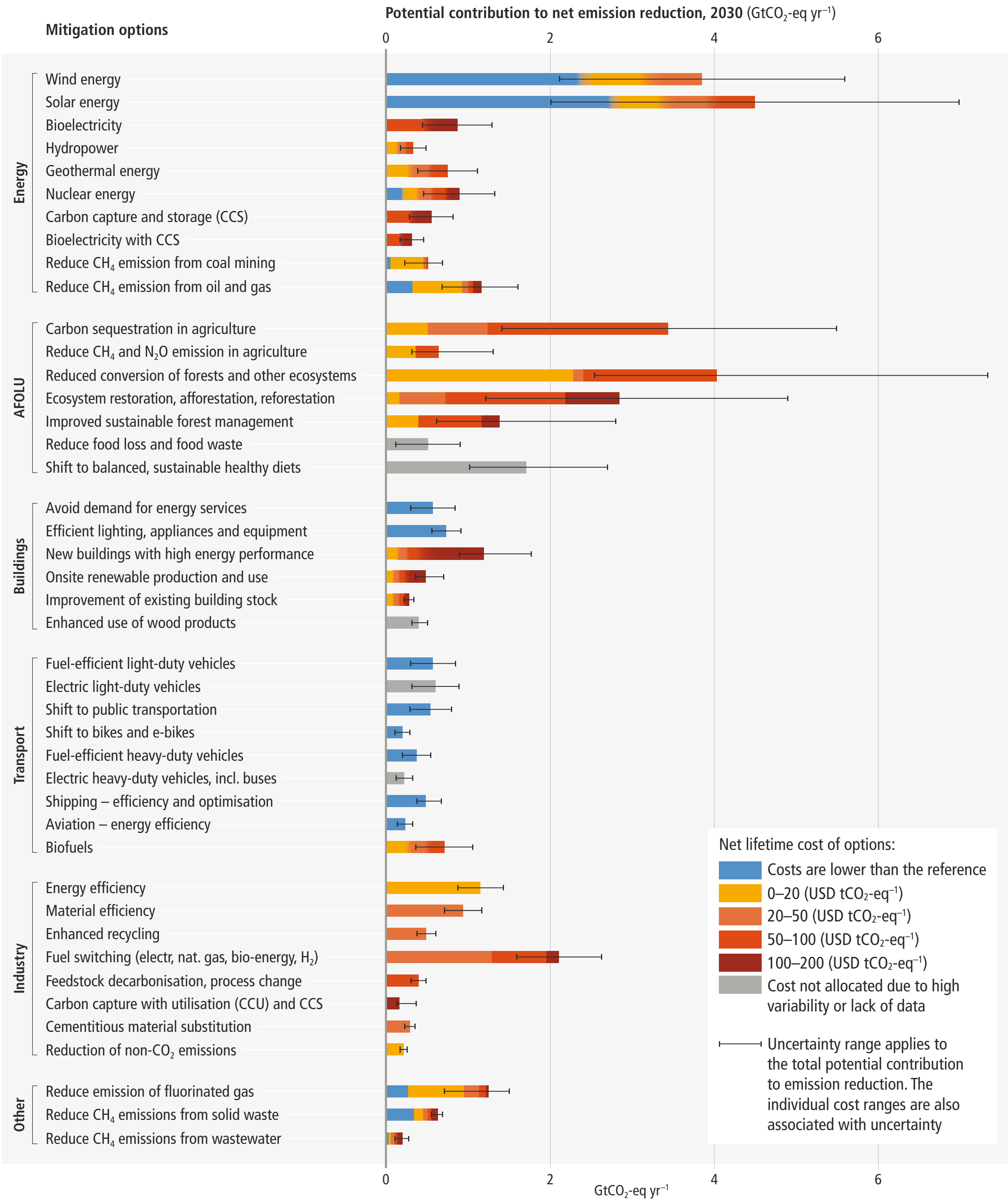

Figure SPM.7 | Overview of mitigation options and their estimated ranges of costs and potentials in 2030.

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.

SPM

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.

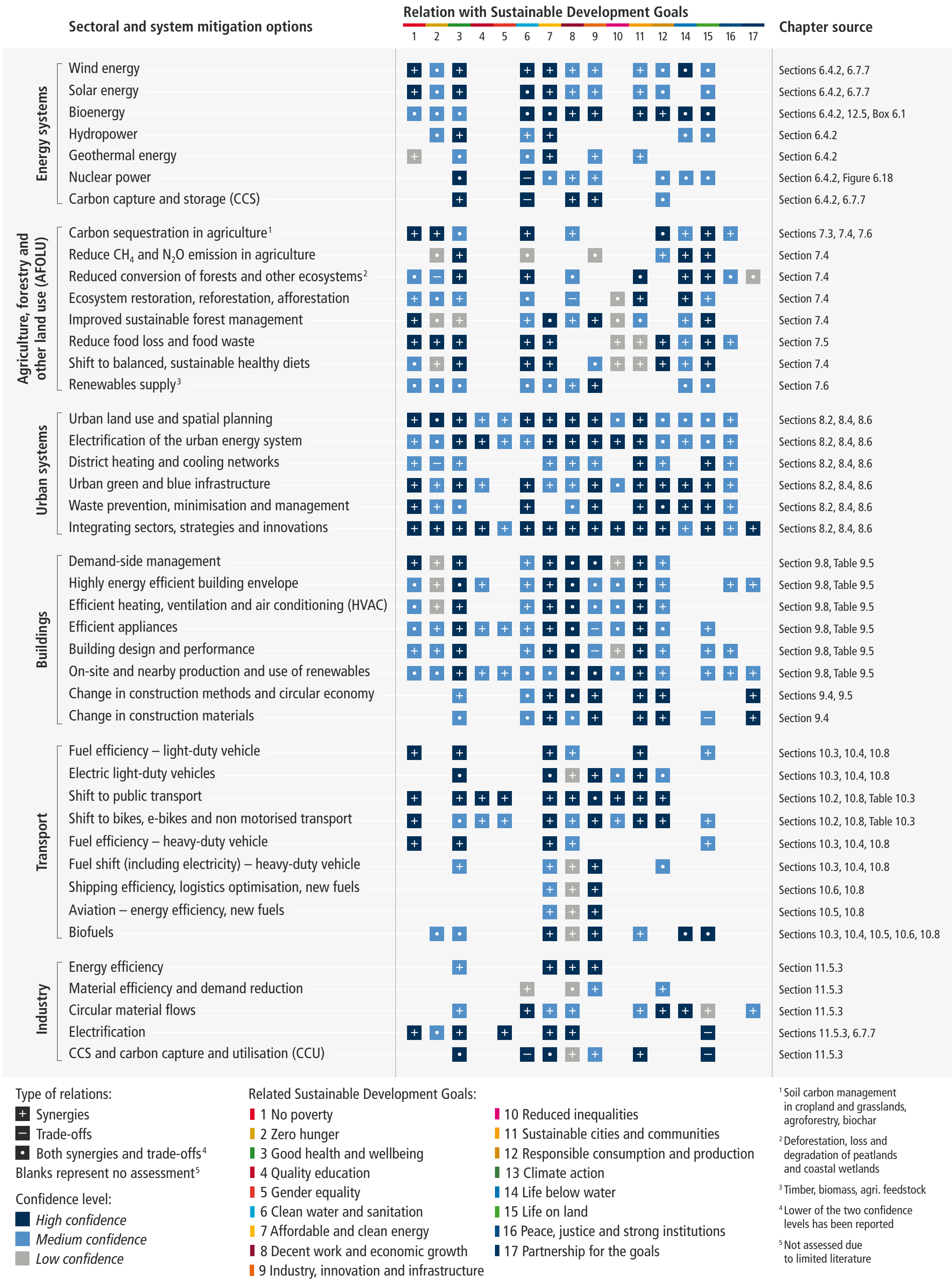

Figure SPM.8 | Synergies and trade-offs between sectoral and system mitigation options and the SDGs.

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}

SPM

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}

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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}

Technical Summary

TS

Technical Summary

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This Technical Summary should be cited as:
M. Pathak, R. Slade, P.R. Shukla, J. Skea, R. Pichs-Madruga, D. Ürge-Vorsatz,2022: Technical Summary. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.002.

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TS.1 Introduction

The Working Group III (WGIII) contribution to the IPCC's Sixth Assessment Report (AR6) assesses the current state of knowledge on the scientific, technological, environmental, economic and social aspects of climate change mitigation. It builds on previous IPCC reports, including the WGIII contribution to the IPCC's Fifth Assessment Report (AR5) and the three Special Reports of the Sixth Assessment cycle on: Global Warming of 1.5°C (SR1.5); Climate Change and Land (SRCCL); and the Ocean and Cryosphere in a Changing Climate (SROCC).[1]

The report assesses new literature, methodological and recent developments, and changes in approaches towards climate change mitigation since the IPCC AR5 report was published in 2014.

The global science and policy landscape on climate change mitigation has evolved since AR5. The development of the literature reflects, among other factors, the UN Framework Convention on Climate Change (UNFCCC), the outcomes of its Kyoto Protocol and the goals of the Paris Agreement {13, 14, 15}, and the UN 2030 Agenda for Sustainable Development {1, 4, 17}. Literature further highlights the growing role of non-state and sub-national actors in the global effort to address climate change, including cities, businesses, citizens, transnational initiatives and public-private entities {5, 8, 13}. It draws attention to the decreasing cost of some low-emission technologies {2, 6, 12} and the evolving role of international cooperation {14}, finance {15} and innovation {16}. Emerging literature examines the global spread of climate policies, strengthened mitigation actions in developing countries, sustained reductions in greenhouse gas (GHG) emissions in some developed countries and the continuing challenges for mitigation. {2, 13}

There are ever closer linkages between climate change mitigation, development pathways and the pursuit of Sustainable Development Goals (SDGs). Development pathways largely drive GHG emissions and hence shape the mitigation challenge and the portfolio of available responses {4}. The co-benefits and risks of mitigation responses also differ according to stages of development and national capabilities {1, 2, 3, 4, 13}. Climate change mitigation framed in the context of sustainable development, equity, and poverty eradication, and rooted in the development aspirations of the society within which they take place, will be more acceptable, durable and effective. {1, 4, 17}

This report includes new assessment approaches that go beyond those evaluated in the previous IPCC WGIII reports. In addition to sectoral and systems chapters {6, 7, 8, 9, 10, 11}, this report includes, for the first time, chapters dedicated to cross-sectoral perspectives {12}, demand, services and social aspects of mitigation (Box TS.11) {5}, and innovation, technology development and transfer {16}. The assessment of future pathways combines a forward-looking assessment of near- to medium-term perspectives up to 2050, including ways of shifting development pathways towards sustainability {4}, with an assessment of long-term outcome-oriented pathways up to 2100 {3}. Collaboration between the IPCC Working Groups is reflected in Cross-Working Group boxes which address topics such as the economic benefits from avoided impacts along mitigation pathways {Cross-Working Group Box 1 in Chapter 3}, climate change and urban areas {Cross-Working Group Box 2 in Chapter 8}, mitigation and adaptation through the bioeconomy {Cross-Working Group Box 3 in Chapter 12} and Solar Radiation Modification (SRM) {Cross-Working Group Box 4 in Chapter 14}. This assessment also gives greater attention than AR5 to social, economic and environmental dimensions of mitigation actions, and institutional, legal and financial aspects. {5, 13, 14, 15}

The report draws from literature on broad and diverse analytic frameworks across multiple disciplines. These include, *inter alia*: economic and environmental efficiency {1}; ethics and equity {4, 5, 17}; innovation and the dynamics of socio-technical transitions {16}; and socio-political-institutional frameworks {1, 5, 13, 14, 17}. These help to identify synergies and trade-offs with Sustainable Development Goals (SDGs), challenges and windows of opportunity for action including co-benefits, and equitable transitions at local, national and global scales. {1, 5, 13, 14, 16}

This Technical Summary (TS) of the WGIII contribution to the IPCC's Sixth Assessment Report (AR6) broadly follows the report chapter order and is structured as follows.

- TS Section 2 (TS.2) sets out how the global context for mitigation has changed and summarises signs of progress and continuing challenges.
- TS Section 3 (TS.3) evaluates emission trends and drivers including recent sectoral, financial, technological and policy developments.
- TS Section 4 (TS.4) identifies mitigation and development pathways in the near and mid-term to 2050, and in the longer term to 2100. This section includes an assessment of how mitigation pathways deploying different portfolios of mitigation responses are consistent with limiting global warming to different levels.
- TS Section 5 (TS.5) summarises recent advances in knowledge across sectors and systems including energy, urban and other settlements, transport, buildings, industry, and agriculture, forestry and other land-use (AFOLU).
- TS Section 6 (TS.6) examines how enabling conditions including behaviour and lifestyle, policy, governance and institutional capacity, international cooperation, finance, and innovation and technology can accelerate mitigation in the context of sustainable development.
- TS Section 7 (TS.7) evaluates how mitigation can be achieved in the context of sustainable development, while maximising co-benefits and minimising risks.

1 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).

Throughout this Technical Summary the validity of findings, confidence in findings, and cross-references to Technical Summary sections, figures and tables are shown in ( ) brackets.[2] *References to the underlying report are shown in { } brackets.*

2 Each finding is grounded in an evaluation of the underlying evidence, typeset in italics. The validity of a finding is evaluated in terms of the evidence quality – '*limited*', '*medium*', '*robust*' – and the degree of agreement between sources – '*low*', '*medium*', '*high*'. A level of confidence is expressed using five qualifiers: *very low*, *low*, *medium*, *high* and *very high*. Generally, the level of confidence is highest where there is robust evidence from multiple sources and high agreement. For findings with, for example, '*robust evidence*, *medium agreement*', a confidence statement may not always be appropriate. The assessed likelihood of an outcome or a result is described as: *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 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.

TS.2 The Changed Global Context, Signs of Progress and Continuing Challenges

Since the IPCC's Fifth Assessment Report (AR5), important changes that have emerged include the specific objectives established in the Paris Agreement of 2015 (for temperature, adaptation and finance), rising climate impacts, and higher levels of societal awareness and support for climate action (*high confidence*). Meeting the long-term temperature goal in the Paris Agreement, however, implies a rapid inflection in GHG emission trends and accelerating decline towards 'net zero'. This is implausible without urgent and ambitious action at all scales. {1.2, 1.3, 1.5, 1.6, Chapters 3 and 4}

Effective and equitable climate policies are largely compatible with the broader goal of sustainable development and efforts to eradicate poverty as enshrined in the UN 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs), notwithstanding trade-offs in some cases (*high confidence*). Taking urgent action to combat climate change and its impacts is one of the 17 SDGs (SDG 13). However, climate change mitigation also has synergies and/or trade-offs with many other SDGs. There has been a strong relationship between development and GHG emissions, as historically both per-capita and absolute emissions have risen with industrialisation. However, recent evidence shows countries can grow their economies while reducing emissions. Countries have different priorities in achieving the SDGs and reducing emissions as informed by their respective national conditions and capabilities. Given the differences in GHG emissions contributions, degree of vulnerability and impacts, as well as capacities within and between nations, equity and justice are important considerations for effective climate policy and for securing national and international support for deep decarbonisation. Achieving sustainable development and eradicating poverty would involve effective and equitable climate policies at all levels from local to global scale. Failure to address questions of equity and justice over time can undermine social cohesion and stability. International cooperation can enhance efforts to achieve ambitious global climate mitigation in the context of sustainable development. Pathways that illustrate movement towards fulfilling the SDGs are shown in Figure TS.1. {1.4, 1.6, Chapters 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13 and 17}

The transition to a low-carbon economy depends on a wide range of closely intertwined drivers and constraints, including policies and technologies where notable advances over the past decade have opened up new and large-scale opportunities for deep decarbonisation, and for alternative development pathways which could deliver multiple social and developmental goals (*high confidence*). Drivers for, and constraints on, low-carbon societal transitions comprise economic and technological factors (the means by which services such as food, heating and shelter are provided and for whom, the emissions intensity of traded products, finance and investment), socio-political issues (political economy, equity and fairness, social innovation and behaviour change), and institutional factors (legal framework and institutions, and the quality of international cooperation). In addition to being deeply intertwined, all the factors matter to varying degrees, depending on the prevailing social, economic, cultural and political context. They often both drive and inhibit transitions at the same time, within and across different scales. The development and deployment of innovative technologies and systems at scale are important for achieving deep decarbonisation, and in recent years, the cost of several low-carbon technologies has declined sharply as deployment has risen rapidly. (Figure TS.7) {1.3, 1.4, Chapters 2, 4, 5, 13,14}

Accelerating mitigation to prevent dangerous anthropogenic interference with the climate system will require the integration of broadened assessment frameworks and tools that combine multiple perspectives, applied in a context of multi-level governance (*high confidence*). Analysing a challenge on the scale of fully decarbonising our economies entails integration of multiple analytic frameworks. Approaches to risk assessment and resilience, established across IPCC Working Groups, are complemented by frameworks for probing the challenges in implementing mitigation. *Aggregate frameworks* include cost-effectiveness analysis towards given objectives, and cost-benefit analysis, both of which have been developing to take fuller account of advances in understanding risks and innovation, the dynamics of sectors and systems and of climate impacts, and welfare economic theory including growing consensus on long-term discounting. *Ethical frameworks* consider the fairness of processes and outcomes which can help ameliorate distributional impacts across income groups, countries and generations. *Transition and transformation frameworks* explain and evaluate the dynamics of transitions to low-carbon systems arising from interactions amongst levels. *Psychological, behavioural and political frameworks* outline the constraints (and opportunities) arising from human psychology and the power of incumbent interests. A comprehensive understanding of climate mitigation must combine these multiple frameworks. Together with established risk frameworks, these collectively help to explain potential synergies and trade-offs in mitigation, implying a need for a wide portfolio of policies attuned to different actors and levels of decision-making, and underpin 'just transition' strategies in diverse contexts. {1.2.2, 1.7, 1.8, Figure 1.7}

The speed, direction, and depth of any transition will be determined by choices in the environmental, technological, economic, socio-cultural and institutional realms (*high confidence*). Transitions in specific systems can be gradual or can be rapid and disruptive. The pace of a transition can be impeded by 'lock-in' generated by existing physical capital, institutions, and social norms. The interaction between politics, economics and power relationships is central to explaining why broad commitments do not always translate to urgent action. At the same time, attention to, and support for, climate policies and low-carbon societal transitions has generally increased, as the impacts have become more salient. Both public and private financing and financial structures strongly affect the scale and balance of high- and low-carbon investments. Societal and behavioural norms, regulations and institutions are essential conditions to accelerate low-carbon transitions in multiple sectors, whilst addressing distributional concerns endemic to any major transition. The COVID-19 pandemic has also had far-reaching impacts on the global economic and social system, and recovery will present both challenges and opportunities for climate mitigation. (Box TS.1) {1.3, Box 1.1, 1.4, 1.8, Chapters 2, 3, 4, 5, 15, 17}

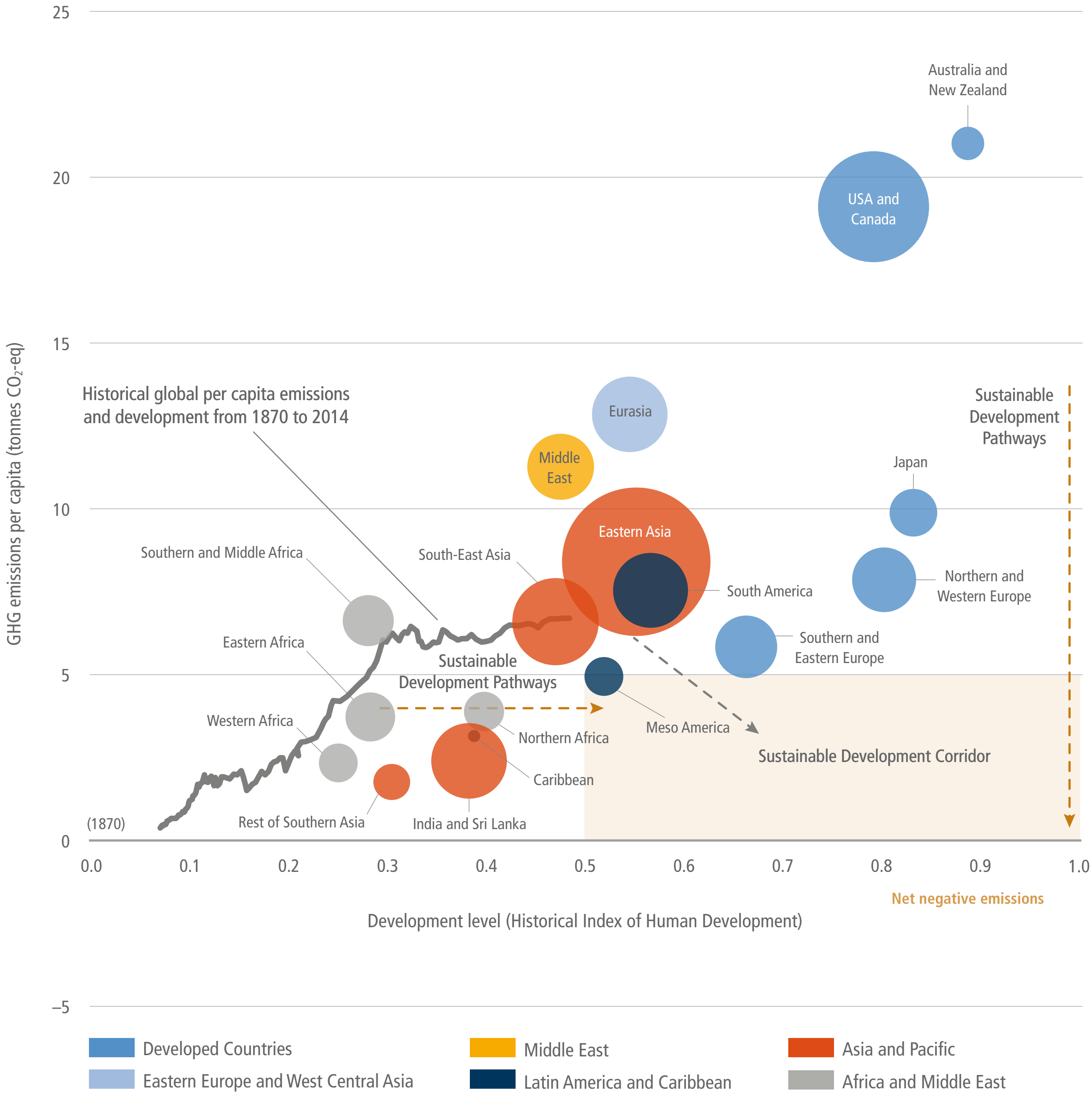


Figure TS.1 | Sustainable development pathways towards fulfilling the Sustainable Development Goals. The graph shows global average per-capita GHG emissions (vertical axis) and relative 'Historic Index of Human Development' (HIHD) levels (horizonal) have increased globally since the industrial revolution (grey line). The bubbles on the graph show regional per-capita GHG emissions and human development levels in the year 2015, illustrating large disparities. Pathways towards fulfilling the Paris Agreement (and SDG 13) involve global average per-capita GHG emissions below about 5 tCO_2-eq by 2030. Likewise, to fulfil SDGs 3, 4 and 8, HIHD levels (see footnote 7 in Chapter 1) need to be at least 0.5 or greater. This suggests a 'sustainable development zone' for year 2030 (in pale brown); the in-figure text also suggests a 'sustainable development corridor', where countries limit per-capita GHG emissions while improving levels of human development over time. The emphasis of pathways into the sustainable development zone differ (dashed brown arrows), but in each case transformations are needed in how human development is attained while limiting GHG emissions.

Achieving the global transition to a low-carbon, climate-resilient and sustainable world requires purposeful and increasingly coordinated planning and decisions at many scales of governance including local, sub-national, national and global levels (*high confidence*). Accelerating mitigation globally would imply strengthening policies adopted to date, expanding the effort across options, sectors, and countries, and broadening responses to include more diverse actors and societal processes at multiple – including international – levels. The effective governance of climate change entails strong action across multiple jurisdictions and decision-making levels, including regular evaluation and learning. Choices that cause climate change as well as the processes for making and implementing relevant decisions involve a range of non-nation state actors such as cities, businesses, and civil society organisations. At global, national and sub-national levels, climate change actions are interwoven with, and embedded in, the context of much broader social, economic and political goals. Therefore, the governance required to address climate change has to navigate power, political, economic, and social dynamics at all levels of decision-making. Effective climate-governing institutions, and openness to experimentation on a variety of institutional arrangements, policies and programmes can play a vital role in engaging stakeholders and building momentum for effective climate action. {1.4, 1.9, Chapters 8, 13, 15, 17}

Table TS.1 | Signs of progress and continuing challenges.

Signs of progress	Continuing challenges
Emissions trends	
The rate of global GHG emissions growth has slowed in recent years, from 2.1% yr^{-1} between 2000 and 2009, to 1.3% yr^{-1} in between 2010 and 2019. (TS.3) {2.2}	**GHG emissions have continued to grow at high absolute rates**. Emissions increased by 8.9 $GtCO_2$-eq from 2000 to 2009 and by 6.5 $GtCO_2$-eq from 2010 to 2019, reaching 59 $GtCO_2$-eq in 2019. (TS.3) {2.2}
A growing number of countries have reduced both territorial carbon dioxide (CO_2) and GHG emissions and consumption-based CO_2 emissions in absolute terms for at least 10 years. These include mainly European countries, some of which have reduced production-based GHG emissions by a third or more since peaking. Some countries have achieved several years of rapid sustained CO_2 reduction rates of 4% yr^{-1}. (TS.3) {2.2}	**The combined emissions reductions achieved by some countries have been outweighed by rapid emissions growth elsewhere**, particularly among developing countries that have grown from a much lower base of per-capita emissions. Uncertainties in emissions levels and changes over time prevents a precise assessment of reductions in some cases. The per-capita emissions of developed countries remain high, particularly in Australia, Canada, and the United States of America. {2.2}
Lockdown policies in response to COVID-19 led to an estimated global drop of 5.8% in CO_2 emissions in 2020 relative to 2019. Energy demand reduction occurred across sectors, except in residential buildings due to teleworking and homeschooling. The transport sector was particularly impacted and international aviation emissions declined by 45%. (Box TS.1) {2.2}	**Atmospheric CO_2 concentrations continued to rise in 2020 and emissions have already rebounded as lockdown policies are eased.** Economic recovery packages currently include support for fossil fuel industries. (Boxes TS.1 and TS.8)
Sectors	
Multiple low-carbon electricity generation and storage technologies have made rapid progress: costs have reduced, deployment has scaled up, and performance has improved. These include solar photovoltaics (PV), onshore and offshore wind, and batteries. In many contexts solar PV and onshore wind power are now competitive with fossil-based generation. (TS.3) {2.5, 6.3}	**Although deployment is increasing rapidly, low-carbon electricity generation deployment levels and rates are currently insufficient to meet stringent climate goals.** The combined market share of solar PV and wind generation technologies are still below 10%. Global low-carbon electricity generation will have to reach 100% by 2050, which is challenged by the continuous global increase in electricity demand. The contribution of biomass has absolute limits. (TS.5) {2.5}
The rate of emissions growth from coal slowed since 2010 as coal power plants were retired in the US and Europe, fewer new plants were added in China, and a large number of planned global plants were scrapped or converted to co-firing with biomass. (TS.3) {2.7, 6.3}	**Global coal emissions may not have peaked yet,** and a few countries and international development banks continue to fund and develop new coal capacity, especially abroad. The lifetime emissions of current fossil-based energy infrastructures may already exceed the remaining carbon budget for keeping warming below 1.5°C. (TS.3) {2.2, 2.7, 6.7}
Deforestation has declined since 2010 and net forest cover increased. Government initiatives and international moratoria were successful in reducing deforestation in the Amazon between 2004 and 2015, while regrowth and regeneration occurred in Europe, Eurasia and North America. (TS.5.6.1) {7.3.1}	**The long-term maintenance of low deforestation rates is challenging.** Deforestation in the Amazon has risen again over the past four years. Other parts of the world also face steady, or rapidly increasing, deforestation. {7.3.1}
Electrification of public transport services is demonstrated as a feasible, scalable and affordable mitigation option to decarbonise mass transportation. Electric vehicles (e-vehicles) are the fastest growing segment of the automobile industry, having achieved double-digit market share by 2020 in many countries. When charged with low-carbon electricity, these vehicles can significantly reduce emissions. {10.4}	**Transport emissions have remained roughly constant, growing at an average of 2% yr^{-1} between 2010 and 2019** due to the persistence of high travel demand, heavier vehicles, low efficiencies, and car-centric development. The full decarbonisation of e-vehicles requires that they are charged with zero-carbon electricity, and that car production, shipping, aviation and supply chains are decarbonised. (TS.3) {2.4}
There has been a significant global transition from coal and biomass use in buildings towards modern energy carriers and efficient conversion technologies. This led to efficiency improvements and some emissions reductions in developed countries, as well as significant gains in health and well-being outcomes in developing regions. Nearly zero energy buildings (nZEB) or low-energy buildings are achievable in all regions and climate zones for both new and existing buildings. {9.3, 9.8}	**There is a significant lock-in risk in all regions given the long lifespans of buildings and the low ambition of building policies.** This is the case for both existing buildings in developed countries, and also for new buildings in developing countries that are also challenged by the lack of technical capacity and effective governance. Emissions reductions in developed countries have been outweighed by the increase in population growth, floor area per capita and the demand for electricity and heat. {9.3, 9.9}
The decarbonisation of most industrial processes has been demonstrated using technologies that include electricity and hydrogen for energy and feedstocks, carbon capture and utilisation technologies, and innovation in circular material flows. (TS.5.5) {11.2}	**Industry emissions continue to increase, driven by a strong global demand for basic materials.** Without reductions in material demand growth and a very rapid scale-up of low-carbon innovations, the long lifetimes of industrial capital stock risks locking-in emissions for decades to come. (TS.5.5) {11.2}

Table TS.1 (continued):

Signs of progress	Continuing challenges
Policies and investment	
The Paris Agreement established a new global policy architecture to meet stringent climate goals, while avoiding many areas of deadlock that had arisen in trying to extend the Kyoto Protocol. (TS.6.3)	**Current national pledges under the Paris Agreement[3] are insufficient to limit warming to 1.5°C (>50%) with no or limited overshoot, and would require an abrupt acceleration of mitigation efforts after 2030 to limit warming to 2°C (>67%).** (TS.6.3)
Most wealthy countries, and a growing list of developing countries, have signalled an intention to achieve net zero GHG (or net zero CO_2) emissions by mid-century. National economy-wide GHG emissions targets covered 90% of global emissions in 2020 compared to 49% in 2010. Direct and indirect climate legislation has also steadily increased and this is supported by a growing list of financial investors. (TS.6.2)	**Many net-zero targets are ambiguously defined, and the policies needed to achieve them are not yet in place.** Opposition from status quo interests, as well as insufficient low-carbon financial flows, act as barriers to establishing and implementing stringent climate policies covering all sectors. (Box TS.6) {13.4}
The global coverage of mandatory policies – pricing and regulation – has increased, and sectoral coverage of mitigation policies has expanded. Emission trading and carbon taxes now cover over 20% of global CO_2 emissions. Allowance prices as of 1 April 2021 ranged from just over USD1 to USD50, covering between 9% and 80% of a jurisdiction's emissions {13.6.3}. Many countries have introduced sectoral regulations that block new investment in fossil fuel technologies. (TS.6)	**There is incomplete global policy coverage of non-CO_2 gases, CO_2 from industrial processes, and emissions outside the energy sector.** Few of the world's carbon prices are at a level consistent with various estimates of the carbon price needed to limit warming to 2°C or 1.5°C. {13.6}
There has been a marked increase in civic and private engagement with climate governance. This includes business measures to limit emissions, invest in reforestation and develop carbon-neutral value chains such as using wood for construction. There is an upsurge in climate activism, and growing engagement of groups such as labour unions {1.3.3, 5.2.3}. The media coverage of climate change has also grown steadily across platforms and has generally become more accurate over time. (TS.6.2)	**There is no conclusive evidence that an increase in engagement results in overall pro-mitigation outcomes.** A broad group of actors influence how climate governance develops over time, including a range of civic organisations, encompassing both pro-and anti-climate action groups. Accurate transference of the climate science has been undermined significantly by climate change counter-movements, in both legacy and new/social media environments through misinformation. (TS.6.2)

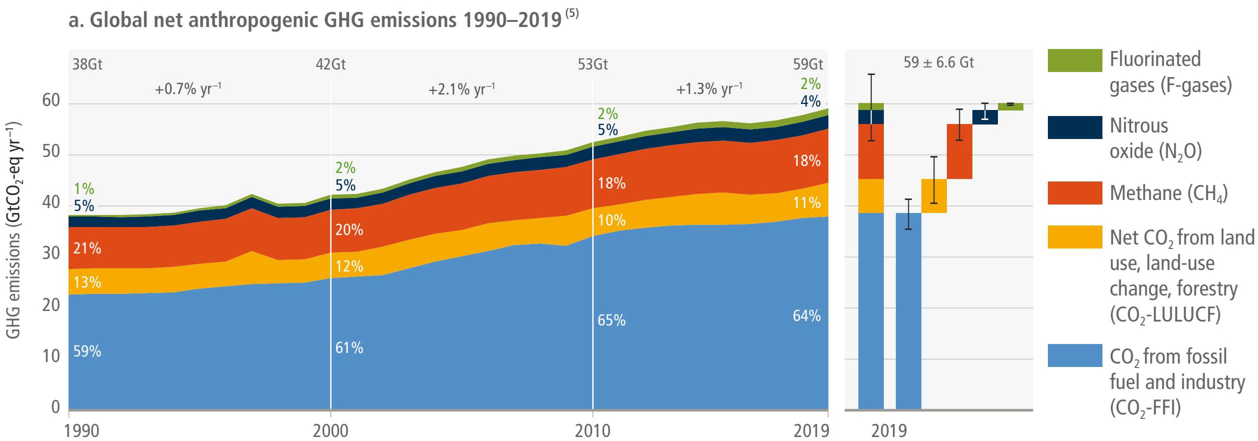
GHG emissions continued to rise to 2019, although the growth of global GHG emissions has slowed over the past decade (*high confidence*). Delivering the updated Nationally Determined Contributions (NDCs) to 2030 would turn this into decline, but the implied global emissions by 2030, still exceed pathways consistent with 1.5°C by a large margin and are near the upper end of the range of modelled pathways that limit warming to 2°C (>67%) or below. In all chapters of this report there is evidence of progress towards deeper mitigation, but there remain many obstacles to be overcome. Table TS.1 summarises some of the key signs of progress in emission trends, sectors, policies and investment, as well as the challenges that persist.

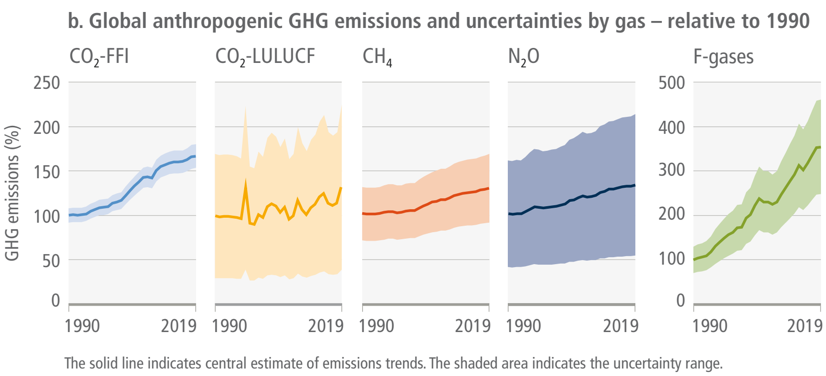
3 Current NDCs refer to Nationally Determined Contributions submitted to the UNFCCC, as well as publicly announced but not yet submitted mitigation pledges with sufficient detail on targets, reflected in studies published up to 11 October 2021. Revised NDCs submitted or announced after 11 October 2021 are not included. Intended Nationally Determined Contributions (INDCs) were converted to NDCs as countries ratified the Paris Agreement. Original INDCs and NDCs refer to those submitted to the UNFCCC in 2015 and 2016.

TS.3 Emission Trends and Drivers

Global net anthropogenic GHG emissions during the decade 2010–2019 were higher than any previous time in human history (*high confidence*). Since 2010, GHG emissions have continued to grow reaching 59 ± 6.6 $GtCO_2$-eq in 2019,[4] but the average annual growth in the last decade (1.3%, 2010–2019) was lower than in the previous decade (2.1%, 2000–2009) (*high confidence*). Average annual GHG emissions were 56 $GtCO_2$-eq yr^{-1} for 2010–2019 (the highest decadal average on record) growing by about 9.1 $GtCO_2$-eq yr^{-1} from the previous decade (2000–2009) (*high confidence*). (Figure TS.2) {2.2.2, Table 2.1, Figure 2.5}

Emissions growth has varied, but has persisted, across all groups of greenhouse gases (*high confidence*). The average annual emission levels of the last decade (2010–2019) were higher than in any previous decade for each group of greenhouse gases (*high confidence*). In 2019, CO_2 emissions were 45 ± 5.5 $GtCO_2$,[5] methane (CH_4) 11 ± 3.2 $GtCO_2$-eq, nitrous oxide (N_2O) 2.7 ± 1.6 $GtCO_2$-eq and fluorinated gases (F-gases[6]) 1.4 ± 0.41 $GtCO_2$-eq. Compared to 1990, the magnitude and speed of these increases differed across gases: CO_2 from fossil fuel and industry (FFI) grew by 15 $GtCO_2$-eq yr^{-1} (67%), CH_4 by 2.4 $GtCO_2$-eq yr^{-1} (29%), F-gases by 0.97 $GtCO_2$-eq yr^{-1} (250%), N_2O by 0.65 $GtCO_2$-eq yr^{-1} (33%). CO_2 emissions from net land use, land-use change and forestry (LULUCF) have shown





	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 TS.2 | 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)[5]; 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}

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4 Emissions of GHGs are weighed by global warming potentials (GWPs) with a 100-year time horizon (GWP100) from the Sixth Assessment Report. GWP100 is commonly used in wide parts of the literature on climate change mitigation and is required for reporting emissions under the United Nations Framework Convention on Climate Change (UNFCCC). All metrics have limitations and uncertainties. {Cross-Chapter Box 2, Annex II.II.8}

5 In 2019, CO_2 from fossil fuel and industry (FFI) was 38 ± 3.0 Gt; CO_2 from net land use, land-use change and forestry (LULUCF) was 6.6 ± 4.6 Gt.

6 Fluorinated gases, also known as 'F-gases', include: hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluouride (SF_6) and nitrogen trifluouride (NF_3).

little long-term change, with large uncertainties preventing the detection of statistically significant trends. F-gases excluded from GHG emissions inventories such as *chlorofluorocarbons* and *hydrochlorofluorocarbons* are about the same size as those included (*high confidence*). (Figure TS.2) {2.2.1, 2.2.2, Table 2.1, Figures 2.2, 2.3 and 2.5}

Globally, gross domestic product (GDP) per capita and population growth remained the strongest drivers of CO_2 emissions from fossil fuel combustion in the last decade (*high confidence*). Trends since 1990 continued in the years 2010 to 2019 with GDP per capita and population growth increasing emissions by 2.3% yr^{-1} and 1.2% yr^{-1}, respectively. This growth outpaced the reduction in the use of energy per unit of GDP (–2% yr^{-1}, globally) as well as improvements in the carbon intensity of energy (–0.3% yr^{-1}). {2.4.1, Figure 2.19}

Box TS.1 | The COVID-19 Pandemic: Impact on Emissions and Opportunities for Mitigation

The COVID-19 pandemic triggered the deepest global economic contraction as well as CO_2 emission reductions since the Second World War {2.2.2}. While emissions and most economies rebounded in 2020, some impacts of the pandemic could last well beyond this. Owing to the very recent nature of this event, it remains unclear what the exact short- and long-term impacts on global emissions drivers, trends, macroeconomics and finance will be.

Starting in the spring of 2020 a major break in global emissions trends was observed due to lockdown policies implemented in response to the pandemic. Overall, global CO_2-FFI emissions are estimated to have declined by 5.8% (5.1–6.3%) in 2020, or about 2.2 (1.9–2.4%) $GtCO_2$ in total. This exceeds any previous global emissions decline since 1970 both in relative and absolute terms (Box TS.1, Figure 1). During periods of economic lockdown, daily emissions, estimated based on activity and power-generation data, declined substantially compared to 2019, particularly in April 2020 – as shown in Box TS.1, Figure 1 – but rebounded by the end of 2020. Impacts were differentiated by sector, with road transport and aviation particularly affected. Different databases estimate the total power-sector CO_2 reduction from 2019 to 2020 at 3% (IEA[7]) and 4.5% (EDGAR[8]). Approaches that predict near real-time estimates of the power-sector reduction are more uncertain and estimates range more widely between 1.8%, 4.1% and 6.8%, the latter taking into account the over-proportional reduction of coal generation due to low gas prices and merit order effects.

The lockdowns implemented in many countries accelerated some specific trends, such as the uptake in urban cycling. The acceptability of collective social change over a longer term towards less resource-intensive lifestyles, however, depends on the social mandate for change. This mandate can be built through public participation, discussion and debate, to produce recommendations that inform policymaking. {Box 5.2}

Most countries were forced to undertake unprecedented levels of short-term public expenditures in 2021. This is expected to slow economic growth and may squeeze financial resources for mitigation and relevant investments in the near future. Pandemic responses have increased sovereign debt across countries in all income bands and the sharp increase in most developing economies and regions has caused debt distress, widening the gap in developing countries' access to capital. {15.6.3}

The wider overall reduction in energy investment has prompted a relative shift towards low-carbon investment particularly for major future investment decisions by the private sector {15.2.1, 15.3.1, 15.6.1}. Some countries and regions have prioritised green stimulus expenditures, for example, as part of a 'Green New Deal' {Box 13.1}. This is motivated by assessments that investing in new growth industries can boost the macroeconomic effectiveness ('multipliers') of public spending, crowd-in and revive private investment, whilst also delivering on mitigation commitments. {15.2.3}

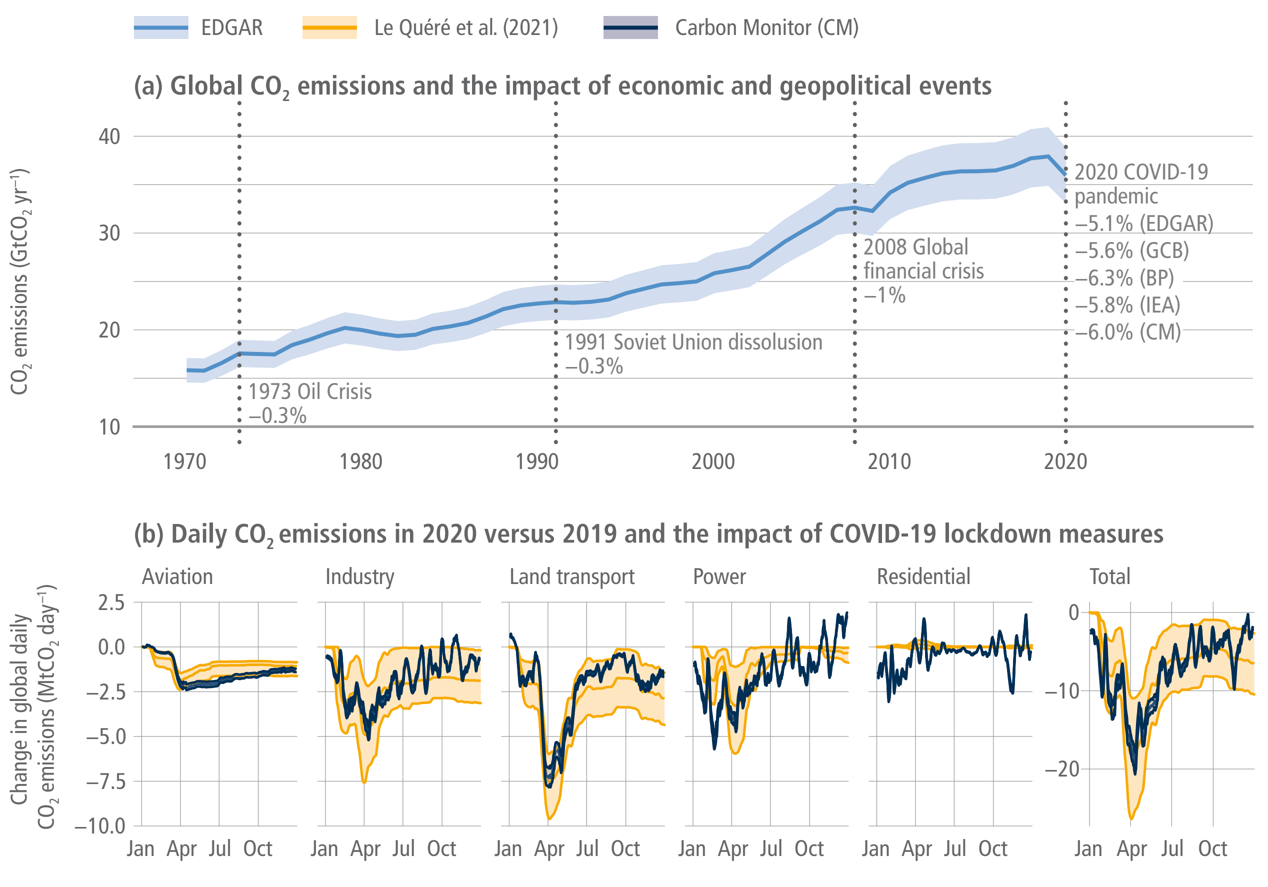
The impacts of COVID-19 may have temporarily set back development and the delivery of many SDGs. It also distracts political and financial capacity away from efforts to accelerate climate change mitigation and shift development pathways to increased sustainability. Yet, studies of previous post-shock periods suggest that waves of innovation that are ready to emerge can be accelerated by crises, which may prompt new behaviours, weaken incumbent systems, and initiate rapid reform. {1.6.5}

Institutional change can be slow but major economic dislocation can create significant opportunities for new ways of financing and enabling 'leapfrogging' investment {10.8}. Given the unambiguous risks of climate change, and consequent stranded asset risks from new fossil fuel investments {Box 6.11}, the most robust recoveries may well be those which align with lower carbon and resilient development pathways.

7 IEA: International Energy Agency

8 EDGAR: Emissions Database for Global Atmospheric Research

Box TS.1 (continued)



Box TS.1, Figure 1 | Global carbon emissions in 2020 and the impact of COVID-19. Panel (a) depicts carbon emissions from fossil fuel and industry over the past five decades. The single-year declines in emissions following major economic and geopolitical events are shown, as well as the decline recorded in five different datasets for emissions in 2020 compared to 2019. **Panel (b)** depicts the perturbation of daily carbon emissions in 2020 compared to 2019, showing the impact of COVID-19 lockdown policies. {Figure 2.6}

Cumulative net CO_2 emissions over the last decade (2010–2019) are about the same size as the remaining carbon budget to limit warming to 1.5°C (>67%) (*medium confidence*). 62% of total cumulative CO_2 emissions from 1850 to 2019 occurred since 1970 (1500 ± 140 $GtCO_2$), about 43% since 1990 (1000 ± 90 $GtCO_2$), and about 17% since 2010 (410 ± 30 $GtCO_2$). For comparison, the remaining carbon budget for keeping warming to 1.5°C with a 67% (50%) probability is about 400 (500) ± 220 $GtCO_2$ (Figure TS.3). {2.2.2, Figure 2.7, AR6 WGI Chapter 5.5, AR6 WGI Chapter 5, Table 5.8}

A growing number of countries have achieved GHG emission reductions over periods longer than 10 years – a few at rates that are broadly consistent with the global rates described in climate change mitigation scenarios that limit warming to 2°C (>67%) (*high confidence*). At least 18 countries have reduced CO_2 and GHG emissions for longer than 10 years. Reduction rates in a few countries have reached 4% in some years, in line with global rates observed in pathways that limit warming to 2°C (>67%). However, the total reduction in annual GHG emissions of these countries is small (about 3.2 $GtCO_2$-eq yr^{-1}) compared to global emissions growth observed over the last decades. Complementary evidence suggests that countries have decoupled territorial CO_2 emissions from GDP, but fewer have decoupled consumption-based emissions from GDP. Decoupling has mostly occurred in countries with high per-capita GDP and high per-capita CO_2 emissions. (Figure TS.4, Box TS.2) {2.2.3, 2.3.3, Figure 2.11, Tables 2.3 and 2.4}

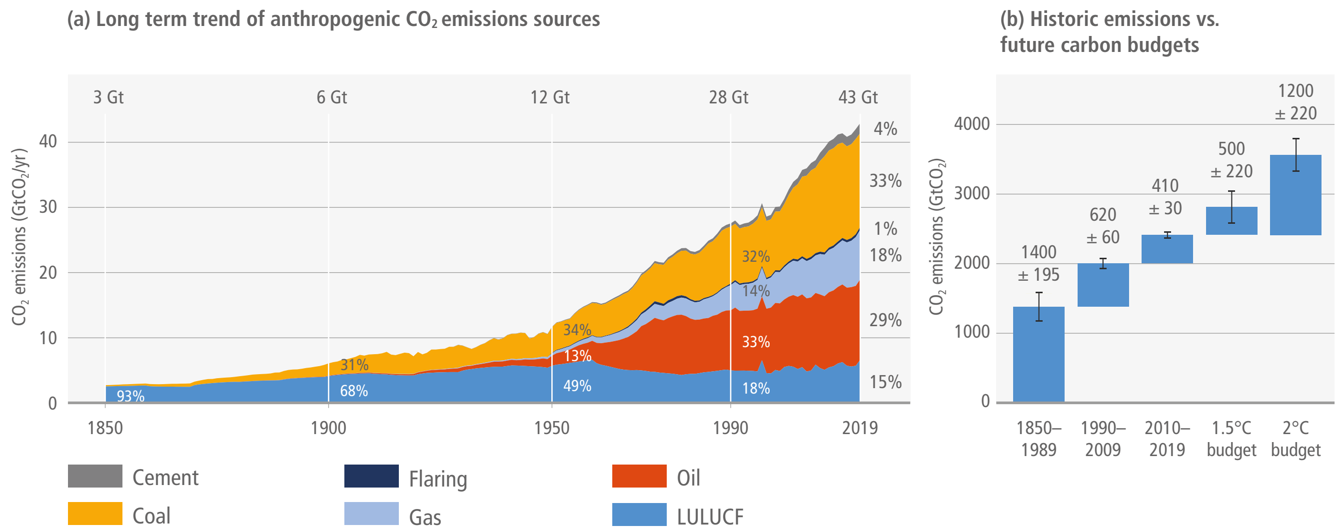


Figure TS.3 | Historic anthropogenic CO_2 emission and cumulative CO_2 emissions (1850–2019) as well as remaining carbon budgets for limiting warming to 1.5°C (>67%) and 2°C (>67%). Panel (a) shows historic annual anthropogenic CO_2 emissions ($GtCO_2\ yr^{-1}$) by fuel type and process. **Panel (b)** shows historic cumulative anthropogenic CO_2 emissions for the periods 1850–1989, 1990–2009, and 2010–2019 as well as remaining future carbon budgets as of 1 January 2020 to limit warming to 1.5°C and 2°C at the 67th percentile of the transient climate response to cumulative CO_2 emissions. The whiskers indicate a budget uncertainty of ±220 $GtCO_2$-eq for each budget and the aggregate uncertainty range at one standard deviation for historical cumulative CO_2 emissions, consistent with WGI. {Figure 2.7}

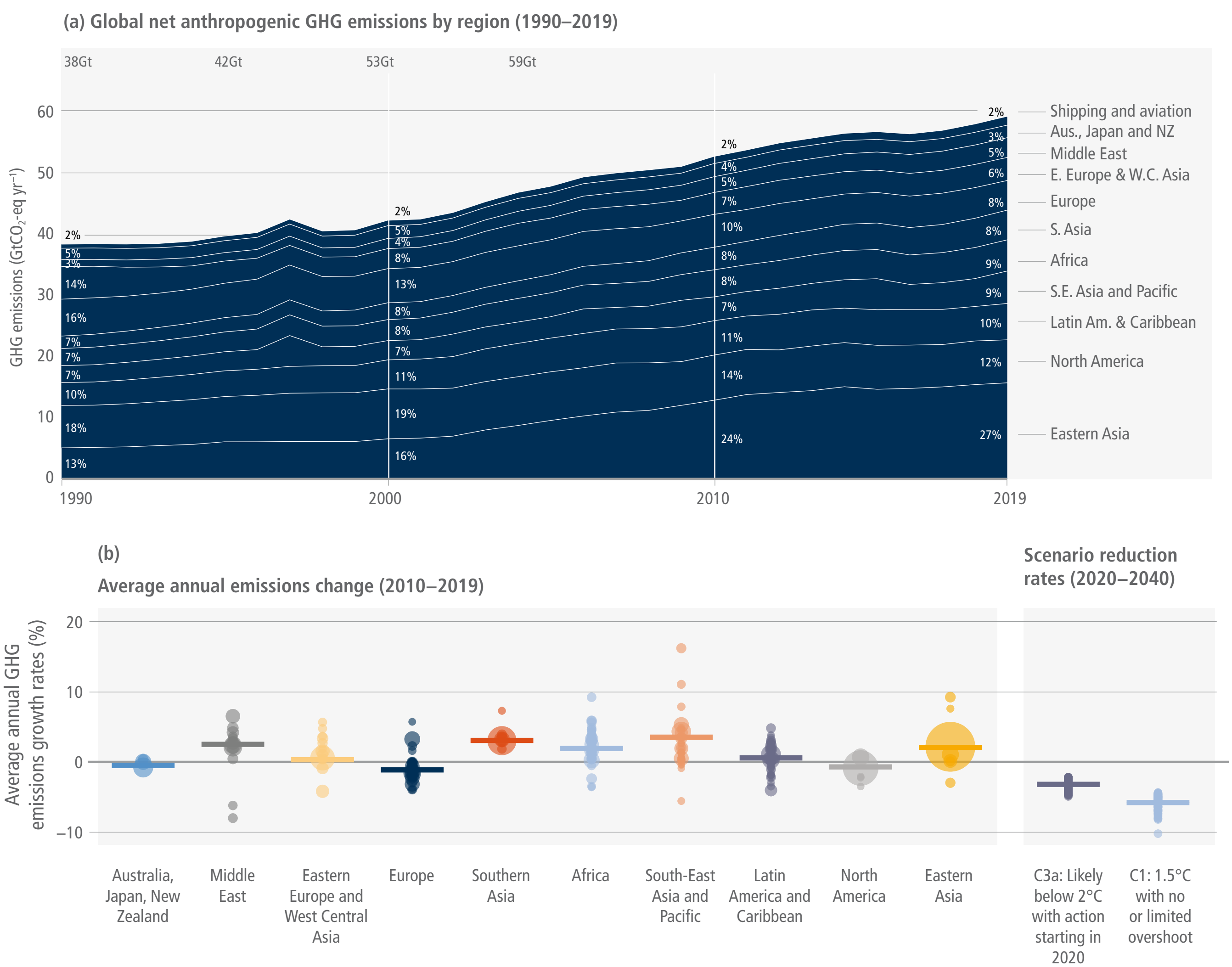


Figure TS.4 | Emissions have grown in most regions, although some countries have achieved sustained emission reductions in line with 2°C scenarios.

Figure TS.4 (continued): Emissions have grown in most regions, although some countries have achieved sustained emission reductions in line with 2°C scenarios. Change in regional GHG emissions and rates of change compatible with warming targets. **Panel (a):** Regional GHG emission trends (in GtCO_2-eq yr^{-1} (GWP100; AR6) for the time period 1990–2019. **Panel (b):** Historical GHG emissions change by region (2010–2019). Circles depict countries, scaled by total emissions in 2019, short horizontal lines depict the average change by region. Also shown are global rates of reduction over the period 2020–2040 in scenarios assessed in AR6 that limit global warming to 1.5°C and 2°C with different probabilities. The 5–95th percentile range of emissions changes for scenarios below 1.5°C with no or limited overshoot (scenario category C1) and scenarios below 2°C (>67%) with immediate action (scenario category C3a) are shown as a shaded area with a horizontal line at the mean value. Panel b excludes CO_2 LULUCF due to a lack of consistent historical national data, and International Shipping and Aviation, which cannot be allocated to regions. Global rates of reduction in scenarios are shown for illustrative purposes only and do not suggest rates of reduction at the regional or national level. {Figures 2.9 and 2.11}

Box TS.2 | Greenhouse Gas (GHG) Emission Metrics Provide Simplified Information About the Effects of Different Greenhouse Gases

Comprehensive mitigation policy relies on consideration of all anthropogenic forcing agents, which differ widely in their atmospheric lifetimes and impacts on the climate system. GHG emission metrics provide simplified information about the effect that emissions of different gases have on global temperature or other aspects of climate, usually expressed relative to the effect of emitting CO_2.[9] This information can support choices about priorities, trade-offs and synergies in mitigation policies and emission targets for non-CO_2 gases relative to CO_2 as well as baskets of gases expressed in CO_2-eq.

The choice of metric can affect the timing and emphasis placed on reducing emissions of short-lived climate forcers (SLCFs) relative to CO_2 within multi-gas abatement strategies as well as the costs of such strategies. Different metric choices can also alter the time at which net zero GHG emissions are calculated to be reached for any given emissions scenario. A wide range of GHG emission metrics has been published in the scientific literature, which differ in terms of: (i) the key measure of climate change they consider, (ii) whether they consider climate outcomes for a specified point in time or integrated over a specified time horizon, (iii) the time horizon over which the metric is applied, (iv) whether they apply to a single emission pulse, to emissions sustained over a period of time, or to a combination of both, and (v) whether they consider the climate effect from an emission compared to the absence of that emission, or compared to a reference emissions level or climate state. {Annex II}

Parties to the Paris Agreement decided to report aggregated emissions and removals (expressed as CO_2-eq) based on the Global Warming Potential (GWP) with a time horizon of 100 years (GWP100) using values from IPCC AR5 or from a subsequent IPCC report as agreed upon by the CMA,[10] and to account for future Nationally Determined Contributions (NDCs) in accordance with this approach. Parties may also report supplemental information on aggregate emissions and removals, expressed as CO_2-eq, using other GHG emission metrics assessed by the IPCC.

The WGIII contribution to AR6 uses updated GWP100 values from AR6 WGI to report aggregate emissions and removals unless stated otherwise. These reflect updated scientific understanding of the response of the climate system to emissions of different gases and include a methodological update to incorporate climate-carbon cycle feedbacks associated with the emission of non-CO_2 gases (see Annex II.II.8 for a list of GWP100 metric values). The choice of GWP100 was made *inter alia* for consistency with decisions under the Rulebook for the Paris Agreement and because it is the dominant metric used in the literature assessed by WGIII. Furthermore, for mitigation pathways that limit global warming to 2°C (>67%) or lower, using GWP100 to inform cost-effective abatement choices between gases would achieve such long-term temperature goals at close to least global cost within a few percent (*high confidence*).

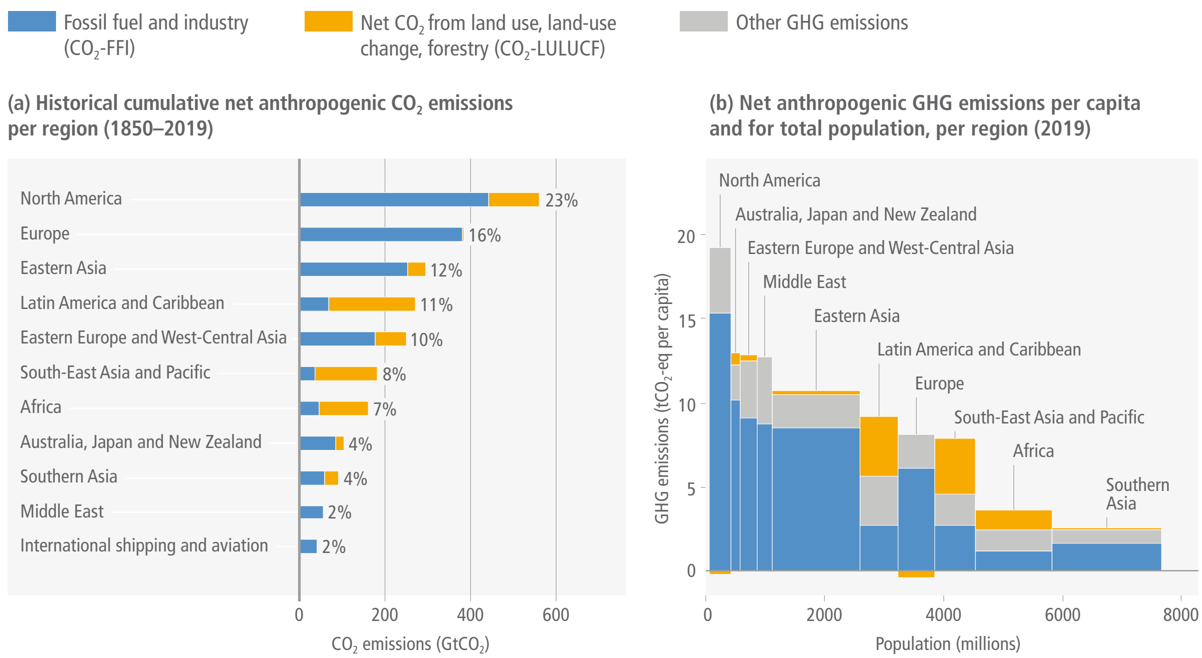
However, GWP100 is not well-suited to estimate the cumulative effect on climate from sustained SLCF emissions and the resulting warming at specific points in time. This is because the warming caused by an individual SLCF emission pulse is not permanent, and hence, unlike CO_2, the warming from successive SLCF emission pulses over multiple decades or centuries depends mostly on their ongoing rate of emissions rather than cumulative emissions. Recently developed step/pulse metrics such as the CGTP (combined global temperature change potential) and GWP* (referred to as GWP-star and indicated by an asterisk) recognise that a sustained increase/decrease in the rate of SLCF emissions has indeed a similar effect on global surface temperature as one-off emission/removal of CO_2. These metrics use this relationship to calculate the CO_2 emissions or removals that would result in roughly the same temperature change as a sustained change in the rate of SLCF emissions (CGTP) over a given time period, or as a varying time series of CH_4 emissions (GWP*). IFrom a mitigation perspective, this makes these metrics well-suited in principle to estimate the effect on the remaining carbon budget from more, or less, ambitious SLCF mitigation over multiple decades compared to a given reference scenario (*high confidence*). However, potential application in wider climate policy (e.g., to inform equitable and ambitious emission targets or to support sector-specific mitigation policies) is contested and relevant literature still limited.

9 Emission metrics also exist for aerosols, but these are not commonly used in climate policy. This assessment focuses on GHG emission metrics only.

10 The CMA is the Conference of the Parties serving as the Meeting of the Parties to the Paris Agreement. See 18/CMA.1 (Annex, para. 37) and 4/CMA.1 (Annex II, para. 1) regarding the use of GHG emission metrics in reporting of emissions and removals and accounting for Parties' NDCs.

Box TS.2 (continued)

All 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. For this reason, the WGIII contribution to the AR6 reports emissions and mitigation options for individual gases where possible; CO_2-equivalent emissions are reported in addition to individual gas emissions where this is judged to be policy-relevant. This approach aims to reduce the ambiguity regarding actual climate outcomes over time arising from the use of any specific GHG emission metric. {Cross-Chapter Box 2 in Chapter 2, SM.2.3, Annex II.II.8; AR6 WGI Chapter 7.6}



(c) 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 TS.5 | Global emissions are distributed unevenly, both in the present day and cumulatively since 1850. Panel (a) 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 fossil fuel and industry (CO_2-FFI); CO_2 land use, land-use change and forestry (CO_2-LULUCF); and other GHG emissions (CH_4, nitrous oxide, F-gas, expressed in CO_2-eq using GWP100). 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 regional. Percentages refer to overall GHG contributions to total global emissions in 2019. Emissions from international aviation and shipping are not included. **Panel (b)** shows the share of historical net CO_2 emissions per region from 1850 to 2019. This includes CO_2-FFI and CO_2-LULUCF ($GtCO_2$). Other GHG emissions are not included. Emissions from international aviation and shipping are included. **Panel (c)** 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 1.2a, 2.2, Figure 2.10}

Consumption-based CO_2 emissions in Developed Countries and the Asia and Pacific region are higher than in other regions (*high confidence*). In Developed Countries, consumption-based CO_2 emissions peaked at 15 $GtCO_2$ in 2007, declining to about 13 $GtCO_2$ in 2018. The Asia and Developing Pacific region, with 52% of the current global population, has become a major contributor to consumption-based CO_2 emission growth since 2000 (5.5% yr^{-1} for 2000–2018); in 2015 it exceeded the Developed Countries region, with 16% of global population, as the largest emitter of consumption-based CO_2. {2.3.2, Figure 2.14}

Carbon-intensity improvements in the production of traded products has led to a net reduction in CO_2 emissions embodied in international trade (*high confidence*). A decrease in the carbon intensity of traded products has offset increased trade volumes between 2006 and 2016. Emissions embodied in internationally traded products depend on the composition of the global supply chain across sectors and countries and the respective carbon intensity of production processes (emissions per unit of economic output). {2.3, 2.4}

Developed Countries tend to be net CO_2 emission importers, whereas developing countries tend to be net emission exporters (*high confidence*). Net CO_2 emission transfers from developing to Developed Countries via global supply chains have decreased between 2006 and 2016. Between 2004 and 2011, CO_2 emissions embodied in trade between developing countries have more than doubled (from 0.47 to 1.1 Gt) with the centre of trade activities shifting from Europe to Asia. {2.3.4, Figure 2.15}

Territorial emissions from developing country regions continue to grow, mostly driven by increased consumption and investment, albeit starting from a low base of per-capita emissions and with a lower historic contribution to cumulative emissions than developed countries (*high confidence*). Average 2019 per-capita CO_2-FFI emissions in three developing regions, Africa (1.2 tCO_2), Asia and Pacific (4.4 tCO_2), and Latin America and Caribbean (2.7 tCO_2), remained less than half of Developed Countries' 2019 CO_2-FFI emissions (9.5 tCO_2). In these three developing regions together, CO_2-FFI emissions grew by 26% between 2010 and 2019 (compared to 260% between 1990 and 2010). In contrast, in Developed Countries emissions contracted by 9.9% between 2010 and 2019 and by 9.6% between 1990 and 2010. Historically, these three developing regions together contributed 28% to cumulative CO_2-FFI emissions between 1850 and 2019, whereas Developed Countries contributed 57%, and least developed countries contributed 0.4%. (Figure TS.5) {2.2, Figures 2.9 and 2.10}

Globally, households with income in the top 10% contribute about 36–45% of global GHG emissions (*robust evidence, medium agreement*). About two thirds of the top 10% live in Developed Countries and one third in other economies. The lifestyle consumption emissions of the middle income and poorest citizens in emerging economies are between five and 50 times below their counterparts in high-income countries (*medium confidence*). Increasing inequality within a country can exacerbate dilemmas of redistribution and social cohesion, and affect the willingness of the rich and poor to accept policies to protect the environment, and to accept and afford lifestyle changes that favour mitigation (*medium confidence*). {2.6.1, 2.6.2, Figure 2.29}

Globally, GHG emissions continued to rise across all sectors and subsectors, and most rapidly in transport and industry (*high confidence*). In 2019, 34% (20 $GtCO_2$-eq) of global GHG emissions came from the energy 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 5.6% (3.3 $GtCO_2$-eq) from buildings. Once indirect emissions from energy use are considered, the relative shares of industry and buildings emissions rise to 34% and 16%, respectively. Average annual GHG emissions growth during 2010–2019 slowed compared to the previous decade in energy supply (from 2.3% to 1.0%) and industry (from 3.4% to 1.4%, direct emissions only), but remained roughly constant at about 2% yr^{-1} in the transport sector (*high confidence*). Emission growth in AFOLU is more uncertain due to the high share of CO_2-LULUCF emissions (*medium confidence*). (Figure TS.8) {2.2.4, Figure 2.13 and Figures 2.16–2.21}

There is a discrepancy, equating to 5.5 $GtCO_2$ yr^{-1}, between alternative methods of accounting for anthropogenic land CO_2 fluxes. Accounting for this discrepancy would assist in assessing collective progress in a global stocktake (*high confidence*). The principal accounting approaches are national GHG inventories (NGHGI) and global modelling[11] approaches. NGHGI, based on IPCC guidelines, consider a much larger area of forest to be under human management than global models. NGHGI consider the fluxes due to human-induced environmental change on this area to be anthropogenic and are thus reported. Global models, in contrast, consider these fluxes to be natural and are excluded from the total reported anthropogenic land CO_2 flux. The accounting method used will affect the assessment of collective progress in a global stocktake (*medium confidence*) {Cross-Chapter Box 6 in Chapter 7}. In the absence of these adjustments, allowing a like-with-like comparison, collective progress would appear better than it is. {7.2}

This accounting discrepancy also applies to Integrated Assessment Models (IAMs), with the consequence that anthropogenic land CO_2 fluxes reported in IAM pathways cannot be compared directly with those reported in national GHG inventories (*high confidence*). Methodologies enabling a more like-for-like comparison between models' and countries' approaches would support more accurate assessment of the collective progress achieved under the Paris Agreement. {3.4, 7.2.2}

Average annual growth in GHG emissions from energy supply decreased from 2.3% for 2000–2009 to 1.0% for 2010–2019 (*high confidence*). This slowing of growth is attributable to further improvements in energy efficiency and reductions in the carbon intensity of energy supply driven by fuel switching from coal to gas, reduced expansion of coal capacity, particularly in Eastern Asia, and the increased use of renewables (*medium confidence*). (Figure TS.6) {2.2.4, 2.4.2.1, Figure 2.17}

11 Bookkeeping models and dynamic global vegetation models.

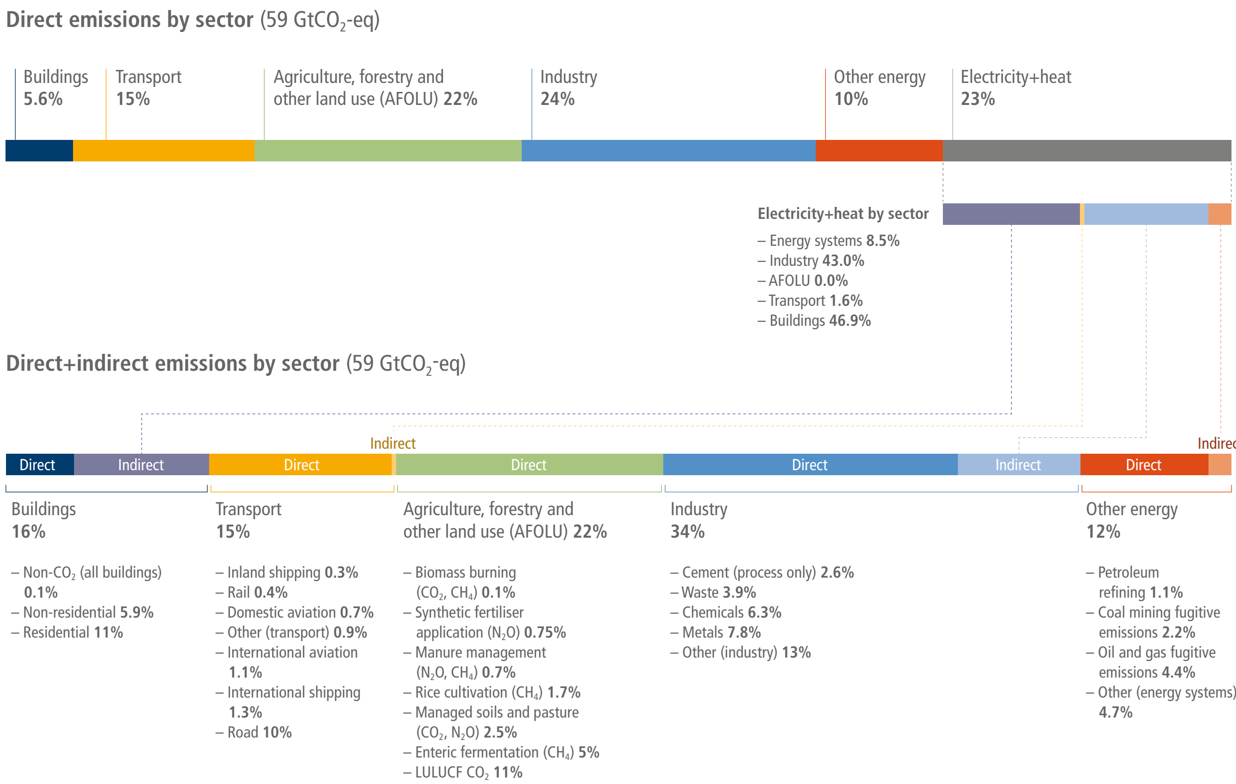


Figure TS.6 | Total anthropogenic direct and indirect GHG emissions for the year 2019 (in $GtCO_2$-eq) by sector and subsector. Direct emissions estimates assign emissions to the sector in which they arise (scope 1 reporting). Indirect emissions – as used here – refer to the reallocation of emissions from electricity and heat to the sector of final use (scope 2 reporting). Note that cement refers to process emissions only, as a lack of data prevents the full reallocation of indirect emissions to this sector. More comprehensive conceptualisations of indirect emissions including all products and services (scope 3 reporting) are discussed in Section 2.3. Emissions are converted into CO_2-equivalents based on global warming potentials with a 100-year time horizon (GWP100) from the IPCC Sixth Assessment Report. Percentages may not add up to 100 across categories due to rounding at the second significant digit. {Figure 2.12, 2.3}

The industry, buildings and transport sectors make up 44% of global GHG emissions, or 66% when the emissions from electricity and heat production are reallocated as *indirect emissions* (*high confidence*). This reallocation makes a substantial difference to overall industry and buildings emissions as shown in Figure TS.6. Industry, buildings, and transport emissions are driven, respectively, by the large rise in demand for basic materials and manufactured products, a global trend of increasing floor space per capita, building energy service use, travel distances, and vehicle size and weight. Between 2010 and 2019, aviation grew particularly fast on average at about 3.3% per annum. Globally, energy efficiency has improved in all three demand sectors, but carbon intensities have not. (Figure TS.6) {2.2.4, Figures 2.18, 2.19 and 2.20}

Providing access to modern energy services universally would increase global GHG emissions by a few percent at most (*high confidence*). The additional energy demand needed to support *decent living standards*[12] for all is estimated to be well below current average energy consumption (*medium evidence*, *high agreement*). More equitable income distribution could also reduce carbon emissions, but the nature of this relationship can vary by level of income and development (*limited evidence*, *medium agreement*). {2.4.3}

Evidence of rapid energy transitions exists in some case studies (*medium confidence*). Emerging evidence since AR5 on past energy transitions identifies a growing number of cases of accelerated technology diffusion at sub-global scales and describes mechanisms by which future energy transitions may occur more quickly than those in the past. Important drivers include technology transfer and cooperation, international policy and financial support, and harnessing synergies among technologies within a sustainable energy system perspective (*medium confidence*). A fast global low-carbon energy transition enabled by finance to facilitate low-carbon technology adoption in developing and particularly in least developed countries can facilitate achieving climate stabilisation targets (*high confidence*). {2.5.2, Table 2.5}

12 Decent Living Standards (DLS) – a benchmark of material conditions for human well-being – overlaps with many Sustainable Development Goals (SDGs). Minimum requirements of energy use consistent with enabling well-being for all is between 20 and 50 GJ per capita yr^{-1} depending on the context. (Figure TS.22) {5.2.2, 5.2.2, Box 5.3}

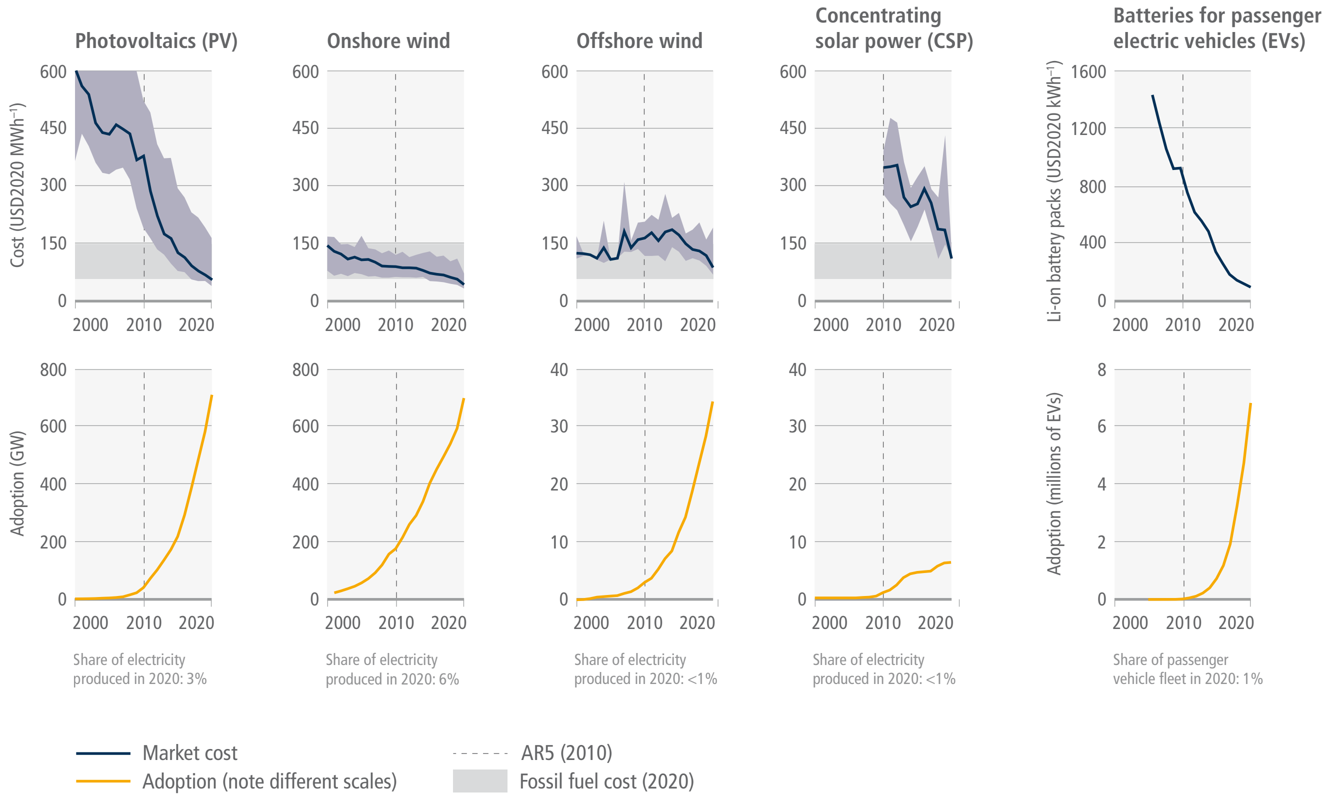


Figure TS.7 | The unit costs of batteries and some forms of renewable energy have fallen significantly, and their adoption continues to increase. The **top panel** shows global costs per unit of energy (USD per MWh) for some rapidly changing mitigation technologies. Solid blue lines indicate average 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.

Multiple low-carbon technologies have shown rapid progress since AR5 – in cost, performance, and adoption – enhancing the feasibility of rapid energy transitions (*high confidence*). The rapid deployment and unit cost decrease of modular technologies like solar, wind, and batteries have occurred much faster than anticipated by experts and modelled in previous mitigation scenarios, as shown in Figure TS.7 (*high confidence*). The political, economic, social, and technical feasibility of solar energy, wind energy and electricity storage technologies has improved dramatically over the past few years. In contrast, the adoption of nuclear energy and CO_2 capture and storage (CCS) in the electricity sector has been slower than the growth rates anticipated in stabilisation scenarios. Emerging evidence since AR5 indicates that small-scale technologies (e.g., solar, batteries) tend to improve faster and be adopted more quickly than large-scale technologies (nuclear, CCS) (*medium confidence*). (Figure TS.7, Box TS.15) {2.5.3, 2.5.4, Figures 2.22 and 2.23}

Robust incentives for investment in innovation, especially incentives reinforced by national policy and international agreements, are central to accelerating low-carbon technological change (*robust evidence, medium agreement*). Policies have driven innovation, including instruments for technology push (e.g., scientific training, research and development (R&D)) and demand pull (e.g., carbon pricing, adoption subsidies), as well as those promoting knowledge flows and especially technology transfer. The magnitude of the scale-up challenge elevates the importance of rapid technology development and adoption. This includes ensuring participation of developing countries in an enhanced global flow of knowledge, skills, experience, equipment, and technology; which in turn requires strong financial, institutional, and capacity-building support. {16.4, 16.5}

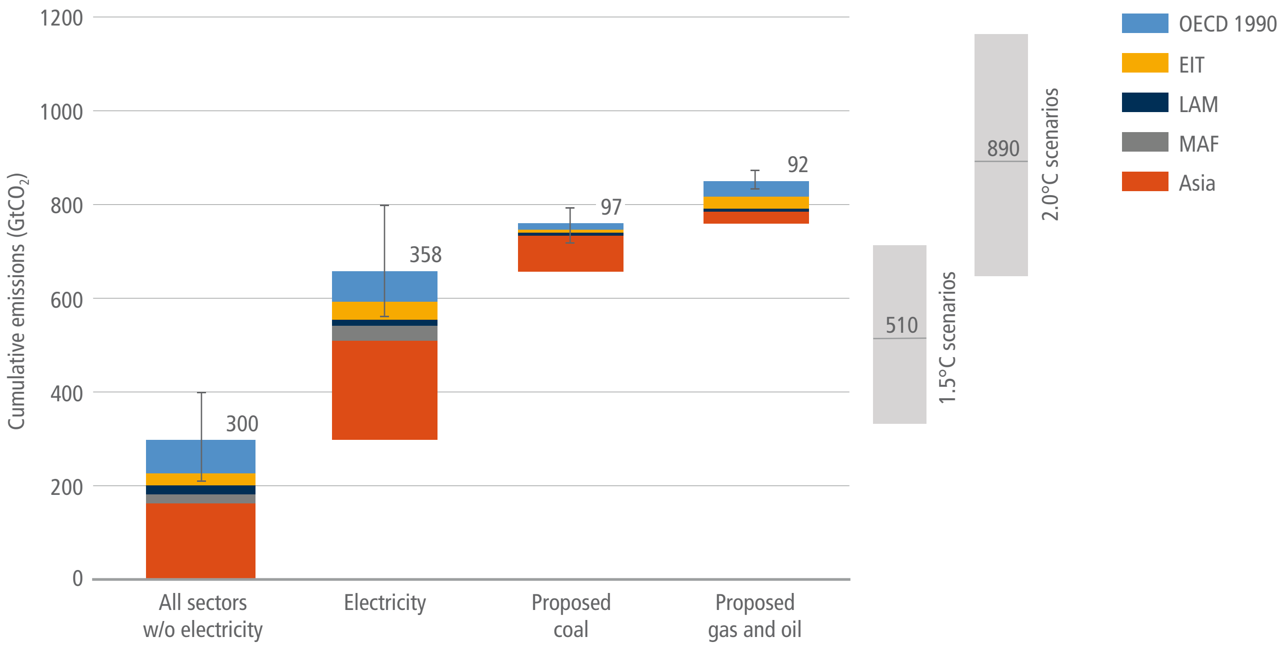


Figure TS.8 | Future CO_2 emissions from existing and currently planned fossil fuel infrastructure in the context of the Paris Agreement carbon budgets in $GtCO_2$ based on historic patterns of infrastructure lifetimes and Future CO_2 emissions estimates of existing infrastructure for the electricity sector as well as all other sectors (industry, transport, buildings, other fossil fuel infrastructures) and of proposed infrastructures for coal power as well as gas and oil power. Grey bars on the right depict the range (5–95th percentile) in overall cumulative net CO_2 emissions until reaching net zero CO_2 in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot (1.5°C scenarios), and in pathways that limit warming to 2°C (>67%) (2°C scenarios). {Figure 2.26}

Estimates of future CO_2 emissions from existing fossil fuel infrastructures already exceed remaining cumulative net CO_2 emissions in pathways limiting warming to 1.5°C (>50%) with no or limited overshoot (*high confidence*). Assuming variations in historic patterns of use and decommissioning, estimated future CO_2 emissions from existing fossil fuel infrastructure alone are 660 (460–890) $GtCO_2$ and from existing and currently planned infrastructure 850 (600–1100) $GtCO_2$. This compares to overall cumulative net CO_2 emissions until reaching net zero CO_2 of 510 (330–710) $GtCO_2$ 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*). While most future CO_2 emissions from existing and currently planned fossil fuel infrastructure are situated in the power sector, most remaining fossil fuel CO_2 emissions in pathways that limit warming to 2°C (>67%) and below are from non-electric energy – most importantly from the industry and transportation sectors (*high confidence*). Decommissioning and reduced utilisation of existing fossil fuel installations in the power sector as well as cancellation of new installations are required to align future CO_2 emissions from the power sector with projections in these pathways (*high confidence*). (Figure TS.8) {2.7.2, 2.7.3, Figure 2.26, Tables 2.6 and 2.7}

TS.4 Mitigation and Development Pathways

While previous WGIII assessments have explored mitigation pathways, since AR5 there has been an increasing emphasis in the literature on development pathways, and in particular at the national scale. Chapter 4 assesses near-term (2019–2030) to mid-term (2030–2050) pathways, complementing Chapter 3 which focuses on long-term pathways (up to 2100). While there is considerable literature on country-level mitigation pathways, including but not limited to NDCs, the country distribution of this literature is very unequal (*high confidence*). {4.2.1, Cross-Chapter Box 4 in Chapter 4}

TS.4.1 Mitigation and Development Pathways in the Near- to Mid-term

An emissions gap persists, exacerbated by an implementation gap, despite mitigation efforts including those in Nationally Determined Contributions (NDCs). In this report the *emissions gap* is understood as the difference between projected global emissions with Nationally Determined Contributions (NDCs) in 2030, and emissions in 2030 if mitigation pathways consistent with the Paris temperature goals were achieved. The term *implementation gap* refers to the gap between NDC mitigation pledges and the expected outcome of existing policies.

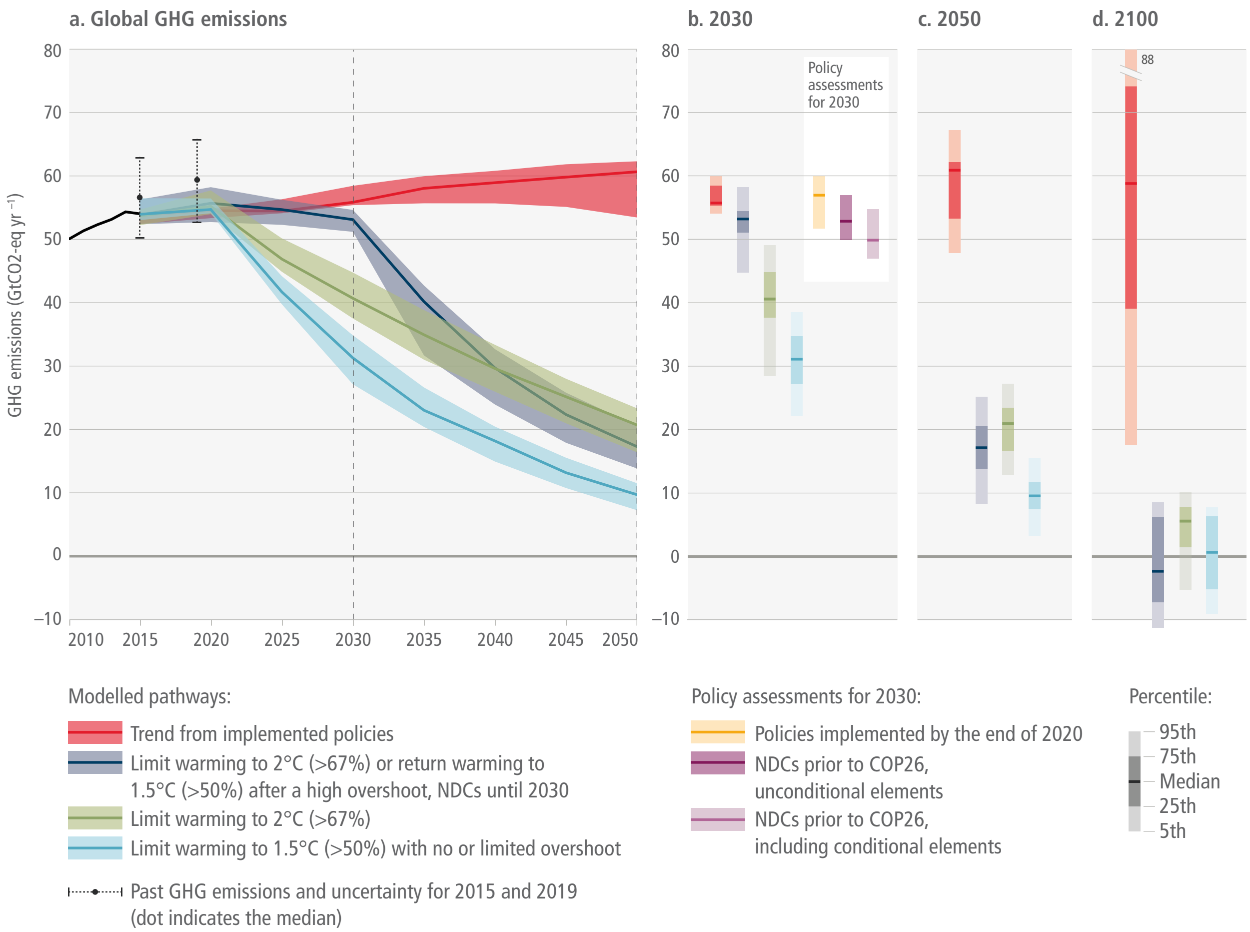


Figure TS.9 | Aggregate greenhouse gas (GHG) emissions of global mitigation pathways (coloured funnels and bars) and projected emission outcomes from current policies and emissions implied by unconditional and conditional elements of NDCs, based on updates available by 11 October 2021 (grey bars). Shaded areas show GHG emission medians and 25–75th percentiles over 2020–2050 for four types of pathways in the AR6 scenario database: (i) pathways with near-term emissions developments in line with current policies and extended with comparable ambition levels beyond 2030; (ii) pathways *likely* to limit warming to 2°C with near-term emissions developments reflecting 2030 emissions implied by current NDCs followed by accelerated emissions reductions; (iii) pathways *likely* to limit warming to 2°C based on immediate actions from 2020 onwards; (iv) pathways that limit warming to 1.5°C with no or limited overshoot. Right-hand panels show two snapshots of the 2030 and 2050 emission ranges of the pathways in detail (median, 25–75th and 5–95th percentiles). The 2030 snapshot includes the projected emissions from the implementation of the NDCs as assessed in Section 4.2 (Table 4.1; median and full range). Historic GHG emissions trends as used in model studies are shown for 2010–2015. GHG emissions are in CO_2-equivalent using GWP100 values from AR6. {3.5, Table 4.1, Cross-Chapter Box 4 in Chapter 4}

Pathways consistent with the implementation and extrapolation of countries' current[13] policies see GHG emissions reaching 57 (52–60) $GtCO_2$-eq yr^{-1} by 2030 and to 46–67 $GtCO_2$-eq yr^{-1} by 2050, leading to a median global warming of 2.4°C to 3.5°C by 2100 (*medium confidence*). NDCs with unconditional and conditional elements[14] lead to 53 (50–57) and 50 (47–55) $GtCO_2$-eq, respectively (*medium confidence*) {Table 4.1}. This leaves median estimated *emissions gaps* of 14–23 $GtCO_2$-eq to limit warming to 2°C and 25–34 $GtCO_2$-eq to limit warming to 1.5°C relative to mitigation pathways. (Figure TS.9) {Cross-Chapter Box 4, Figure 1 in Chapter 4}

Projected global emissions from aggregated NDCs place limiting global warming to 1.5°C beyond reach and make it harder after 2030 to limit warming to 2°C (*high confidence*). Pathways following NDCs until 2030 show a smaller reduction in fossil fuel use, slower deployment of low-carbon alternatives, and a smaller reduction in CO_2, CH_4 and overall GHG emissions in 2030 compared to immediate action scenarios. This is followed by a much faster reduction of emissions and fossil fuels after 2030, and a larger increase in the deployment of low-carbon alternatives during the medium term in order to get close to the levels of the immediate action pathways in 2050. Those pathways also deploy a larger amount of carbon dioxide removal (CDR) to compensate for higher emissions before 2030. The faster transition during 2030 to 2050 entails greater investment in fossil fuel infrastructure and lower deployment of low-carbon alternatives in 2030, which adds to the socio-economic challenges in realising the higher transition rates. (TS.4.2) {3.5}

Studies evaluating up to 105 updated NDCs[15] indicate that emissions in NDCs with conditional elements have been reduced by 4.5 (2.7–6.3) $GtCO_2$-eq. This closes the emission gaps by about one third to 2°C and about 20% to 1.5°C compared to the original NDCs submitted in 2015/16 (*medium confidence*) {4.2.2, Cross-Chapter Box 4 in Chapter 4}. An *implementation gap* also exists between the projected emissions with 'current policies' and the projected emissions resulting from the implementation of the unconditional and conditional elements of NDCs; this is estimated to be around 4 and 7 $GtCO_2$-eq in 2030, respectively (*medium confidence*) {4.2.2}. Many countries would therefore require additional policies and associated action on climate change to meet their autonomously determined mitigation targets as specified under the first NDCs (*limited evidence*). The disruptions triggered by the COVID-19 pandemic increase uncertainty over the range of projections relative to pre-COVID-19 literature. As indicated by a growing number of studies at the national and global level, how large near- to mid-term emissions implications of the COVID-19 pandemic are, to a large degree depends on how stimulus or recovery packages are designed. {4.2}

There is a need to explore how accelerated mitigation – relative to NDCs and current policies – could close both emission gaps and implementation gaps. There is increasing understanding of the technical content of accelerated mitigation pathways, differentiated by national circumstances, with considerable, though uneven, literature at country-level (*medium evidence*, *high agreement*). Transformative technological and institutional changes for the near term include demand reductions through efficiency and reduced activity, rapid decarbonisation of the electricity sector and low-carbon electrification of buildings, industry and transport (*robust evidence*, *medium agreement*). A focus on energy use and supply is essential, but not sufficient on its own – the land sector and food systems deserve attention. The literature does not adequately include demand-side options and systems analysis, and captures the impact from non-CO_2 GHGs (*medium confidence*). {4.2.5}

If obstacles to accelerated mitigation are rooted in underlying structural features of society, then transforming such structures can support emission reductions {4.2.6}. Countries and regions will have different starting points for transition pathways. Some critical differences between countries include climate conditions resulting in different heating and cooling needs, endowments with different energy resources, patterns of spatial development, and political and economic conditions {4.2.5}. The way countries develop determines their capacity to accelerate mitigation and achieve other sustainable development objectives simultaneously (*medium confidence*) {4.3.1, 4.3.2}. Yet meeting ambitious mitigation and development goals cannot be achieved through incremental change (*robust evidence*, *medium agreement*). Though development pathways result from the actions of a wide range of actors, it is possible to shift development pathways through policies and enhancing enabling conditions (*limited evidence*, *medium agreement*).

***Shifting development pathways towards sustainability* offers ways to broaden the range of levers and enablers that a society can use to accelerate mitigation and increases the likelihood of making progress simultaneously on climate action and other development goals (Box TS.3) {Cross-Chapter Box 5 in Chapter 4, Figure 4.7, 4.3}.** There are practical options to shift development pathways in ways that advance mitigation and other sustainable development objectives, support political feasibility, increase resources to meet multiple goals, and reduce emissions (*limited evidence*, *high agreement*). Concrete examples, assessed in Chapter 4 of this report, include high-employment and low-emissions structural change; fiscal reforms for mitigation and social contract, combining housing policies to deliver both housing and transport mitigation; and changed economic, social and spatial patterns of agriculture sector development, providing the basis for sustained reductions in emissions from deforestation. {4.4.1, 4.4, 1.10}

13 Current NDCs refers to the most recent Nationally Determined Contributions submitted to the UNFCCC as well as those publicly announced (with sufficient detail on targets, but not yet submitted) up to 11 October 2021, and reflected in literature published up to 11 October 2021. Original INDCs and NDCs refer to those submitted to the UNFCCC in 2015 and 2016.

14 See {4.2.1} for descriptions of 'unconditional' and 'conditional' elements of NDCs.

15 Submitted by 11 October 2021.

Table TS.2 | Comparison of key characteristics of mitigation pathways with immediate action towards limiting warming to 1.5-2°C vs. pathways following NDCs announced prior to COP26 until 2030. Key characteristics are reported for five groups of mitigation pathways: (i) immediate action to limit warming to 1.5°C (>50%) with no or limited overshoot (C1 in Table TS.3; 97 scenarios), (ii) near term action following the NDCs until 2030 and returning warming to 1.5°C (> 50%) by 2100 after a high overshoot (subset of 42 scenarios following the NDCs until 2030 in C2), (iii) immediate action to limit warming to 2°C (>67%), (C3a in Table TS.3; 204 scenarios), (iv) near term action following the NDCs until 2030 followed by post-2030 action to limit warming to 2°C (>67%) (C3b in Table TS.3; 97 scenarios). Also shown are the characteristics for (v) the combined class of all scenarios that limit warming to 2°C (>67%). The groups (i), (iii), and the combination of (ii) and (iv) are depicted in Figure TS.9. Reported are median and interquartile ranges (in brackets) for selected global indicators. Numbers are rounded to the nearest five, with the exception of cumulative net negative CO_2 emissions rounded to the nearest 10. Changes from 2019 are relative to modelled 2019 values. Emissions reductions are based on harmonised model emissions used for the climate assessment. {Section 3.5} {Table 3.6}

Global indicators	1.5°C (>50%)	1.5°C (>50%) by 2100	2°C (>67%)		
	Immediate action, with no or limited overshoot	NDCs until 2030, with overshoot before 2100	Immediate action	NDCs until 2030	All
Cumulative net negative CO_2 emissions until 2100 ($GtCO_2$)	220 (70,430)	380 (300,470)	30 (0,130)	60 (20,210)	40 (10,180)
Change in GHG emissions in 2030 (% rel to 2019)	–45 (–50,–40)	–5 (–5,0)	–25 (–35,–20)	–5 (–10,0)	–20 (–30,–10)
in 2050 (% rel to 2019)	–85 (–90,–80)	–75 (–85,–70)	–65 (–70,–60)	–70 (–70,–60)	–65 (–70,–60)
Change in CO_2 emissions in 2030 (% rel to 2019)	–50 (–60,–40)	–5 (–5,0)	–25 (–35,–20)	–5 (–5,0)	–20 (–30,–5)
in 2050 (% rel to 2019)	–100 (–105,–95)	–85 (–95,–80)	–70 (–80,–65)	–75 (–80,–65)	–75 (–80,–65)
Change in net land use CO_2 emissions in 2030 (% rel to 2019)	–100 (–105,–95)	–30 (–60,–20)	–90 (–105,–75)	–20 (–80,–20)	–80 (–100,–30)
in 2050 (% rel to 2019)	–150 (–200,–100)	–135 (–165,–120)	–135 (–185,–100)	–130 (–145,–115)	–135 (–180,–100)
Change in CH_4 emissions in 2030 (% rel to 2019)	–35 (–40,–30)	–5 (–5,0)	–25 (–35,–20)	–10 (–15,–5)	–20 (–25,–10)
in 2050 (% rel to 2019)	–50 (–60,–45)	–50 (–60,–45)	–45 (–50,–40)	–50 (–65,–45)	–45 (–55,–40)
Change in primary energy from coal in 2030 (% rel to 2019)	–75 (–80,–65)	–10 (–20,–5)	–50 (–65,–35)	–15 (–20,–10)	–35 (–55,–20)
in 2050 (% rel to 2019)	–95 (–100,–80)	–90 (–100,–85)	–85 (–100,–65)	–80 (–90,–70)	–85 (–95,–65)
Change in primary energy from oil in 2030 (% rel to 2019)	–10 (–25,0)	5 (5,10)	0 (–10,10)	10 (5,10)	5 (0,10)
in 2050 (% rel to 2019)	–60 (–75,–40)	–50 (–65,–35)	–30 (–45,–15)	–40 (–55,–20)	–30 (–50,–15)
Change in primary energy from gas in 2030 (% rel to 2019)	–10 (–30,0)	15 (10,25)	10 (0,15)	15 (10,15)	10 (0,15)
in 2050 (% rel to 2019)	–45 (–60,–20)	–45 (–55,–30)	–10 (–35,15)	–30 (–45,–5)	–15 (–40,10)
Change in primary energy from nuclear in 2030 (% rel to 2019)	40 (10,70)	10 (0,25)	35 (5,50)	10 (0,30)	25 (0,45)
in 2050 (% rel to 2019)	90 (15,295)	100 (45,130)	85 (30,200)	75 (30,120)	80 (30,140)
Change in primary energy from modern biomass in 2030 (% rel to 2019)	75 (55,130)	45 (20,75)	60 (35,105)	45 (20,80)	55 (35,105)
in 2050 (% rel to 2019)	290 (215,430)	230 (170,420)	240 (130,355)	260 (95,435)	250 (115,405)
Change in primary energy from non-biomass renewables in 2030 (% rel to 2019)	225 (155,270)	100 (85,145)	150 (115,190)	115 (85,130)	130 (90,170)
in 2050 (% rel to 2019)	725 (545,950)	665 (535,925)	565 (415,765)	625 (545,700)	605 (470,735)
Change in carbon intensity of electricity in 2030 (% rel to 2019)	–75 (–80,–70)	–30 (–40,–30)	–60 (–70,–50)	–35 (–40,–30)	–50 (–65,–35)
in 2050 (% rel to 2019)	–100 (–100,–100)	–100 (–100,–100)	–95 (–100,–95)	–100 (–100,–95)	–95 (–100,–95)

Box TS.3 | Shifting Development Pathways to Increase Sustainability and Broaden Mitigation Options

In this report, *development pathways* refer to the patterns of development resulting from multiple decisions and choices made by many actors in the national and global contexts. Each society whether in developing or developed regions follows its own pattern of growth (Figure TS.13). Development pathways can also be described at smaller scales (e.g., for regions or cities) and for sectoral systems.

Development pathways are major drivers of GHG emissions {1, 2}. There is compelling evidence to show that continuing along existing development pathways will not achieve rapid and deep emission reductions. In the absence of shifts in development pathways, conventional mitigation policy instruments may not be able to limit global emissions to a degree sufficient to meet ambitious mitigation goals or they may only be able to do so at very high economic and social costs.

Policies to shift development pathways, on the other hand, make mitigation policies more effective. Shifting development pathways broadens the scope for synergies between sustainable development objectives and mitigation. Development pathways also determine the enablers and levers available for adaptation {AR6 WGII TS.E.1.2} and for achieving other SDGs.

There are many instances in which reducing GHG emissions and moving towards the achievement of other development objectives can go hand in hand {Chapter 3, Figure 3.33, Chapters 6–12, and 17}. Integrated policies can support the creation of synergies between *action to combat climate change and its impacts* (SDG 13 – climate action) and other SDGs. For example, when measures promoting walkable urban areas are combined with electrification and clean renewable energy, there are several co-benefits to be attained. These include reduced pressures on agricultural land from reduced urban growth, health co-benefits from cleaner air, and benefits from enhanced mobility {8.2, 8.4, 4.4.1}. Energy efficiency in buildings and energy poverty alleviation through improved access to clean fuels also deliver significant health benefits. {9.8.1 and 9.8.2}

However, decisions about mitigation actions, and their timing and scale, may entail trade-offs with the achievement of other national development objectives in the near, mid- and long term {Chapter 12}. In the near term, for example, regulations may ban vehicles from city centres to reduce congestion and local air pollution but reduce mobility and choice. Increasing green spaces within cities without caps on housing prices may involve trade-offs with affordable housing and push low-income residents outside the city {8.2.2}. In the mid- and long term, large-scale deployment of biomass energy raises concerns about food security and biodiversity conservation {3.7.1, 3.7.5, 7.4.4, 9.8.1, 12.5.2, 12.5.3}. Prioritising is one way to manage these trade-offs, addressing some national development objectives earlier than others. Another way is to adopt policy packages aimed at shifting development pathways towards increased sustainability (SDPS) as they expand the range of tools available to simultaneously achieve multiple development objectives and accelerate mitigation. (Box TS.3, Figure 1)

What does *shifting development pathways towards increased sustainability* entail?

Shifting development pathways towards increased sustainability implies making transformative changes that disrupt existing developmental trends. Such choices would not be marginal, but include technological, systemic and socio-behavioural changes {4.4}. Decision points also arise with new infrastructure, sustainable supply chains, institutional capacities for evidence-based and integrated decision-making, financial alignment towards low-carbon socially responsible investments, just transitions and shifts in behaviour and norms to support shifts away from fossil fuel consumption. Adopting multi-level governance modes, tackling corruption where it inhibits shifts to sustainability, and improving social and political trust are also key for aligning and supporting long-term environmentally just policies and processes. {4.4, Cross-Chapter Box 5 in Chapter 4}

How can development pathways be 'shifted'?

Shifting development paths is complex. Changes that involve 'dissimilar, unfamiliar and more complex science-based components' take more time, acceptance and legitimation and involve complex social learning, even when they promise large gains. Despite the complexities of the interactions that result in patterns of development, history also shows that societies can influence the direction of development pathways based on choices made by decision-makers, citizens, the private sector, and social stakeholders. Shifts in development pathways result from both sustained political interventions and bottom-up changes in public opinion. Collective action by individuals as part of social movements or lifestyle changes underpins system change. {5.2.3, 5.4.1, 5.4.5}

Sectoral transitions that aim to shift development pathways often have multiple objectives and deploy a diverse mix of policies and institutional measures. Context-specific governance conditions can significantly enable or disable sectoral transitions. {Cross-Chapter Box 12 in Chapter 16}

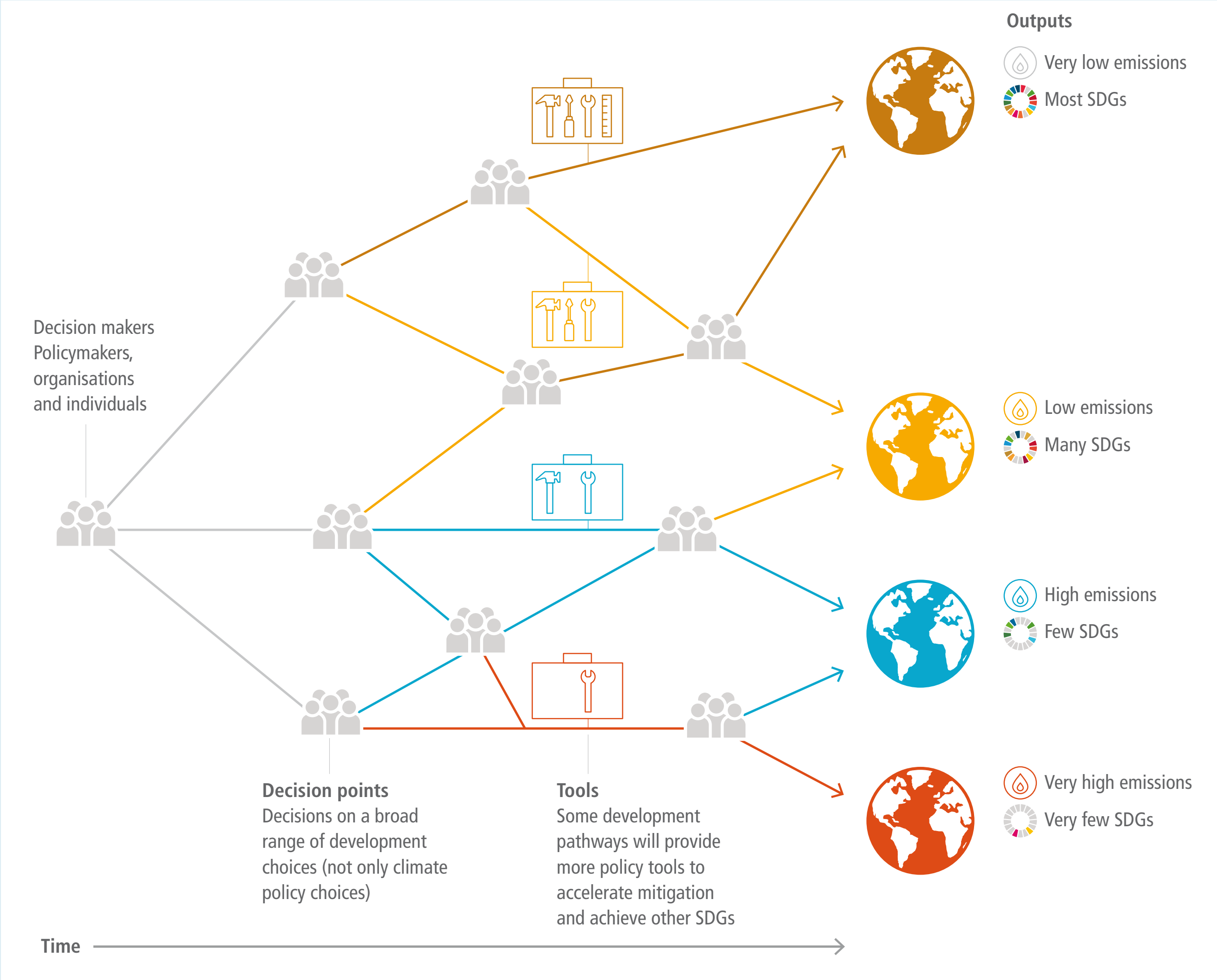
Box TS.3 (continued)

The necessary transformational changes are anticipated to be more acceptable if rooted in the development aspirations of the economy and society within which they take place and may enable a new social contract to address a complex set of interlinkages across sectors, classes, and the whole economy. Taking advantage of windows of opportunity and disruptions to mindsets and socio-technical systems could advance deeper transformations.

How can shifts in development pathways be implemented by actors in different contexts?

Shifting development pathways to increased sustainability is a shared aspiration. Yet since countries differ in starting points (e.g., social, economic, cultural, political) and historical backgrounds, they have different urgent needs in terms of facilitating the economic, social, and environmental dimensions of sustainable development and, therefore, give different priorities {4.3.2, 17.1}. The appropriate set of policies to shift development pathways thus depends on national circumstances and capacities.

Shifting development pathways towards sustainability needs to be supported by multilateral partnerships to strengthen suitable capacity, technological innovation (TS.6.5), and financial flows (TS.6.4). The international community can play a particularly key role by helping ensure the necessary broad participation in climate-mitigation efforts, including by countries at different development levels, through sustained support for policies and partnerships that support shifting development pathways towards sustainability while promoting equity and being mindful of different transition capacities. {4.3, 16.5, 16.6}



Box TS.3, Figure 1 | Shifting development pathways to increased sustainability: choices by a wide range of actors at key decision points on development pathways can reduce barriers and provide more tools to accelerate mitigation and achieve other Sustainable Development Goals. {4.7}

Policies can *shift* development pathways. There are examples of policies implemented in the pursuit of overall societal development objectives, such as job creation, macroeconomic stability, economic growth, and public health and welfare. In some countries, such policies are framed as part of a *Just Transition* (Box TS.3), however, they can have major influence on mitigative capacity, and hence can be seen as tools to broaden mitigation options (*medium confidence*) {4.3.3}. Coordinated policy mixes would need to orchestrate multiple actors – individuals, groups and collectives, corporate actors, institutions and infrastructure actors – to deepen decarbonisation and shift pathways towards sustainability. Shifts in one country may spill over to other countries. Shifting development pathways can jointly support mitigation and adaptation {4.4.2}. Some studies explore the risks of high complexity and potential delay attached to shifting development pathways. (Box TS.4, Figure TS.11) {4.4.3}

An increasing number of mitigation strategies up to 2050 (mid-term) have been developed by various actors. A growing number of such strategies aim at net zero GHG or CO_2 emissions, but it is not yet possible to draw global implications due to the limited size of sample (*medium evidence, low agreement*) {4.2.4}. Non-state actors are also engaging in a wide range of mitigation initiatives. When adding up emission reduction potentials, sub-national and non-state international cooperative initiatives could reduce emissions by up to about 20 $GtCO_2$-eq in 2030 (*limited evidence*, *medium agreement*) {4.2.3}. Yet perceived or real conflicts between mitigation and other SDGs can impede such action. If undertaken without precaution, accelerated mitigation is found to have significant implications for development objectives and macroeconomic costs at country level. The literature shows that the employment effect of mitigation policies tends to be limited on aggregate but can be significant at sectoral level (*limited evidence*, *medium agreement*). Detailed design of mitigation policies is critical for distributional impacts and avoiding lock-in (*high confidence*), though further research is needed in that direction. {4.2.6}

The literature identifies a broad set of enabling conditions that can both foster *shifting development pathways* and *accelerated mitigation* (*medium evidence, high agreement*). Policy integration is a necessary component of shifting development pathways, addressing multiple objectives. To this aim, mobilising a range of policies is preferable to single policy instruments (*high confidence*). {4.4.1}. Governance for climate mitigation and shifting development pathways is enhanced when tailored to national and local contexts. Improved institutions and effective governance enable ambitious action on climate and can help bridge implementation gaps (*medium evidence*, *high agreement*). Given that strengthening institutions may be a long-term endeavour, it needs attention in the near term {4.4.1}. Accelerated mitigation and shifting development pathways necessitates both redirecting existing financial flows from high- to low-emissions technologies and systems, and providing additional resources to overcome current financial barriers (*high confidence*) {4.4.1}. Opportunities exist in the near term to close the finance gap {15.2.2}. At the national level, public finance for actions promoting sustainable development helps broaden the scope of mitigation (*medium confidence*). Changes in behaviour and lifestyles are important to move beyond mitigation as incremental change, and when supporting shifts to more sustainable development pathways will broaden the scope of mitigation (*medium confidence*). {4.4.1, Figure 4.8}

Some enabling conditions can be put in place relatively quickly while some others may take time to establish underscoring the importance of early action (*high confidence*). Depending on context, some enabling conditions such as promoting innovation may take time to establish. Other enabling conditions, such as improved access to financing, can be put in place in a relatively short time frame, and can yield rapid results {4.4, Figure 5.14, 13.9, 14.5, 15.6, 16.3, 16.4, 16.5, Cross-Chapter Box 12 in Chapter 16}. Focusing on development pathways and considering how to shift them may also yield rapid results by providing tools to accelerate mitigation and achieve other sustainable development goals {4.4.1}. Charting just transitions to net zero may provide a vision, which policy measures can help achieve (Boxes TS.4 and TS.8).

Equity can be an important enabler, increasing the level of ambition for accelerated mitigation (*high confidence*) {4.5}. Equity deals with the distribution of costs and benefits and how these are shared, as per social contracts, national policy and international agreements. Transition pathways have distributional consequences such as large changes in employment and economic structure (*high confidence*). The *Just Transition* concept has become an international focal point tying together social movements, trade unions, and other key stakeholders to ensure equity is better accounted for in low-carbon transitions (Box TS.4). The effectiveness of cooperative action and the perception of fairness of such arrangements are closely related in that pathways that prioritise equity and allow broad stakeholder participation can enable broader consensus for the transformational change implicit in the need for deeper mitigation (*robust evidence*, *medium agreement*). (Box TS.4) {4.5, Figure 4.9}

Box TS.4 | Just Transition

The Just Transition framework refers to a set of principles, processes and practices aimed at ensuring that no people, workers, places, sectors, countries or regions are left behind in the move from a high-carbon to a low-carbon economy. It includes respect and dignity for vulnerable groups; creation of decent jobs; social protection; employment rights; fairness in energy access and use and social dialogue and democratic consultation with relevant stakeholders.

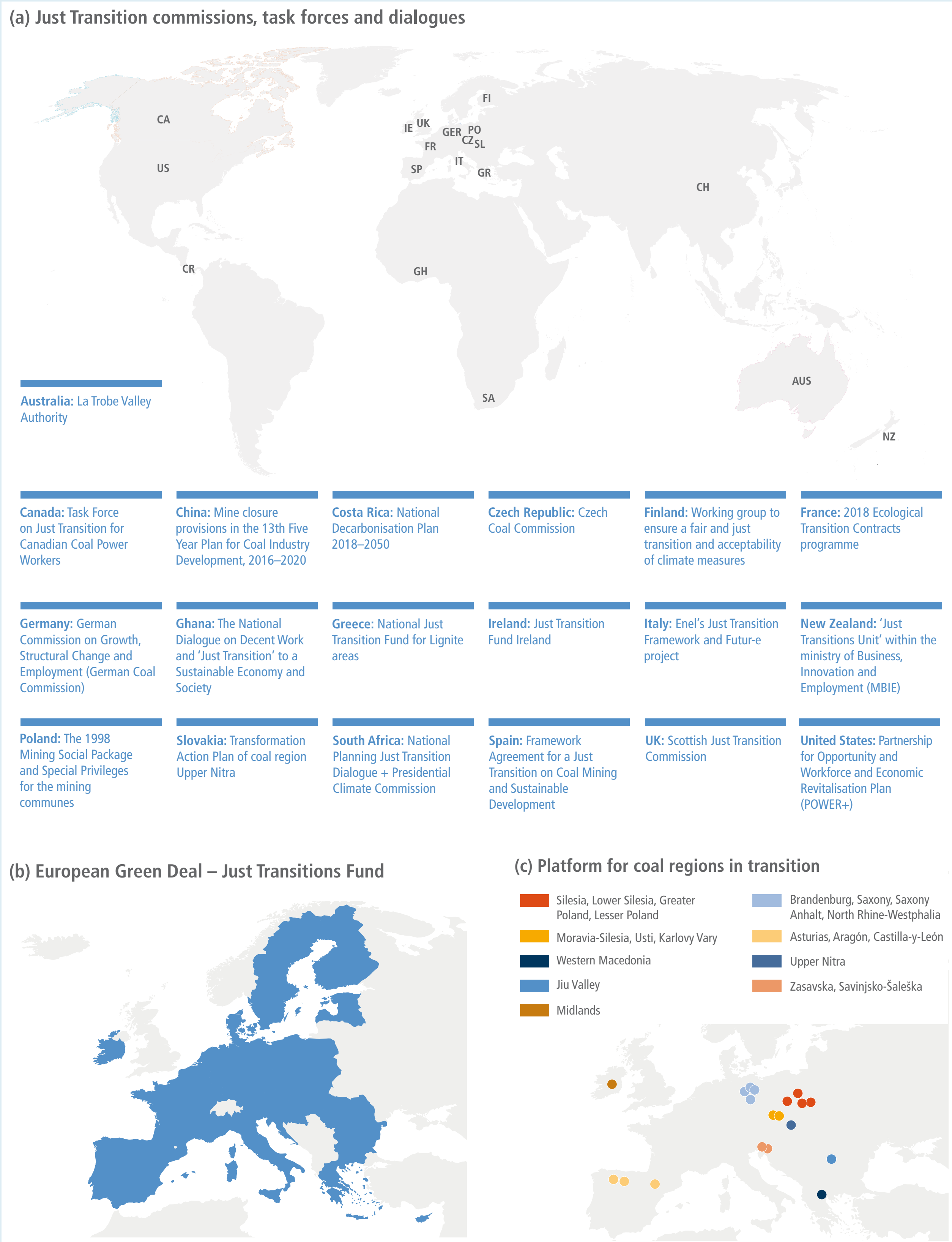
The concept has evolved, becoming prominent in the United States of America in 1980, related to environmental regulations that resulted in job losses from highly polluting industries. Traced from a purely labour movement, trade union space, the Just Transition framework emphasises that decent work and environmental protection are not incompatible. During COP 24, with the Just Transition Silesia Declaration, the concept gained in recognition and was signed by 56 heads of state.

Implicit in a Just Transition is the notion of well-being, equity and justice – the realisation that transitions are inherently disruptive and deliberate effort may be required to ensure communities dependent on fossil-fuel based economies and industries do not suffer disproportionately {Chapter 4}. 'Just Transitions' are integral to the European Union as mentioned in the EU Green Deal, the Scottish Government's development plans and other national low-carbon transition strategies. The US Green New Deal Resolution puts structural inequality, poverty mitigation, and 'Just Transitions' at its centre. There is a growing awareness of the need for shifting finance towards Just Transition in the context of COVID-19, in particular, public finance and governance have a major role in allowing a Just Transition more broadly {Chapter 15}.

In the immediate aftermath of the COVID-19 pandemic, low oil prices created additional financial problems for fossil fuel producer countries faced with loss of revenue and reduced fiscal latitude and space. Public spending and social safety nets associated with the proceeds from producer economies can be affected as assets become stranded and spending on strategic sustainable development goals such as free education and health-care services are neglected. Fiscal challenges are intricately linked to 'Just Transitions' and the management associated with sustainable energy transition. There is no certainty on how energy systems will recover post-COVID-19. However, 'Just Transitions' will have equity implications if stimulus packages are implemented without due regard for the differentiated scales and speeds and national and regional contexts, especially in the context of developing countries.

A Just Transition entails targeted and proactive measures from governments, agencies, and other non-state authorities to ensure that any negative social, environmental, or economic impacts of economy-wide transitions are minimised, whilst benefits are maximised for those disproportionally affected. These proactive measures include eradication of poverty, regulating prosperity and creating jobs in 'green' sectors. In addition, governments, polluting industries, corporations, and those more able to pay higher associated taxes, can pay for transition costs by providing a welfare safety net and adequate compensation to people, communities, and regions that have been impacted by pollution, or are marginalised, or are negatively impacted by a transition from a high- to low-carbon economy and society. There is, nonetheless, increased recognition that resources that can enable the transition, international development institutions, as well as other transitional drivers such as tools, strategies and finance, are scarce. A sample of global efforts is summarised in Box TS.4, Figure 1.

Box TS.4 (continued)



Box TS.4 Figure 1 | Just Transitions around the world, 2020. Panel (a) shows commissions, task forces, and dialogues behind a Just Transition in many countries. **Panel (b)** shows the funds related to the Just Transition within the European Union Green Deal. **Panel (c)** shows the European Union's Platform for Coal Regions in Transition. {Figure 4.9}

TS.4.2 Long-term Mitigation Pathways

The characteristics of a wide range of long-term mitigation pathways, their common elements and differences are assessed in Chapter 3. Differences between pathways typically represent choices that can steer the system in alternative directions through the selection of different combinations of response options (*high confidence*). More than 2000 quantitative emissions pathways were submitted to the AR6 scenarios database, of which more than 1200 pathways included sufficient information for the associated warming to be assessed (consistent with AR6 WGI methods). (Box TS.5) {3.2, 3.3}

Many pathways in the literature show how to limit global warming to 2°C (>67%) with no overshoot or to limit warming to 1.5°C (>50%) with limited overshoot compared to 1850–1900. The likelihood of limiting warming to 1.5°C with no or limited overshoot has dropped in AR6 WGIII compared to AR6 SR1.5 because global GHG emissions have risen since 2017, leading to higher near-term emissions (2030) and higher cumulative CO_2 emissions until the time of net zero (*medium confidence*). Only a small number of published pathways limit global warming to 1.5°C without overshoot over the course of the 21st century. {3.3, Annex III.II.3}

Mitigation pathways limiting warming to 1.5°C with no or limited overshoot reach 50% CO_2 reductions in the 2030s, relative to 2019, then reduce emissions further to reach net zero CO_2 emissions in the 2050s. Pathways limiting warming to 2°C (>67%) reach 50% reductions in the 2040s and net zero CO_2 by the 2070s (*medium confidence*). (Figure TS.10, Box TS.6) {3.3}

Cost-effective mitigation pathways assuming immediate action to limit warming to 2°C (>67%) are associated with net global GHG emissions of 30–49 $GtCO_2$-eq yr^{-1} by 2030 and 14–27 $GtCO_2$-eq yr^{-1} by 2050 (*medium confidence*). This corresponds to reductions, relative to 2019 levels, of 13–45% by 2030 and 52–76% by 2050. Pathways that limit global warming to below 1.5°C with no or limited overshoot require a further acceleration in the pace of transformation, with net GHG emissions typically around 21–36 $GtCO_2$-eq yr^{-1} by 2030 and 1–15 $GtCO_2$-eq yr^{-1} by 2050; this corresponds to reductions of 34–60% by 2030 and 73–98% by 2050 relative to 2019 levels. {3.3}

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Box TS.5 | Illustrative Mitigation Pathways (IMPs), and Shared Socio-economic Pathways (SSPs)

The Illustrative Mitigation Pathways (IMPs)

The over 2500 model-based pathways submitted to the AR6 scenarios database pathways explore different possible evolutions of future energy and land use (with and without climate policy) and the consequences for greenhouse gas emissions.

From the full range of pathways, five archetype scenarios – referred to in this report as *Illustrative Mitigation Pathways* (IMPs) – were selected to illustrate key mitigation-strategy themes that flow through several chapters in this report. A further two *pathways illustrative of high emissions* assuming continuation of current policies or moderately increased action were selected to show the consequences of current policies and pledges. Together these pathways provide illustrations of potential future developments that can be shaped by human choices, including: Where are current policies and pledges leading us? What is needed to reach specific temperature goals? What are the consequences of using different strategies to meet these goals? What are the consequences of delay? How can we shift development from current practices to give higher priority to sustainability and the SDGs?

Each of the IMPs comprises: a *storyline* and a *quantitative illustration*. The *storyline* describes the key characteristics of the pathway qualitatively; the *quantitative illustration* is selected from the literature on long-term scenarios to effectively represent the IMP numerically. The five Illustrative Mitigation Pathways (IMPs) each emphasise a different scenario element as its defining feature, and are named accordingly: heavy reliance on renewables (IMP-Ren), strong emphasis on low demand for energy (IMP-LD), extensive use of carbon dioxide removal (CDR) in the energy and the industry sectors to achieve net negative emissions (IMP-Neg), mitigation in the context of broader sustainable development and shifting development pathways (IMP-SP), and the implications of a less rapid and gradual strengthening of near-term mitigation actions (IMP-GS). In some cases, sectoral chapters may use different quantifications that follow the same storyline narrative but contain data that better exemplify the chapter's assessment. Some IMP variants are also used to explore the sensitivity around alternative temperature goals. {3.2, 3.3}

The two additional *pathways illustrative of higher emissions* are current policies (CurPol) and moderate action (ModAct).

This framework is summarised in Box TS.5, Table.1 below, which also shows where the IMPs are situated with respect to the classification of emissions scenarios into warming levels (C1–C8) introduced in Chapter 3, and the CMIP6 (Coupled Model Intercomparison Project 6) scenarios used in the AR6 WGI report.

Box TS.5 (continued)

Box TS.5, Table.1 | *Illustrative Mitigation Pathways (IMPs)* and *pathways illustrative of higher emissions* in relation to scenarios' categories, and CMIP6 scenarios.

Classification of emissions scenarios into warming levels: C1–C8	Pathways illustrative of higher emissions	Illustrative mitigation pathways (IMPs)	CMIP6 scenarios
C8 exceeding warming of 4°C (≥50%)			SSP5-8.5
C7 limit warming to 4°C (>50%)	CurPol		SSP3-7.0
C6 limit warming to 3°C (>50%)	ModAct		SSP2-4.5
C5 limit warming to 2.5°C (>50%)			SSP4-3.7
C4 limit warming to 2°C (>50%)			
C3 limit warming to 2°C (>67%)		IMP-GS (Sensitivities: Neg; Ren)	SSP2-2.6
C2 return warming to 1.5°C (>50%) after a high overshoot		IMP-Neg	
C1 limit warming to 1.5°C (>50%) with no or limited overshoot		IMP-LD IMP-Ren IMP-SP	SSP1-1.9

The Shared Socio-economic Pathways (SSPs)

First published in 2017, the Shared Socio-economic Pathways (SSPs) are alternative projections of socio-economic developments that may influence future GHG emissions.

The initial set of SSP narratives described worlds with different challenges to mitigation and adaptation: SSP1 (*sustainability*), SSP2 (*middle of the road*), SSP3 (*regional rivalry*), SSP4 (*inequality*) and SSP5 (*rapid growth*). The SSPs were subsequently quantified in terms of energy, land-use change, and emission pathways for both (i) no-climate-policy reference scenarios and (ii) mitigation scenarios that follow similar radiative forcing pathways as the representative concentration pathways (RCPs) assessed in AR5 WGI. {3.2.3}

Most of the scenarios in the AR6 database are SSP-based. The majority of the assessed scenarios are consistent with SSP2. Using the SSPs permits a more systematic assessment of future GHG emissions and their uncertainties than was possible in AR5. The main emissions drivers across the SSPs include growth in population reaching 8.5–9.7 billion by 2050, and an increase in global GDP of 2.7–4.1% per year between 2015 and 2050. Final energy demand in the absence of any new climate policies is projected to grow to around 480 to 750 EJ yr^{-1} in 2050 (compared to around 390 EJ yr^{-1} in 2015) (*medium confidence*). The highest emissions scenarios in the literature result in global warming of >5°C by 2100, based on assumptions of rapid economic growth and pervasive climate policy failures (*high confidence*). {3.3}

Table TS.3 | GHG, CO_2 emissions and warming characteristics of different mitigation pathways submitted to the AR6 scenarios database, and as categorised in the climate assessment. {Table 3.2}

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]				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]	2020–2025 (100%) [2020–2025]		2050–2055 (100%) [2035–2070]	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 TS.3 (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]	2020–2025 (100%) [2020–2030]		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]			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%) [2020–2090]	2020–2025 (97%)	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%) [2040–…]	2090–2095 (56%)				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 TS.3 (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 and Table 3.1.

[c] All global warming levels are relative to 1850–1900. (See footnote n below and Box SPM.1 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]. (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. {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. {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. (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.

Pathways following current NDCs until 2030 reach annual emissions of 47–57 $GtCO_2$-eq yr^{-1} by 2030, thereby making it impossible to limit warming to 1.5°C (>50%) with no or limited overshoot and strongly increasing the challenge of limiting warming to 2°C (>67%) (*high confidence*). A high overshoot of 1.5°C increases the risks from climate impacts and increases dependence on large-scale carbon dioxide removal (CDR) from the atmosphere. A future consistent with current NDCs implies higher fossil fuel deployment and lower reliance on low-carbon alternatives until 2030, compared to mitigation pathways describing immediate action that limits warming to 1.5°C (>50%) with no or limited overshoot, or limits warming to 2°C (>67%) and below. After following the NDCs to 2030, to limit warming to 2°C (>67%) the pace of global GHG emission reductions would need to abruptly increase from 2030 onward to an average of 1.3–2.1 $GtCO_2$-eq per year between 2030 and 2050. This is similar to the global CO_2 emission reductions in 2020 that occurred due to the COVID-19 pandemic lockdowns, and around 70% faster than in pathways where immediate action is taken to limit warming to 2°C (>67%). Accelerating emission reductions after following an NDC pathway to 2030 would also be particularly challenging because of the continued buildup of fossil fuel infrastructure that would take place between now and 2030. (TS4.1, Table TS.3) {3.5, 4.2}

Pathways accelerating action compared to current NDCs – that reduce annual GHG emissions to 47 (38–51) $GtCO_2$-eq by 2030 (which is 3–9 $GtCO_2$-eq below projected emissions from fully implementing current NDCs) – make it less challenging to limit warming to 2°C (>67%) after 2030 (*medium confidence*). The accelerated action pathways are characterised by a global, but regionally differentiated, roll-out of regulatory and pricing policies. Compared to current NDCs, they describe less fossil fuel use and more low-carbon fuel use until 2030; they narrow, but do not close the gap to pathways that assume immediate global action using all available least-cost abatement options. All delayed or accelerated action pathways limiting warming to below 2°C (>67%) converge to a global mitigation regime at some point after 2030 by putting a significant value on reducing carbon and other GHG emissions in all sectors and regions. {3.5}

In mitigation pathways, peak warming is determined by the cumulative net CO_2 emissions until the time of net zero CO_2 together with the warming contribution of other GHGs and climate forcers at that time (*high confidence*). Cumulative net CO_2 emissions from 2020 to the time of net zero CO_2 are 510 (330–710) $GtCO_2$ in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot and 890 (640–1160) $GtCO_2$ in pathways limiting warming to 2°C (>67%). These estimates are consistent with the AR6 WGI assessment of remaining carbon budgets adjusting for methodological differences and non-CO_2 warming. {3.3, Box 3.4}

Rapid reductions in non-CO_2 GHGs, particularly CH_4, would lower the level of peak warming (*high confidence*). Non-CO_2 emissions – at the time of reaching net zero CO_2 – range between 4–11 $GtCO_2$-eq yr^{-1} in pathways limiting warming to 2°C (>67%) or below. CH_4 is reduced by around 20% (1–46%) in 2030 and almost 50% (26–64%) in 2050, relative to 2019. CH_4 emission reductions in pathways limiting warming to 1.5°C with no or limited overshoot are substantially higher by 2030, 33% (19–57%), but only moderately so by 2050, 50% (33–69%). CH_4 emissions reductions are thus attainable at comparatively low costs, but, at the same time, reductions are limited in scope in most 1.5°C–2°C pathways. Deeper CH_4 emissions reductions by 2050 could further constrain the peak warming. N_2O emissions are also reduced, but similar to CH_4, N_2O emission reductions saturate for more stringent climate goals. The emissions of cooling aerosols in mitigation pathways decrease as fossil fuels use is reduced. The overall impact on non-CO_2-related warming combines all these factors. {3.3}

Net zero GHG emissions imply net negative CO_2 emissions at a level that compensates for residual non-CO_2 emissions. Only 30% of the pathways limiting warming to 2°C (>67%) or below reach net zero GHG emissions in the 21st century (*high confidence*). In those pathways reaching net zero GHGs, net zero GHGs is achieved around 10–20 years later than net zero CO_2 is achieved (*medium confidence*). The reported quantity of residual non-CO_2 emissions depends on accounting choices, and in particular the choice of GHG metric (Box TS.2). Reaching and sustaining global net zero GHG emissions – when emissions are measured and reported in terms of GWP100 – results in a gradual decline in temperature (*high confidence*). (Box TS.6) {3.3}

Pathways that limit warming to 2°C (>67%) or lower exhibit substantial reductions in emissions from all sectors (*high confidence*). Pathways that limit warming to 1.5°C (>50%) with no or limited overshoot entail CO_2 emissions reductions between 2019 and 2050 of around 77% (31–96%) for energy demand, around 115% (90–167%) for energy supply, and around 148% (94–387%) for AFOLU.[16] In pathways that limit warming to 2°C (>67%), projected CO_2 emissions are reduced between 2019 and 2050 by around 49% for energy demand, 97% for energy supply, and 136% for AFOLU (*medium confidence*). {3.4}

If warming is to be limited, delaying or failing to achieve emissions reductions in one sector or region necessitates compensating reductions in other sectors or regions (*high confidence*). Mitigation pathways show differences in the timing of decarbonisation and when net zero CO_2 emissions are achieved across sectors and regions. At the time of *global net zero CO_2 emissions*, emissions in some sectors and regions are positive while others are negative; whether specific sectors and regions are positive or negative depends on the availability and cost of mitigation options in those regions, and the policies implemented. In cost-effective mitigation pathways, the energy supply sector typically reaches net zero CO_2 before the economy as a whole, while the demand sectors reach net zero CO_2 later, if ever (*high confidence*). (Figure TS.10) {3.4}

Pathways limiting warming to 2°C (>67%) or 1.5°C involve substantial reductions in fossil fuel consumption and a near elimination of coal use without CCS (*high confidence*). These pathways show an increase in low-carbon energy, with 88% (69–97%) of primary energy coming from low-carbon sources by 2100. {3.4}

16 Reductions greater than 100% in energy supply and AFOLU indicate that these sectors would become carbon sinks.

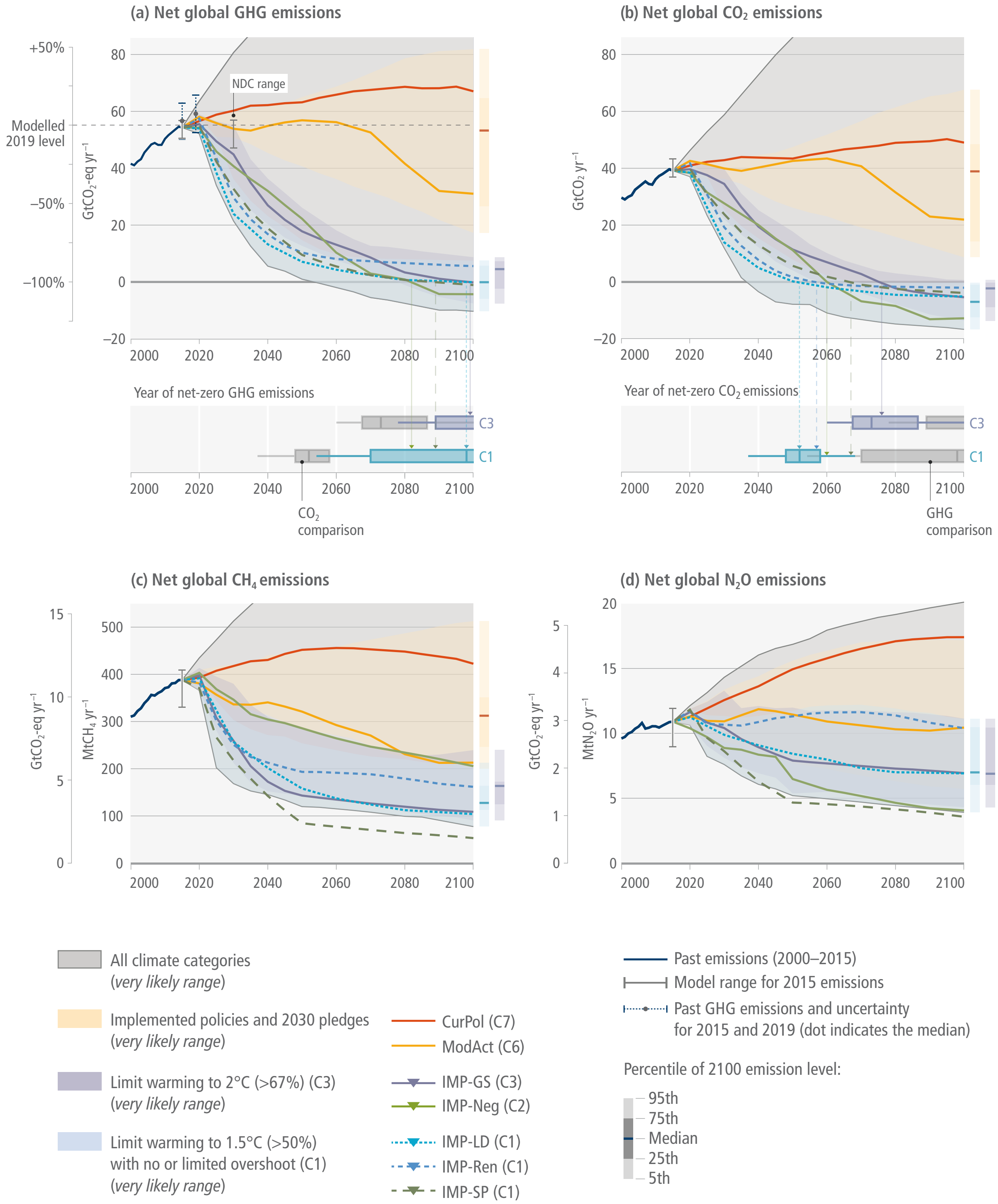


Figure TS.10 | Mitigation pathways that limit warming to 1.5°C, or 2°C, involve deep, rapid and sustained emissions reductions. Net zero CO_2 and net zero GHG emissions are possible through different mitigation portfolios.

Net zero CO_2 and net zero GHG emissions are possible through different modelled mitigation pathways.

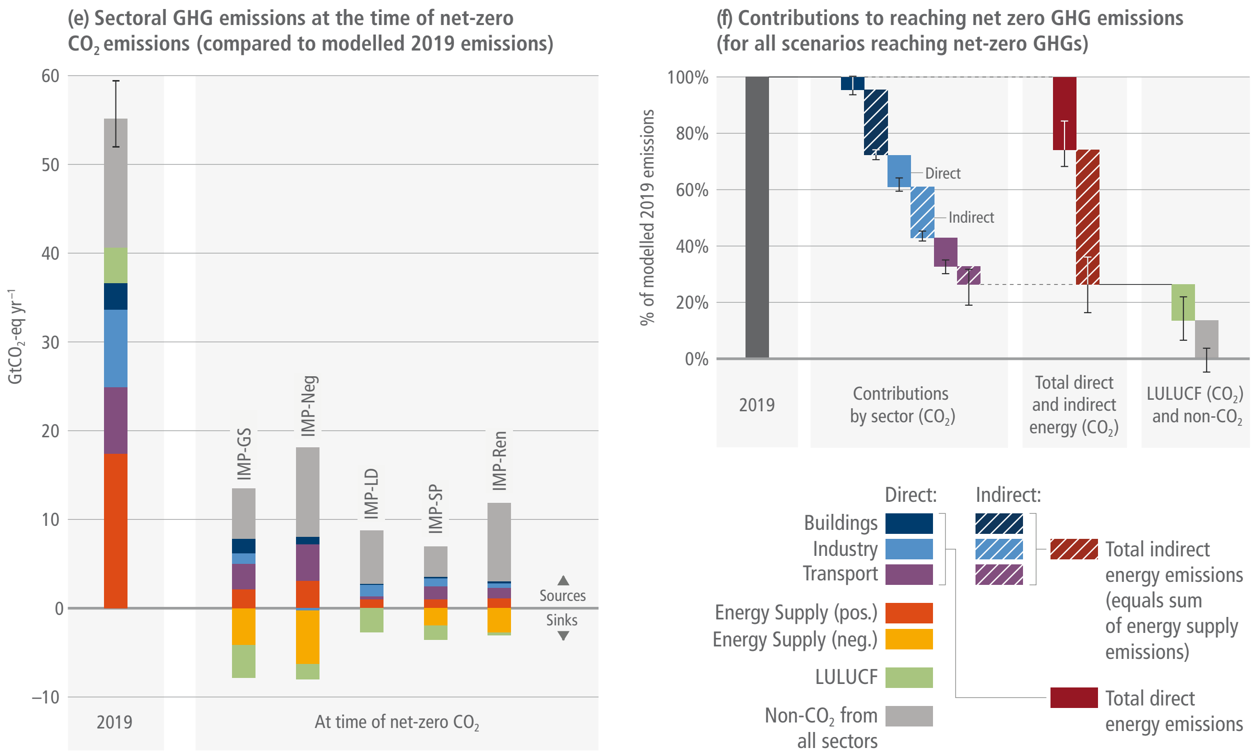


Figure TS.10 (continued): Mitigation pathways that limit warming to 1.5°C, or 2°C, involve deep, rapid and sustained emissions reductions. Net zero CO_2 and net zero GHG emissions are possible through different mitigation portfolios. Panels (a) and (b) show the development of global GHG and CO_2 emissions 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.[17] **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}

Stringent emissions reductions at the level required for 2°C or 1.5°C are achieved through the increased electrification of buildings, transport, and industry, consequently all pathways entail increased electricity generation (*high confidence*). Nearly all electricity in pathways limiting warming to 2°C (>67%) or 1.5°C (>50%) is also from low- or no-carbon technologies, with different shares across pathways of: nuclear, biomass, non-biomass renewables, and fossil fuels in combination with CCS. {3.4}

Measures required to limit warming to 2°C (>67%) or below can result in large-scale transformation of the land surface (*high confidence*). These pathways are projected to reach net zero CO_2 emissions in the AFOLU sector between the 2020s and 2070.

17 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.

Pathways limiting warming to 1.5°C with no or limited overshoot show an increase in forest cover of about 322 (–67 to 890) million ha in 2050 (*high confidence*). In these pathways the cropland area to supply biomass for bioenergy (including bioenergy with carbon capture and storage (BECCS)) is around 199 (56–482) million ha in 2050. The use of bioenergy can lead to either increased or reduced emissions, depending on the scale of deployment, conversion technology, fuel displaced, and how, and where, the biomass is produced (*high confidence*). {3.4}

Pathways limiting warming to 2°C (>67%) or 1.5°C (>50%) require some amount of CDR to compensate for residual GHG emissions, even alongside substantial direct emissions reductions are achieved in all sectors and regions (*high confidence*). CDR deployment in pathways serves multiple purposes: accelerating the pace of emissions reductions, offsetting residual emissions, and creating the option for net negative CO_2 emissions in case temperature reductions need to be achieved in the long term (*high confidence*). CDR options in pathways are mostly limited to BECCS, afforestation and direct air CO_2 capture and storage (DACCS). CDR through some measures in AFOLU can be maintained for decades but not over the very long term because these sinks will ultimately saturate (*high confidence*). {3.4}

Mitigation pathways show reductions in energy demand, relative to reference scenarios that assume continuation of current policies, through a diverse set of demand-side interventions (*high confidence*). Bottom-up and non-IAM studies show significant potential for demand-side mitigation. A stronger emphasis on demand-side mitigation implies less dependence on CDR and, consequently, reduced pressure on land and biodiversity. {3.4, 3.7}

Limiting warming requires shifting energy investments away from fossil fuels and towards low-carbon technologies (*high confidence*). The bulk of investments are needed in medium- and low-income regions. Investment needs in the electricity sector are on average 2.3 trillion USD2015 yr^{-1} over 2023–2052 for pathways limiting temperature to 1.5°C (>50%) with no or limited overshoot, and 1.7 trillion USD2015 yr^{-1} for pathways limiting warming to 2°C (>67%). {3.6.1}

Pathways *that* avoid overshoot of 2°C (>67%) warming require more rapid near-term transformations and are associated with higher upfront transition costs, but at the same time bring long-term gains for the economy as well as earlier benefits in avoided climate change impacts (*high confidence*). This conclusion is independent of the discount rate applied, though the modelled cost-optimal balance of mitigation action over time does depend on the discount rate. Lower discount rates favour earlier mitigation, reducing reliance on CDR and temperature overshoot. {3.6.1, 3.8}

Mitigation pathways *that* limit warming to 2°C (>67%) entail losses in global GDP with respect to reference scenarios of between 1.3% and 2.7% in 2050. In pathways limiting warming to 1.5°C (>50%) with no or limited overshoot, losses are between 2.6% and 4.2%. These estimates do not account for the economic benefits of avoided climate change impacts (*medium confidence*). In mitigation pathways limiting warming to 2°C (>67%), marginal abatement costs of carbon are about 90 (60–120) USD2015 tCO_2 in 2030 and about 210 (140–340) USD2015/tCO_2 in 2050. This compares with about 220 (170–290) USD2015 tCO_2 in 2030 and about 630 (430–990) USD2015 tCO_2 in 2050[18] in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. Reference scenarios, in the AR6 scenarios database, describe possible emission trajectories in the absence of new stringent climate policies. Reference scenarios have a broad range depending on socio-economic assumptions and model characteristics. {3.2.1, 3.6.1}

The global benefits of pathways limiting warming to 2°C (>67%) outweigh global mitigation costs over the 21st century, if aggregated economic impacts of climate change are at the moderate to high end of the assessed range, and a weight consistent with economic theory is given to economic impacts over the long term. This holds true even without accounting for benefits in other sustainable development dimensions or non-market damages from climate change (*medium confidence*). The aggregate global economic repercussions of mitigation pathways include: the macroeconomic impacts of investments in low-carbon solutions and structural changes away from emitting activities; co-benefits and adverse side effects of mitigation; avoided climate change impacts; and reduced adaptation costs. Existing quantifications of the global aggregate economic impacts show a strong dependence on socio-economic development conditions, as these shape exposure and vulnerability and adaptation opportunities and responses. Avoided impacts for poorer households and poorer countries represent a smaller share in aggregate economic quantifications expressed in GDP or monetary terms, whereas their well-being and welfare effects are comparatively larger. When aggregate economic benefits from avoided climate change impacts are accounted for, mitigation is a welfare-enhancing strategy (*high confidence*). {3.6.2}

The economic benefits on 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*). {3.6.3}

Differences in aggregate employment between mitigation pathways and reference scenarios are relatively small, although there may be substantial reallocations across sectors, with job creation in some sectors and job losses in others (*medium confidence*). The net employment effect (and whether employment increases or decreases) depends on the scenario assumptions, modelling framework, and modelled policy design. Mitigation has implications for employment through multiple channels, each of which impacts geographies, sectors and skill categories differently. {3.6.4}

18 Numbers in parentheses represent he interquartile range of the scenario samples.

The economic repercussions of mitigation vary widely across regions and households, depending on policy design and the level of international cooperation (*high confidence*). Delayed global cooperation increases policy costs across regions, especially in those that are relatively carbon intensive at present (*high confidence*). Pathways with uniform carbon values show higher mitigation costs in more carbon-intensive regions, in fossil fuel-exporting regions, and in poorer regions (*high confidence*). Aggregate quantifications expressed in GDP or monetary terms undervalue the economic effects on households in poorer countries; the actual effects on welfare and well-being are comparatively larger (*high confidence*). Mitigation at the speed and scale required to limit warming to 2°C (>67%) or below implies deep economic and structural changes, thereby raising multiple types of distributional concerns across regions, income classes, and sectors (*high confidence*). (Box TS.7) {3.6.1, 3.6.4}

Box TS.6 | Understanding Net Zero CO_2 and Net Zero GHG Emissions

Reaching net zero CO_2 emissions[19] globally along with reductions in other GHG emissions is necessary to halt global warming at any level. At the point of net zero, the amount of CO_2 human activity is putting into the atmosphere equals the amount of CO_2 human activity is removing from the atmosphere. Reaching and sustaining net zero CO_2 emissions globally would stabilise CO_2-induced warming. Moving to net negative CO_2 emissions globally would reduce peak cumulative net CO_2 emissions – which occurs at the time of reaching net zero CO_2 emissions – and lead to a peak and decline in CO_2-induced warming. {Cross-Chapter Box 3 in Chapter 3}

Reaching net zero CO_2 emissions sooner can reduce cumulative CO_2 emissions and result in less human-induced global warming. Overall human-induced warming depends not only on CO_2 emissions but also on the contribution from other anthropogenic climate forcers, including aerosols and other GHGs (e.g., CH_4 and F-gases). To halt total human-induced warming, emissions of other GHGs, in particular CH_4, need to be strongly reduced.

In the AR6 scenario database, global emissions pathways limi warming to 1.5°C (>50%) with no or limited overshoot reach net zero CO_2 emissions between 2050–2055 (2035–2070) (median and 5–95th percentile ranges; 100% of pathways); pathways limiting warming to 2°C (>67%) reach net zero CO_2 emissions between 2070–2075 (2055–…) (median and 5–95th percentile ranges; 90% of pathways). This is later than assessed in the AR6 SR1.5 primarily due to more pathways in the literature that approach net zero CO_2 emissions more gradually after a rapid decline of emissions until 2040. (Box TS.6, Figure 1)

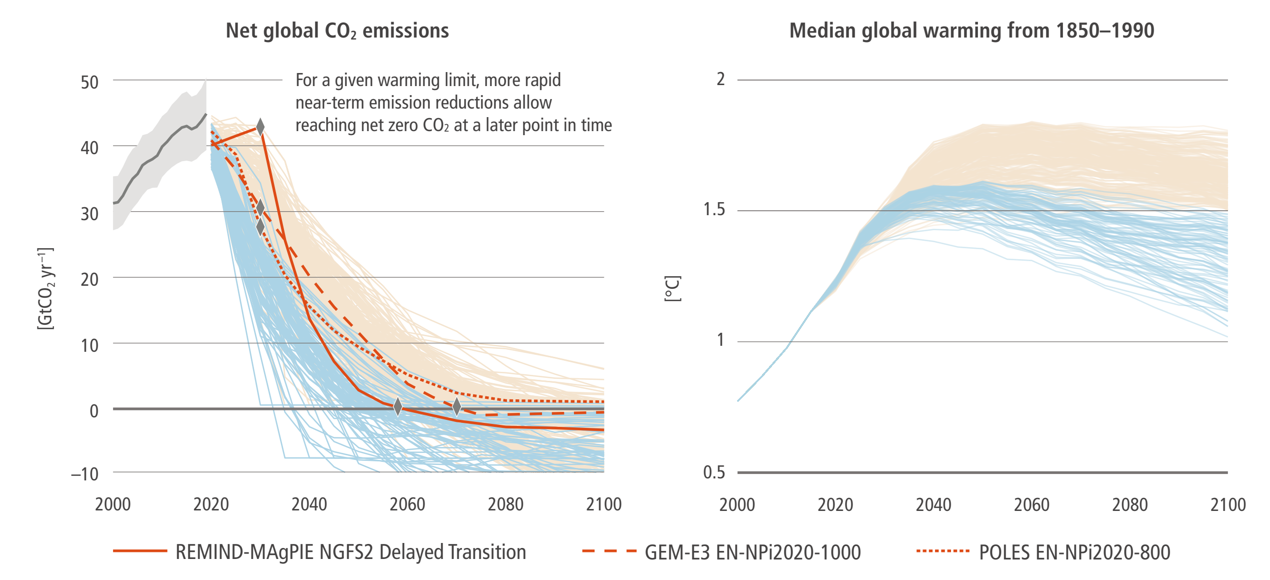
It does not mean that the world has more time for emissions reductions while still limiting warming to 1.5°C than reported in the SR1.5. It only means that the exact timing of reaching net zero CO_2 after a steep decline of CO_2 emissions until 2040 can show some variation. The SR1.5 median value of 2050 is still close to the middle of the current range. If emissions are reduced less rapidly in the period up to 2030, an earlier net zero year is needed.

Reaching net zero GHG emissions requires net negative CO_2 emissions to balance residual CH_4, N_2O and F-gas emissions. If achieved globally, net zero GHG emissions would reduce global warming from an earlier peak. Around half global emission pathways limiting warming to 1.5°C (>50%), and a third of pathways limiting warming to 2°C (>67%), reach net zero GHG emissions (based on GWP100) in the second half of the century, around 10 to 40 years later than net zero CO_2 emissions. They show warming being halted at some peak value followed by a gradual decline towards the end of the century. The remainder of the pathways do not reach net zero GHG emissions during the 21st century and show little decline of warming after it stabilised.

Global net zero CO_2 or GHG emissions can be achieved even while some sectors and regions continue to be net emitters, provided that others achieve net GHG removal. Sectors and regions have different potentials and costs to achieve net zero or even net GHG removal. The adoption and implementation of net zero emission targets by countries and regions depends on multiple factors, including equity and capacity criteria and international and cross-sectoral mechanisms to balance emissions and removals. The formulation of net zero pathways by countries will benefit from clarity on scope, plans of action, and fairness. Achieving net zero emission targets relies on policies, institutions and milestones against which to track progress.

19 In this assessment the terms *net zero CO_2* emissions and *carbon neutrality* have different meanings and are only equivalent at the global scale. At the scale of regions, or sectors, each term applies different system boundaries. This is also the case for the related terms *net zero GHG* and *GHG neutrality*. {Cross-Chapter Box 3 in Chapter 3}

Box TS.6 (continued)



Box TS.6, Figure 1 | CO_2 Emissions (panel (a)) and temperature change (panel (b)) of three alternative pathways limiting warming to 2°C (>67%) and reaching net zero CO_2 emissions at different points in time. Limiting warming to a specific level can be consistent with a range of dates when net zero CO_2 emissions need to be achieved. This difference in the date of net zero CO_2 emissions reflects the different emissions profiles that are possible while staying within a specific carbon budget and the associated warming limit. Shifting the year of net zero to a later point in time (>2050), however, requires more rapid and deeper near-term emissions reductions (in 2030 and 2040) if warming is to be limited to the same level. Funnels show pathways limiting warming to 1.5°C (>50%) with no or limited overshoot (light blue) and limiting warming to 2°C (>67%) (beige).

Box TS.7 | The Long-term Economic Benefits of Mitigation from Avoided Climate Change Impacts

Integrated studies use either a cost-effectiveness analysis (CEA) approach (minimising the total mitigation costs of achieving a given policy goal) or a cost-benefit analysis (CBA) approach (balancing the cost and benefits of climate action). In the majority of studies that have produced the body of work on the cost of mitigation assessed in this report, a CEA approach is adopted, and the feedbacks of climate change impacts on the economic development pathways are not accounted for. This omission of climate impacts leads to overly optimistic economic projections in the reference scenarios, in particular in reference scenarios with no or limited mitigation action where the extent of global warming is the greatest. Mitigation cost estimates computed against no or limited policy reference scenarios therefore omit economic benefits brought by avoided climate change impact along mitigation pathways. {1.7, 3.6.1}

The difference in aggregate economic impacts from climate change between two given temperature levels represents the aggregate economic benefits arising from avoided climate change impacts due to mitigation action. Estimates of these benefits vary widely, depending on the methodology used and impacts included, as well as on assumed socio-economic development conditions, which shape exposure and vulnerability. The aggregate economic benefits of avoiding climate impacts increase with the stringency of the mitigation. Global economic impact studies with regional estimates find large differences across regions, with developing and transitional economies typically more vulnerable. Furthermore, avoided impacts for poorer households and poorer countries represent a smaller share in aggregate quantifications expressed in GDP terms or monetary terms, compared to their influence on well-being and welfare (*high confidence*). {3.6.2, Cross-Working Group Box 1 in Chapter 3}

Box TS.7 (continued)

CBA analysis and CBA integrated assessment models (IAMs) remain limited in their ability to represent all damages from climate change, including non-monetary damages, and capture the uncertain and heterogeneous nature of damages and the risk of catastrophic damages, such that other lines of evidence should be considered in decision-making. However, emerging evidence suggests that, even without accounting for co-benefits of mitigation on other sustainable development dimensions, the global benefits of pathways limiting warming to 2°C (>67%) outweigh global mitigation costs over the 21st century (*medium confidence*). Depending on the study, the reason for this result lies in assumptions of economic damages from climate change in the higher end of available estimates, in the consideration of risks of tipping points or damages to natural capital and non-market goods, or in the combination of updated representations of carbon cycle and climate modules, updated damage estimates and updated representations of economic and mitigation dynamics. In the studies that perform a sensitivity analysis, this result is found to be robust to a wide range of assumptions on social preferences (in particular on inequality aversion and pure rate of time preference), and holds except if assumptions of economic damages from climate change are in the lower end of available estimates and the pure rate of time preference is in the higher range of values usually considered (typically above 1.5%). However, although such pathways bring overall net benefits over time (in terms of aggregate discounted present value), they involve distributional consequences between and within generations. {3.6.2}

TS.5 Mitigation Responses in Sectors and Systems

Chapters 5 to 12 assess recent advances in knowledge in individual sectors and systems. These chapters – *Energy* (Chapter 6), *Urban and Other Settlements* (Chapter 8), *Transport* (Chapter 10), *Buildings* Chapter 9), *Industry* (Chapter 11), and *Agriculture, Forestry and Other Land Use (AFOLU)* (Chapter 7) – correspond broadly to the IPCC National Greenhouse Gas Inventory reporting categories and build on similar chapters in previous WGIII reports. Chapters 5 and 12 tie together the cross-sectoral aspects of this group of chapters including the assessment of costs and potentials, demand-side aspects of mitigation, and carbon dioxide removal (CDR).

TS.5.1 Energy

A broad-based approach to deploying energy-sector mitigation options can reduce emissions over the next ten years and set the stage for still deeper reductions beyond 2030 (*high confidence*). There are substantial, cost-effective opportunities to reduce emissions rapidly, including in electricity generation, but near-term reductions will not be sufficient to limit warming to 2°C (>67%) or limit warming to 1.5°C (>50%) with no or limited overshoot. {6.4, 6.6, 6.7}

Warming cannot be limited to 2°C or 1.5°C without rapid and deep reductions in energy system CO_2 and GHG emissions (*high confidence*). In scenarios limiting warming to 1.5°C (>50%) with no or limited overshoot (*likely* below 2°C), net energy system CO_2 emissions fall by 87–97% (interquartile range 60–79%) in 2050. In 2030, in scenarios limiting warming to 1.5°C with no or limited overshoot, net CO_2 and GHG emissions fall by 35–51% and 38–52% respectively. In scenarios limiting warming to 1.5°C with no or limited overshoot (*likely* below 2°C), net electricity sector CO_2 emissions reach zero globally between 2045 and 2055 (2050 and 2080) (*high confidence*). {6.7}

Limiting warming to 2°C or 1.5°C will require substantial energy system changes over the next 30 years. This includes reduced fossil fuel consumption, increased production from low- and zero-carbon energy sources, and increased use of electricity and alternative energy carriers (*high confidence*). Coal consumption without CCS falls by 67–82% (interquartile range) in 2030 in scenarios limiting warming to 1.5°C with no or limited overshoot. Oil and gas consumption fall more slowly. Low-carbon sources produce 93–97% of global electricity by 2050 in scenarios that limit warming to 2°C (>67%) or below. In scenarios limiting warming to 1.5°C with no or limited overshoot (*likely* below 2°C), electricity supplies 48–58% (36–47%) of final energy in 2050, up from 20% in 2019. {6.7}

Net zero energy systems will share common characteristics, but the approach in every country will depend on national circumstances (*high confidence*). Common characteristics of net-zero energy systems will include: (i) electricity systems that produce no net CO_2 or remove CO_2 from the atmosphere; (ii) widespread electrification of end uses, including light-duty transport, space heating, and cooking; (iii) substantially lower use of fossil fuels than today; (iv) use of alternative energy carriers such as hydrogen, bioenergy, and ammonia to substitute for fossil fuels in sectors less amenable to electrification; (v) more efficient use of energy than today; (vi) greater energy system integration across regions and across components of the energy system; and (vii) use of CO_2 removal including DACCS and BECCS to offset residual emissions. {6.6}

Energy demands and energy sector emissions have continued to rise (*high confidence*). From 2015 to 2019, global final energy consumption grew by 6.6%, CO_2 emissions from the global energy system grew by 4.6%, and total GHG emissions from energy supply rose by 2.7%. Fugitive CH_4 emissions from oil, gas, and coal, accounted for 18% of GHG emissions in 2019. Coal electricity capacity grew by 7.6% between 2015 and 2019, as new builds in some countries offset declines in others. Total consumption of oil and oil products increased by 5%, and natural gas consumption grew by 15%. Declining energy intensity in almost all regions has been balanced by increased energy consumption. {6.3}

The unit costs for several key energy system mitigation options have dropped rapidly over the last five years, notably solar PV, wind power, and batteries (*high confidence*). From 2015 to 2020, the costs of electricity from PV and wind dropped 56% and 45%, respectively, and battery prices dropped by 64%. Electricity from PV and wind is now cheaper than electricity from fossil sources in many regions, electric vehicles are increasingly competitive with internal combustion engines, and large-scale battery storage on electricity grids is increasingly viable. (Figure TS.7) {6.3, 6.4}

Global wind and solar PV capacity and generation have increased rapidly driven by policy, societal pressure to limit fossil generation, low interest rates, and cost reductions (*high confidence*). Solar PV grew by 170% (to 680 TWh); wind grew by 70% (to 1420 TWh) from 2015 to 2019. Solar PV and wind together accounted for 21% of total low-carbon electricity generation and 8% of total electricity generation in 2019. Nuclear generation grew 9% between 2015 and 2019 and accounted for 10% of total generation in 2019 (2790 TWh); hydro-electric power grew by 10% and accounted for 16% (4290 TWh) of total generation. In total, low- and zero-carbon electricity generation technologies produced 37% of global electricity in 2019. {6.3, 6.4}

If investments in coal and other fossil infrastructure continue, energy systems will be locked-in to higher emissions, making it harder to limit warming to 2°C or 1.5°C (*high confidence*). Many aspects of the energy system – physical infrastructure; institutions, laws, and regulations; and behaviour – are resistant to change or take many years to change. New investments in coal-fired electricity without CCS are inconsistent with limiting warming to well below 2°C. {6.3, 6.7}

Limiting warming to 2°C or 1.5°C will strand fossil-related assets, including fossil infrastructure and unburned fossil fuel resources (*high confidence*). The economic impacts of stranded assets could amount to trillions of dollars. Coal assets are most vulnerable over the coming decade; oil and gas assets are more vulnerable toward mid-century. CCS can allow fossil fuels to be used longer, reducing potential stranded assets. (Box TS.8) {6.7}

Box TS.8 | Stranded Assets

Limiting warming to 2°C or 1.5°C is expected to result in the 'stranding' of carbon-intensive assets. Stranded assets can be broadly defined as assets which 'suffer from unanticipated or premature write-offs, downward revaluations or conversion to liabilities'. Climate policies, other policies and regulations, innovation in competing technologies, and shifts in fuel prices could all lead to stranded assets. The loss of wealth from stranded assets would create risks for financial market stabilityand reduce fiscal revenue for hydrocarbon-dependent economies, which in turn could affect macroeconomic stability and the prospects for a Just Transition. (Box TS.4) {6.7, 15.6, Chapter 17}

Two types of assets are at risk of being stranded: (i) in-ground fossil resources and (ii) human-made capital assets (e.g., power plants and cars). About 30% of oil, 50% of gas, and 80% of coal reserves will remain unburnable if warming is limited to 2°C. {6.7, Box 6.11}

Practically all long-lived technologies and investments that cannot be adapted to low-carbon and zero-emission modes could face stranding under climate policy – depending on their current age and expected lifetimes. Scenario evidence suggests that without carbon capture, the worldwide fleet of coal- and gas power plants would need to retire about 23 and 17 years earlier than expected lifetimes, respectively, in order to limit global warming to 1.5°C and 2°C {2.7}. Blast furnaces and cement factories without CCS {11.4}, new fleets of airplanes and internal combustion engine vehicles {10.4, 10.5}, and new urban infrastructures adapted to sprawl and motorisation may also be stranded. {Chapter 8; Box 10.1}

Many countries, businesses, and individuals stand to lose wealth from stranded assets. Countries, businesses, and individuals may therefore desire to keep assets in operation even if financial, social, or environmental concerns call for retirement. This creates political economic risks, including actions by asset owners to hinder climate policy reform {6.7; Box 6.11}. It will be easier to retire these assets if the risks are communicated, if sustainability reporting is mandated and enforced, and if corporations are protected with arrangements that shield them from short-term shareholder value maximisation.

Without early retirements, or reductions in utilisation, the current fossil infrastructure will emit more GHGs than is compatible with limiting warming to 1.5°C {2.7}. Including the pipeline of planned investments would push these future emissions into the uncertainty range of 2°C carbon budgets {2.7}. Continuing to build new coal-fired power plants and other fossil infrastructure will increase future transition costs and may jeopardise efforts to limit warming to 2°C (>67%) or 1.5°C with no or limited overshoot. One study has estimated that USD11.8 trillion in current assets will need to be stranded by 2050 for a 2°C world; further delaying action for another 10 years would result in an additional USD7.7 trillion in stranded assets by 2050. {15.5.2}

Experience from past stranding indicates that compensation for the devaluation costs of private-sector stakeholders by the public sector is common. Limiting new investments in fossil technologies hence also reduces public finance risks in the long term. {15.6.3}

A low-carbon energy transition will shift investment patterns and create new economic opportunities (*high confidence*). Total energy investment needs will rise, relative to today, over the next decades, if warming is limited to 2°C or lower (>67%), or if warming is limited to 1.5°C (>50%) with no or limited overshoot. These increases will be far less pronounced, however, than the reallocations of investment flows that are anticipated across subsectors, namely from fossil fuels (extraction, conversion, and electricity generation) without CCS and toward renewables, nuclear power, CCS, electricity networks and storage, and end-use energy efficiency. A significant and growing share of investments between now and 2050 will be made in emerging economies, particularly in Asia. {6.7}

Climate change will affect many future local and national low-carbon energy systems. The impacts, however, are uncertain, particularly at the regional scale (*high confidence*). Climate change will alter hydropower production, bioenergy and agricultural yields, thermal power plant efficiencies, and demands for heating and cooling, and it will directly impact power system infrastructure. Climate change will not affect wind and solar resources to the extent that it would compromise their ability to reduce emissions. {6.5}

Electricity systems powered predominantly by renewables will be increasingly viable over the coming decades, but it will be challenging to supply the entire energy system with renewable energy (*high confidence*). Large shares of variable solar PV and wind power can be incorporated in electricity grids through batteries, hydrogen, and other forms of storage; transmission; flexible non-renewable generation; advanced controls; and greater demand-side responses. Because some applications (e.g., aviation) are not currently amenable to electrification, it is anticipated that 100% renewable energy systems will need to include alternative fuels such as hydrogen or biofuels. Economic, regulatory, social, and operational challenges increase with higher shares of renewable electricity and energy. The ability to overcome these challenges in practice is not fully understood. (Box TS.9) {6.6}

Box TS.9 | The Transformation in Energy Carriers: Electrification and Hydrogen

To use energy, it must be 'carried' from where it was produced – at a power plant, for example, or a refinery, or a coal mine – to where it is used. As countries reduce CO_2 emissions, they will need to switch from gasoline and other petroleum-based fuels, natural gas, coal, and electricity produced from these fossil fuels to energy carriers with little or no carbon footprint. An important question is which new energy carriers will emerge to support low-carbon transitions.

Low-carbon energy systems are expected to rely heavily on end-use electrification, where electricity produced with low GHG emissions is used for building and industrial heating, transport and other applications that rely heavily on fossil fuels at present. But not all end-uses are expected to be commercially electrifiable in the short to medium term {11.3.5}, and many will require low GHG liquid and gaseous fuels, that is, hydrogen, ammonia, and biogenic and synthetic low GHG hydrocarbons made from low GHG hydrogen, oxygen and carbon sources (the latter from CCU,[20] biomass, or direct air capture {11.3.6}). The future role of hydrogen and hydrogen derivatives will depend on how quickly and how far production technology improves, that is, from electrolysis ('green'), biogasification, and fossil fuel reforming with CCS ('blue') sources. As a general rule, and across all sectors, it is more efficient to use electricity directly and avoid the progressively larger conversion losses from producing hydrogen, ammonia, or constructed low GHG hydrocarbons. What hydrogen does do, however, is add time and space option value to electricity produced using variable clean sources, for use as hydrogen, as stored future electricity via a fuel cell or turbine, or as an industrial feedstock. Furthermore, electrification and hydrogen involve a symbiotic range of general-purpose technologies, such as electric motors, power electronics, heat pumps, batteries, electrolysis, fuel cells, and so on, that have different applications across sectors but cumulative economies of innovation and production scale benefits. Finally, neither electrification nor hydrogen produce local air pollutants at point of end-use.

For almost 140 years we have primarily produced electricity by burning coal, oil, and gas to drive steam turbines connected to electricity generators. When switching to low-carbon energy sources – renewable sources, nuclear power, and fossil or bioenergy with CCS – electricity is expected to become a more pervasive energy carrier. Electricity is a versatile energy carrier, with much higher end-use efficiencies than fuels, and it can be used directly to avoid conversion losses.

An increasing reliance on electricity from variable renewable sources, notably wind and solar power, disrupts old concepts and makes many existing guidelines obsolete for power system planning, for example, that specific generation types are needed for baseload, intermediate load, and peak load to follow and meet demand. In future power systems with high shares of variable electricity from renewable sources, system planning and markets will focus more on demand flexibility, grid infrastructure and interconnections, storage on various timelines (on the minute, hourly, overnight and seasonal scale), and increased coupling between the energy sector and the building, transport and industrial sectors. This shifts the focus to energy systems that can handle variable supply rather than always follow demand. Hydrogen may prove valuable to improve the resilience of electricity systems with high penetration of variable renewable electricity. Flexible hydrogen electrolysis, hydrogen power plants and long-duration hydrogen storage may all improve resilience. Electricity-to-hydrogen-to-electricity round-trip efficiencies are projected to reach up to 50% by 2030. {6.4.3}

Electrification is expected to be the dominant strategy in buildings as electricity is increasingly used for heating and for cooking. Electricity will help to integrate renewable energy into buildings and will also lead to more flexible demand for heating, cooling, and electricity. District heating and cooling offers potential for demand flexibility through energy storage and supply flexibility through cogeneration. Heat pumps are increasingly used in buildings and industry for heating and cooling {9.3.3, Box 9.3}. The ease of switching to electricity means that hydrogen is not expected to be a dominant pathway for buildings {Box 9.6}. Using electricity directly for heating, cooling and other building energy demand is more efficient than using hydrogen as a fuel, for example, in boilers or fuel cells. In addition, electricity distribution is already well developed in many regions compared to essentially non-existent hydrogen infrastructure, except for a few chemicals industry pipelines. At the same time, hydrogen could potentially be used for on-site storage should technology advance sufficiently.

20 Carbon dioxide capture and utilisation (CCU) refers to a process in which CO_2 is captured and the carbon is then used in a product. The climate effect of CCU depends on the product lifetime, the product it displaces, and the CO_2 source (fossil, biomass or atmosphere). CCU is sometimes referred to as carbon dioxide capture and use, or carbon capture and utilisation.

Box TS.9 (continued)

Electrification is already occurring in several modes of personal and light-freight transport, and vehicle-to-grid solutions for flexibility have been extensively explored in the literature and small-scale pilots. The role of hydrogen in transport depends on how far technology develops. Batteries are currently a more attractive option than hydrogen and fuel cells for light-duty vehicles. Hydrogen and hydrogen-derived synthetic fuels, such as ammonia and methanol, may have a more important role in heavy vehicles, shipping, and aviation {10.3}. Current transport of fossil fuels may be replaced by future transport of hydrogen and hydrogen carriers such as ammonia and methanol, or energy-intensive basic materials processed with hydrogen (e.g., reduced iron) in regions with bountiful renewable resources. {Box 11.1}

Both light and heavy industry are potentially large and flexible users of electricity for both final energy use (e.g., directly and using heat pumps in light industry) and for feedstocks (e.g., hydrogen for steel-making and chemicals). For example, industrial process heat demand, ranging from below 100°C to above 1000°C, can be met through a wide range of electrically powered technologies instead of using fuels. Future demand for hydrogen (e.g., for nitrogen fertiliser or as a reduction agent in steel production) also offers electricity-demand flexibility for electrolysis through hydrogen storage and flexible production cycles {11.3.5}. The main use of hydrogen and hydrogen carriers in industry is expected to be as feedstock (e.g., for ammonia and organic chemicals) rather than for energy as industrial electrification increases.

Multiple energy supply options are available to reduce emissions over the next decade (*high confidence*). Nuclear power and hydropower are already established technologies. Solar PV and wind are now cheaper than fossil-generated electricity in many locations. Bioenergy accounts for about a tenth of global primary energy. Carbon capture is widely used in the oil and gas industry, with early applications in electricity production and biofuels. It will not be possible to widely deploy all of these and other options without efforts to address the geophysical, environmental-ecological, economic, technological, socio-cultural, and institutional factors that can facilitate or hinder their implementation (*high confidence*). (Figures TS.11 and TS.31) {6.4}

Enhanced integration across energy system sectors and across scales will lower costs and facilitate low-carbon energy system transitions (*high confidence*). Greater integration between the electricity sector and end-use sectors can facilitate integration of variable renewable energy options. Energy systems can be integrated across district, regional, national, and international scales (*high confidence*). {6.4, 6.6}

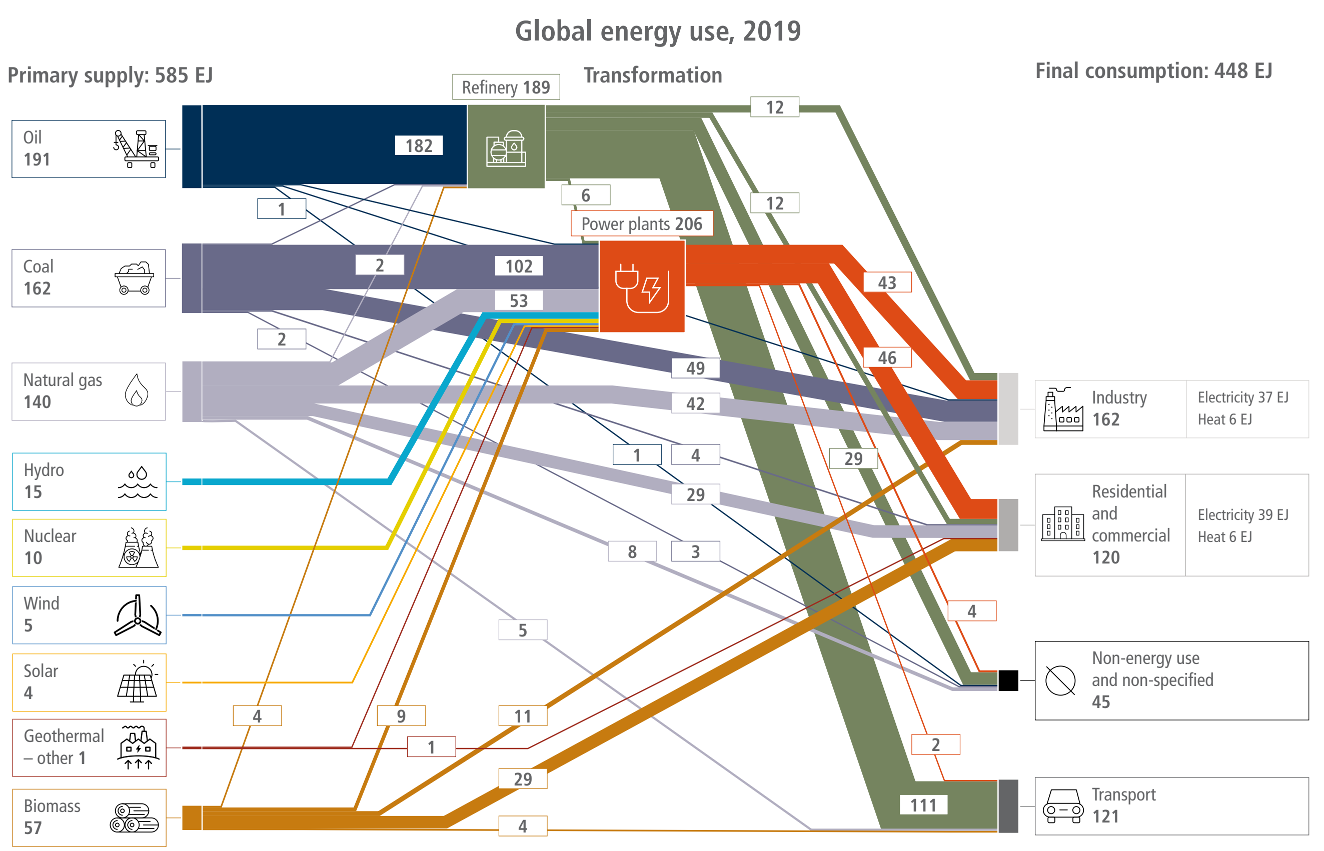
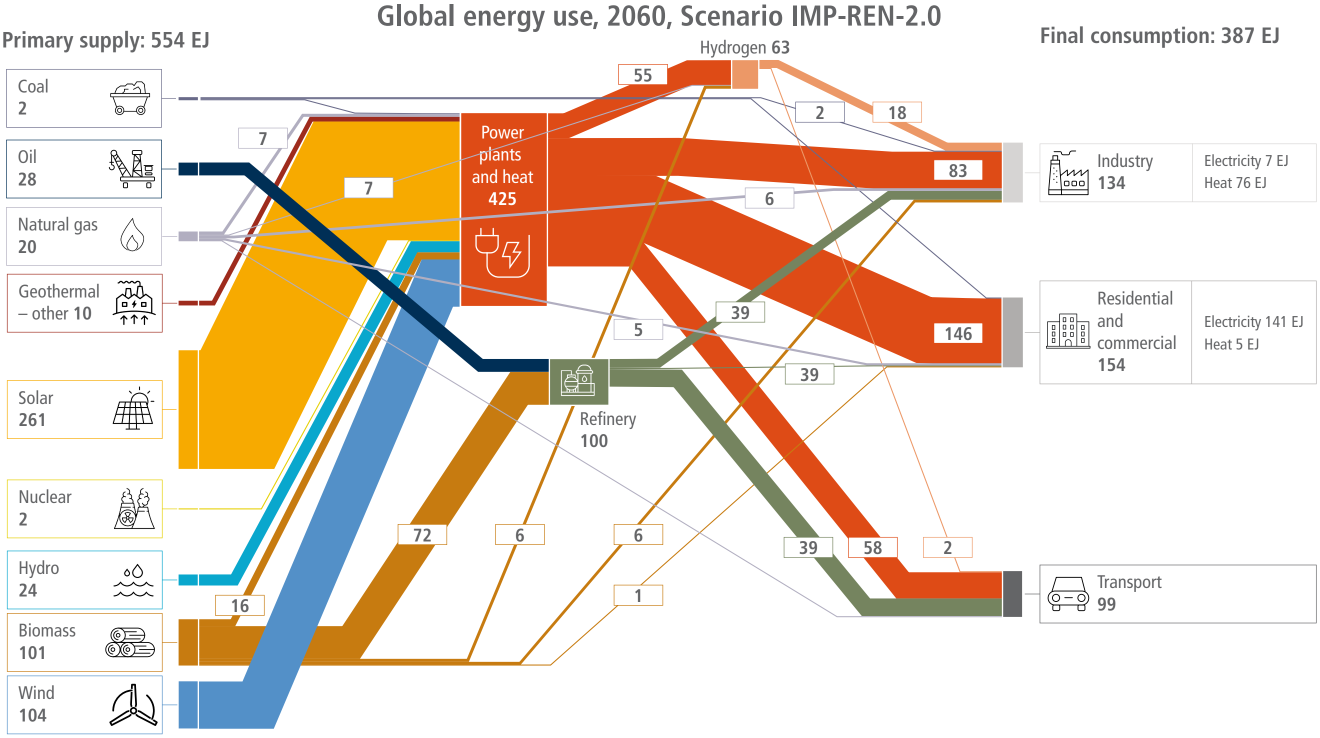


Figure TS.11 | Global energy flows within the 2019 global energy system (top panel) and within two illustrative future, net-zero CO_2 emissions global energy system (bottom panels).



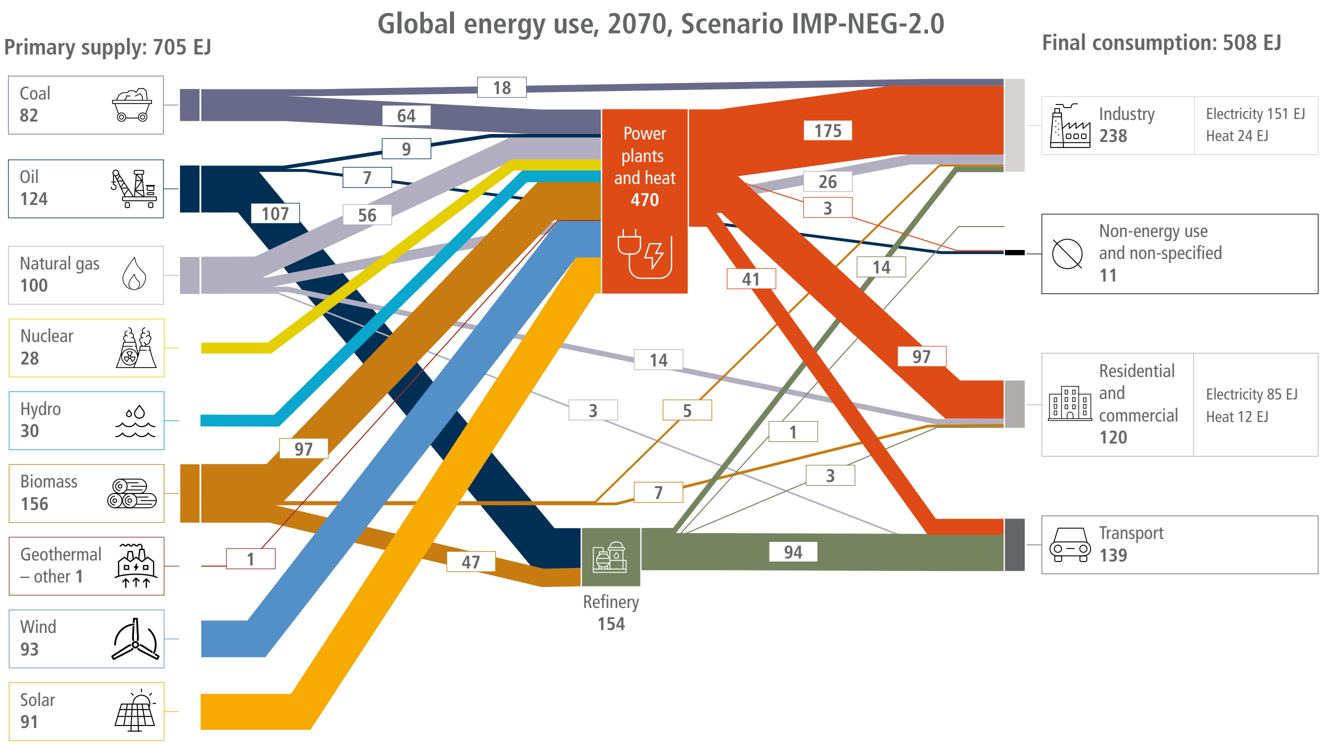


Figure TS.11 continued: Global energy flows within the 2019 global energy system (top panel) and within two illustrative future, net-zero CO_2 emissions global energy system (bottom panels). Source: IEA, AR6 Scenarios Database. Flows below 1 EJ are not represented. The illustrative net-zero scenarios correspond to the years in which net energy system CO_2 emissions reach zero – 2045 in IMP-Ren and 2060 in IMP-Neg-2.0. Source: data from IMP-Ren: Luderer et al.(2022); IMP-Neg-2.0: Riahi, K. et al. 2021.

The viable speed and scope of a low-carbon energy system transition will depend on how well it can support SDGs and other societal objectives (*high confidence*). Energy systems are linked to a range of societal objectives, including energy access, air and water pollution, health, energy security, water security, food security, economic prosperity, international competitiveness, and employment. These linkages and their importance vary among regions. Energy-sector mitigation and efforts to achieve SDGs generally support one another, though there are important region-specific exceptions (*high confidence*). (Figure TS.29) {6.1, 6.7}

The economic outcomes of low-carbon transitions in some sectors and regions may be on par with, or superior to those of an emissions-intensive future (*high confidence*). Cost reductions in key technologies, particularly in electricity and light-duty transport, have increased the economic attractiveness of near-term low-carbon transitions. Long-term mitigation costs are not well understood and depend on policy design and implementation, and the future costs and availability of technologies. Advances in low-carbon energy resources and carriers such as next-generation biofuels, hydrogen produced from electrolysis, synthetic fuels, and carbon-neutral ammonia would substantially improve the economics of net zero energy systems (*medium confidence*). {6.4, 6.7}

TS.5.2 Urban Systems and Other Settlements

Although urbanisation is a global trend often associated with increased incomes and higher consumption, the growing concentration of people and activities is an opportunity to increase resource efficiency and decarbonise at scale (*very high confidence*). The same urbanisation level can have large variations in per-capita urban carbon emissions. For most regions, per-capita urban emissions are lower than per-capita national emissions (excluding aviation, shipping and biogenic sources) (*very high confidence*). {8.1.4, 8.3.3, 8.4, Box 8.1}

Most future urban population growth will occur in developing countries, where per-capita emissions are currently low, but are expected to increase with the construction and use of new infrastructure, and the built environment, and changes in incomes and lifestyles (*very high confidence*). The drivers of urban GHG emissions are complex and include an interplay of population size, income, state of urbanisation, and how cities are laid out (i.e., urban form). How new cities and towns are designed, constructed, managed, and powered will lock-in behaviour, lifestyles, and future urban GHG emissions. Urban strategies can improve well-being while minimising impact on GHG emissions. However, urbanisation can result in increased global GHG emissions through emissions outside the city's boundaries (*very high confidence*). {8.1.4, 8.3, Box 8.1, 8.4, 8.6}

The urban share of combined global CO_2 and CH_4) emissions is substantial and continues to increase (*high confidence*). In 2015, urban emissions were estimated to be 25GtCO_2-eq (about 62% of the global share) and in 2020 were 29 GtCO_2-eq (67–72% of the global share).[21] Around 100 of the highest-emitting urban areas account for approximately 18% of the global carbon footprint (*high confidence*). {8.1, 8.3}

The urban share of regional GHG emissions increased between 2000 and 2015, with much inter-regional variation in the magnitude of the increase (*high confidence*). Globally, the urban share of national emissions increased six percentage points, from 56% in 2000 to 62% in 2015. For 2000 to 2015, the urban emissions share increased from 28% to 38% in Africa, from 46% to 54% in Asia and Pacific, from 62% to 72% in Developed Countries, from 57% to 62% in Eastern Europe and West Central Asia, from 55% to 66% in Latin America and Caribbean, and from 68% to 69% in the Middle East (*high confidence*). {8.1.6, 8.3.3}

Per-capita urban GHG emissions increased between 2000 and 2015, with cities in developed countries accounting for nearly seven times more per capita than the lowest emitting region (*medium confidence*). From 2000 to 2015, global urban GHG emissions per capita increased from 5.5 to 6.2 tCO_2-eq per person (an increase of 11.8%). Emissions in Africa increased from 1.3 to 1.5 tCO_2-eq per person (22.6%); in Asia and Pacific from 3.0 to 5.1 tCO_2-eq per person (71.7%); in Eastern Europe and West Central Asia from 6.9 to 9.8 tCO_2-eq per person (40.9%); in Latin America and the Caribbean from 2.7 to 3.7 tCO_2-eq per person (40.4%); and in the Middle East from 7.4 to 9.6 tCO_2-eq per person (30.1%). Albeit starting from the highest level, developed countries showed a modest decline of 11.4 to 10.7 tCO_2-eq per person (–6.5%). (Figure TS.12) {8.3.3}

21 These estimates are 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. 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}

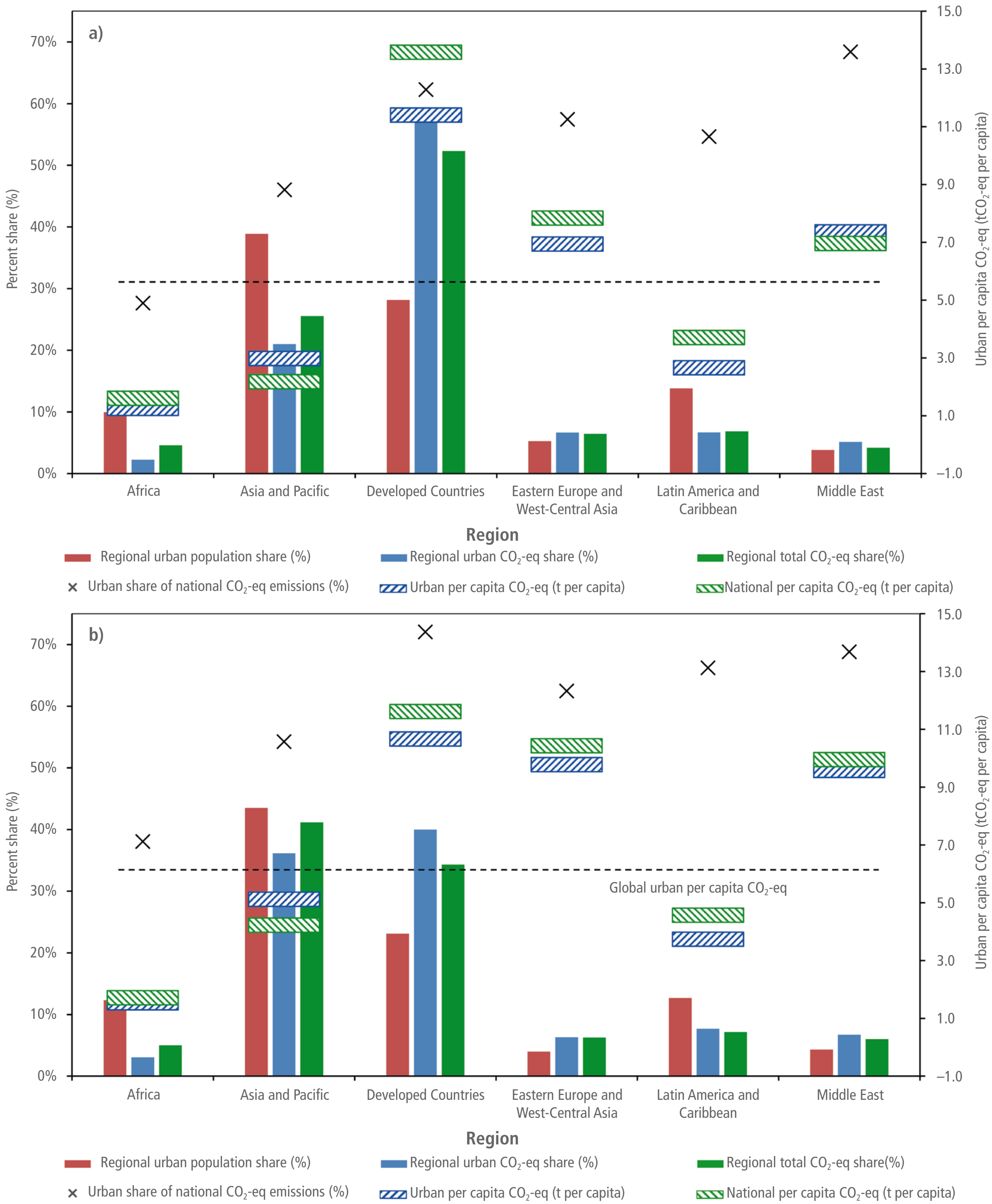


Figure TS.12 | Changes in six metrics associated with urban and national-scale combined CO_2 and CH_4 emissions represented in the AR6 WGIII six-region aggregation, with (a) 2000 and (b) 2015. The trends in Luqman et al. (2021) were combined with the work of Moran et al. (2018) to estimate the regional urban CO_2-eq share of global urban emissions, the urban share of national CO_2-eq emissions, and the urban per capita CO_2-eq emissions by region. This estimate is derived from consumption-based accounting that includes 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. It incorporates all CO_2 and CH_4 emissions except aviation, shipping and biogenic sources (i.e., land-use change, forestry, and agriculture). The dashed grey line represents the global average urban per capita CO_2-eq emissions. The regional urban population share, regional CO_2-eq share in total emissions, and national per capita CO_2-eq emissions by region are given for comparison. Source: adapted from Gurney et al. (2022).

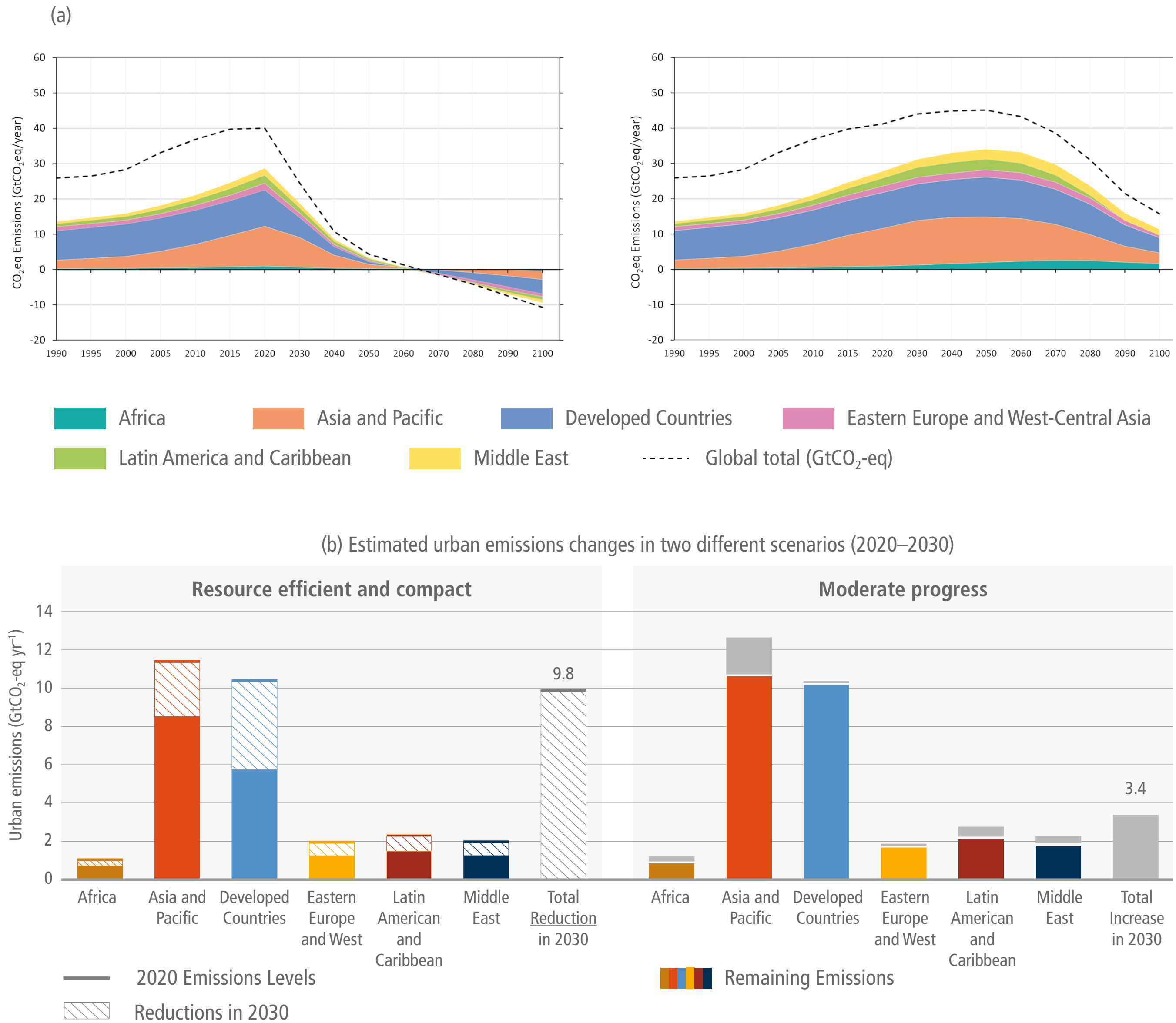


Figure TS.13 | Panel (a): carbon dioxide-equivalent emissions from global urban areas from 1990 to 2100. Urban areas are aggregated to six regional domains; Panel (b): comparison of urban emissions under different urbanisation scenarios ($GtCO_2$-eq yr^{-1}) for different regions.[21] {Figures 8.13 and 8.14}

The global share of future urban GHG emissions is expected to increase through 2050 with moderate to low mitigation efforts due to growth trends in population, urban land expansion, and infrastructure and service demands, but the extent of the increase depends on the scenario and the scale and timing of urban mitigation action (*medium confidence*). In modelled scenarios, global consumption-based urban CO_2 and CH_4 emissions 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, SSP 3-7.0). With aggressive and immediate mitigation efforts to limit global warming to 1.5°C (>50%) with no or limited overshoot by the end of the century (very low emissions, SSP1-1.9), including high levels of electrification, energy and material efficiency, renewable energy preferences, and socio-behavioural responses, urban GHG emissions could approach net-zero and reach a maximum of 3 $GtCO_2$-eq in 2050. Under a scenario with aggressive but not immediate urban mitigation policies to limit global warming to 2°C (>67%) (low emissions, SSP1-2.6), urban emissions could reach 17 $GtCO_2$-eq in 2050.[23] (Figure TS.13) {8.3.4}

Urban land areas could triple between 2015 and 2050, with significant implications for future carbon lock-in (*medium confidence*). There is a large range in the forecasts of urban land expansion across scenarios and models, which highlights an opportunity to shape future urban development towards low- or net zero GHG

22 These scenarios have been assessed by WGI to correspond to intermediate, high, and very low GHG emissions.

23 These scenarios have been assessed by WGI to correspond to intermediate, high, and very low GHG emissions.

emissions. By 2050, urban areas could increase up to 211% over the 2015 global urban extent, with the median projected increase ranging from 43% to 106%. While the largest absolute amount of new urban land is forecasted to occur in Asia and Pacific, and in Developed Countries, the highest rate of urban land growth is projected to occur in Africa, Eastern Europe and West Central Asia, and in the Middle East. Given past trends, the expansion of urban areas is expected to take place on agricultural lands and forests, with implications for the loss of carbon stocks. The infrastructure that will be constructed concomitant with urban land expansion will lock-in patterns of energy consumption that will persist for decades. {8.3.1, 8.3.4, 8.4.1, 8.6}

The construction of new, and upgrading of existing, urban infrastructure through 2030 will add to emissions (*medium evidence, high agreement*). The construction of new and upgrading of existing urban infrastructure using conventional practices and technologies can result in a significant increase in CO_2 emissions, ranging from 8.5 $GtCO_2$ to 14 $GtCO_2$ annually up to 2030 and more than double annual resource requirements for raw materials to about 90 billion tonnes per year by 2050, up from 40 billion tonnes in 2010. {8.4.1, 8.6}

Given the dual challenges of rising urban GHG emissions and future projections of more frequent extreme climate events, there is an urgent need to integrate urban mitigation and adaptation strategies for cities to address climate change (*very high confidence*). Mitigation strategies can enhance resilience against climate change impacts while contributing to social equity, public health, and human well-being. Urban mitigation actions that facilitate economic decoupling can have positive impacts on employment and local economic competitiveness. {8.2, Cross-Working Group Box 2 in Chapter 8, 8.4}

Cities can achieve net-zero GHG emissions only through deep decarbonisation and systemic transformation (*very high confidence*). Three broad mitigation strategies have been found to be effective in reducing emissions when implemented concurrently: (i) reducing or changing urban energy and material use towards more sustainable production and consumption across all sectors, including through compact and efficient urban forms and supporting infrastructure; (ii) electrification and switching to low-carbon energy sources; and (iii) enhancing carbon uptake and storage in the urban environment (*high confidence*). Given the regional and global reach of urban supply chains, cities can achieve net-zero emissions only if emissions are reduced both within and outside of their administrative boundaries through supply chains. {8.1.6, 8.3.4, 8.4, 8.6}

Packages of mitigation policies that implement multiple urban-scale interventions can have cascading effects across sectors, reduce GHG emissions outside a city's administrative boundaries, and reduce emissions more than the net sum of individual interventions, particularly if multiple scales of governance are included (*high confidence*). Cities have the ability to implement policy packages across sectors using an urban systems approach, especially those that affect key infrastructure based on spatial planning, electrification of the urban energy system, and urban green and blue infrastructure. The institutional capacity of cities to develop, coordinate, and integrate sectoral mitigation strategies within their jurisdiction varies by context, particularly those related to governance, the regulatory system, and budgetary control. {8.4, 8.5, 8.6}

Integrated spatial planning to achieve compact and resource-efficient urban growth through co-location of higher residential and job densities, mixed land use, and transit-oriented development could reduce urban energy use between 23% and 26% by 2050 compared to the business-as-usual scenario (*high confidence*). Compact cities with shortened distances between housing and jobs, and interventions that support a modal shift away from private motor vehicles towards walking, cycling, and low-emissions shared, or public, transportation, passive energy comfort in buildings, and urban green infrastructure can deliver significant public health benefits and lower GHG emissions. {8.2, 8.3.4, 8.4, 8.6}

Urban green and blue infrastructure can mitigate climate change through carbon sinks, avoided emissions, and reduced energy use while offering multiple co-benefits (*high confidence*). Urban green and blue infrastructure, including urban forests and street trees, permeable surfaces, and green roofs[24] offer potentials to mitigate climate change directly through storing carbon, and indirectly by inducing a cooling effect that both reduces energy demand and reduces energy use for water treatment. Globally, urban trees store approximately 7.4 billion tonnes of carbon, and sequester approximately 217 million tonnes of carbon annually, although carbon storage is highly dependent on biome. Among the multiple co-benefits of green and blue infrastructure are reducing the urban heat island (UHI) effect and heat stress, reducing stormwater runoff, improving air quality, and improving the mental and physical health of urban dwellers. Many of these options also provide benefits to climate adaptation. (*high agreement, robust evidence*) {8.2, 8.4.4}

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 (i.e., whether it is an established city with existing infrastructure, a rapidly growing city with new infrastructure, or an emerging city with infrastructure buildup) (*high confidence*). 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). The long lifespan of urban infrastructures locks in behaviour and committed emissions. Urban infrastructures and urban form can enable sociocultural and lifestyle changes that can significantly reduce carbon footprints. Rapidly growing cities can avoid higher future emissions through urban planning to co-locate jobs and housing to achieve compact urban form, and by leapfrogging to low-carbon technologies. Established cities will achieve the largest GHG emissions savings by replacing, repurposing, or retrofitting the building stock, targeted infilling and densifying, as well as through modal shift and the electrification of the urban energy system. New and emerging cities

24 These examples are considered to be a subset of 'nature-based solutions' or 'ecosystem-based approaches'.

have unparalleled potential to become low or net zero GHG emissions while achieving high quality of life by creating compact, co-located, and walkable urban areas with mixed land use and transit-oriented design, that also preserve existing green and blue assets. {8.2, 8.4, 8.6}

With over 880 million people living in informal settlements, there are opportunities to harness and enable informal practices and institutions in cities related to housing, waste, energy, water, and sanitation to reduce resource use and mitigate climate change (*low evidence, medium agreement*). The upgrading of informal settlements and inadequate housing to improve resilience and well-being offers a chance to create a low-carbon transition. However, there is limited quantifiable data on these practices and their cumulative impacts on GHG emissions. {8.1.4, 8.2.2, Cross-Working Group Box 2 in Chapter 8, 8.3.2, 8.4, 8.6, 8.7}

Achieving transformational changes in cities for climate change mitigation and adaptation will require engaging multiple scales of governance, including governments and non-state actors, and in connection with substantial financing beyond sectoral approaches (*very high confidence*). Large and complex infrastructure projects for urban mitigation are often beyond the capacity of local municipality budgets, jurisdictions, and institutions. Partnerships between cities and international institutions, national and regional governments, transnational networks, and local stakeholders play a pivotal role in mobilising global climate finance resources for a range of infrastructure projects with low-carbon emissions and related spatial planning programs across key sectors. {8.4, 8.5}

TS.5.3 Transport

Meeting climate mitigation goals would require transformative changes in the transport sector. In 2019, direct GHG emissions from the transport sector were 8.7 $GtCO_2$-eq (up from 5.0 $GtCO_2$-eq in 1990) and accounted for 23% of global energy-related CO_2 emissions. Road vehicles accounted for 70% of direct transport emissions, while 1%, 11%, and 12% of direct emissions came from rail, shipping, and aviation, respectively. Emissions from shipping and aviation continue to grow rapidly. Transport-related emissions in developing regions of the world have increased more rapidly than in Europe or North America, a trend that is expected to continue in coming decades (*high confidence*). {10.1, 10.5, 10.6}

Since AR5 there has been a growing awareness of the need for demand management solutions combined with new technologies, such as the rapidly growing use of electromobility for land transport and the emerging options in advanced biofuels and hydrogen-based fuels for shipping and aviation and in other specific land-based contexts (*high confidence*). There is a growing need for systemic infrastructure changes that enable behavioural modifications and reductions in demand for transport services that can in turn reduce energy demand. The response to the COVID-19 pandemic has also shown that behavioural interventions can reduce transport-related GHG emissions. For example, COVID-19-based lockdowns have confirmed the transformative value of telecommuting replacing significant numbers of work and personal journeys as well as promoting local active transport. There are growing opportunities to implement strategies that drive behavioural change and support the adoption of new transport technology options. {Chapter 5, 10.2, 10.3, 10.4, 10.8}

Changes in urban form, behaviour programs, the circular economy, the shared economy, and digitalisation trends can support systemic changes that lead to reductions in demand for transport services or expand the use of more efficient transport modes (*high confidence*). Cities can reduce their transport-related fuel consumption by around 25% through combinations of more compact land use and the provision of less car-dependent transport infrastructure. Appropriate infrastructure, including protected pedestrian and bike pathways, can also support much greater localised active travel.[25] Transport demand management incentives are expected to be necessary to support these systemic changes. There is mixed evidence of the effect of circular economy initiatives, shared economy initiatives, and digitalisation on demand for transport services (Box TS.14). For example, while dematerialisation can reduce the amount of material that needs to be transported to manufacturing facilities, an increase in online shopping with priority delivery can increase demand for freight transport. Similarly, while teleworking could reduce travel demand, increased ride-sharing could increase vehicle kilometres travelled (VKT). {Chapters 1 and 5, 10.2, 10.8}

Battery electric vehicles (BEVs) have lower lifecycle greenhouse gas (GHG) emissions than internal combustion engine vehicles (ICEVs) when BEVs are charged with low-carbon electricity (*high confidence*). Electromobility is being rapidly implemented in micro-mobility (e-autorickshaws, e-scooters, e-bikes), in transit systems, especially buses, and to a lesser degree, in personal vehicles. BEVs could also have the added benefit of supporting grid operations. The commercial availability of mature lithium-ion batteries (LIBs) has underpinned this growth in electromobility. As global battery production increases, unit costs are declining. Further efforts to reduce the GHG footprint of battery production, however, are essential for maximising the mitigation potential of BEVs. The continued growth of electromobility for land transport would entail investments in electric charging and related grid infrastructure. Electromobility powered by low-carbon electricity has the potential to rapidly reduce transport GHG and can be applied with multiple co-benefits, especially in developing countries. {10.3, 10.4, 10.8}

Land-based, long-range, heavy-duty trucks can be decarbonised through battery-electric haulage (including the use of electric road systems), complemented by hydrogen- and biofuel-based fuels in some contexts. These same technologies and expanded use of available electric rail systems can support rail decarbonisation (*medium confidence*). Initial deployments of battery-electric, hydrogen- and bio-based haulage are underway, and commercial operations of some of these technologies are considered

25 'Active travel' is travel that requires physical effort, for example journeys made by walking or cycling.

feasible by 2030 (*medium confidence*). These technologies nevertheless face challenges regarding driving range, capital and operating costs, and infrastructure availability. In particular, fuel-cell durability, high energy consumption, and costs continue to challenge the commercialisation of hydrogen-based fuel-cell vehicles. Increased capacity for low-carbon hydrogen production would also be essential for hydrogen-based fuels to serve as an emissions reduction strategy (*high confidence*). (Box TS.15) {10.3, 10.4, 10.8}

Decarbonisation options for shipping and aviation still require R&D, though advanced biofuels, ammonia, and synthetic fuels are emerging as viable options (*medium confidence*). Increased efficiency has been insufficient to limit the emissions from shipping and aviation, and natural gas-based fuels are expected to be inadequate to meet stringent decarbonisation goals for these segments (*high confidence*). High-energy density, low-carbon fuels are required, but they have not yet reached commercial scale. Advanced biofuels could provide low-carbon jet fuel (*medium confidence*). The production of synthetic fuels using low-carbon hydrogen with CO_2 captured through DACCS/BECCS could provide jet and marine fuels but these options still require demonstration at scale (*low confidence*). Ammonia produced with low-carbon hydrogen could also serve as a marine fuel (*medium confidence*). Deployment of these fuels requires reductions in production costs. (Figure TS.14) {10.2, 10.3, 10.4, 10.5, 10.6, 10.8}

Scenarios from bottom-up and top-down models indicate that, without intervention, CO_2 emissions from transport could grow in the range of 16% and 50% by 2050 (*medium confidence*). The scenarios literature projects continued growth in demand for freight and passenger services, particularly in developing countries in Africa and Asia (*high confidence*). This growth is projected to take place across all transport modes. Increases in demand notwithstanding, scenarios that limit warming to 1.5°C degree with no or limited overshoot suggest that a 59% reduction (42–68% interquartile range) in transport-related CO_2 emissions by 2050, compared to modelled 2020 levels is required. While many global scenarios place greater reliance on emissions reduction in sectors other than transport, a quarter of the 1.5°C scenarios describe transport-related CO_2 emissions reductions in excess of 68% (relative to modelled 2020 levels) (*medium confidence*). Illustrative Mitigation Pathways IMP-Ren and IMP-LD (TS 4.2) describe emission reductions of 80% and 90% in the transport sector, respectively, by 2050. Transport-related emission reductions, however, may not happen uniformly across regions. For example, transport emissions from the Developed Countries, and Eastern Europe and West Central Asia countries decrease from 2020 levels by 2050 across all scenarios limiting global warming to 1.5°C by 2100, but could increase in Africa, Asia and Pacific (APC), Latin America and Caribbean, and the Middle East in some of these scenarios. {10.7}

The scenarios literature indicates that fuel and technology shifts are crucial in reducing carbon emissions to meet temperature goals (*high confidence*). In general terms, electrification tends to play the key role in land-based transport, but biofuels and hydrogen (and derivatives) could play a role in decarbonisation of freight in some contexts. Biofuels and hydrogen (and derivatives) are expected to be more prominent in shipping and aviation. The shifts towards these alternative fuels must occur alongside shifts towards clean technologies in other sectors. {10.7}

There is a growing awareness of the need to plan for the significant expansion of low-carbon energy infrastructure, including low-carbon power generation and hydrogen production, to support emissions reductions in the transport sector (*high confidence*). Integrated energy planning and operations that take into account energy demand and system constraints across all sectors (transport, buildings, and industry) offer the opportunity to leverage sectoral synergies and avoid inefficient allocation of energy resources. Integrated planning of transport and power infrastructure would be particularly useful in developing countries where 'greenfield' development doesn't suffer from constraints imposed by legacy systems. {10.3, 10.4, 10.8}

The deployment of low-carbon aviation and shipping fuels that support decarbonisation of the transport sector could require changes to national and international governance structures (*medium confidence*). The UNFCCC does not specifically cover emissions from international shipping and aviation. Reporting emissions from international transport is at the discretion of each country. While the International Civil Aviation Organization (ICAO) and International Maritime Organization (IMO) have established emissions reductions targets, only strategies to improve fuel efficiency and demand reductions have been pursued, and there has been minimal commitment to new technologies. {10.5, 10.6, 10.7}

There are growing concerns about resource availability, labour rights, non-climate environmental impacts, and costs of critical minerals needed for lithium-ion batteries (*medium confidence*). Emerging national strategies on critical minerals and the requirements from major vehicle manufacturers are leading to new, more geographically diverse mines. The standardisation of battery modules and packaging within and across vehicle platforms, as well as increased focus on design for recyclability are important. Given the high degree of potential recyclability of lithium-ion batteries, a nearly closed-loop system in the future could mitigate concerns about critical mineral issues (*medium confidence*). {10.3, 10.8}

Legislated climate strategies are emerging at all levels of government, and together with pledges for personal choices, could spur the deployment of demand- and supply-side transport mitigation strategies (*medium confidence*). At the local level, legislation can support local transport plans that include commitments or pledges from local institutions to encourage behaviour change by adopting an organisational culture that motivates sustainable behaviour with inputs from the creative arts. Such institution-led mechanisms could include bike-to-work campaigns, free transport passes, parking charges, or eliminating car benefits. Community-based solutions such as *solar sharing*, *community charging*, and *mobility as a service* can generate new opportunities to facilitate low-carbon transport futures. At the regional and national levels, legislation can include vehicle and fuel efficiency standards, R&D support, and large-scale investments in low-carbon transport infrastructure. (Figure TS.14) {10.8, Chapter 15}

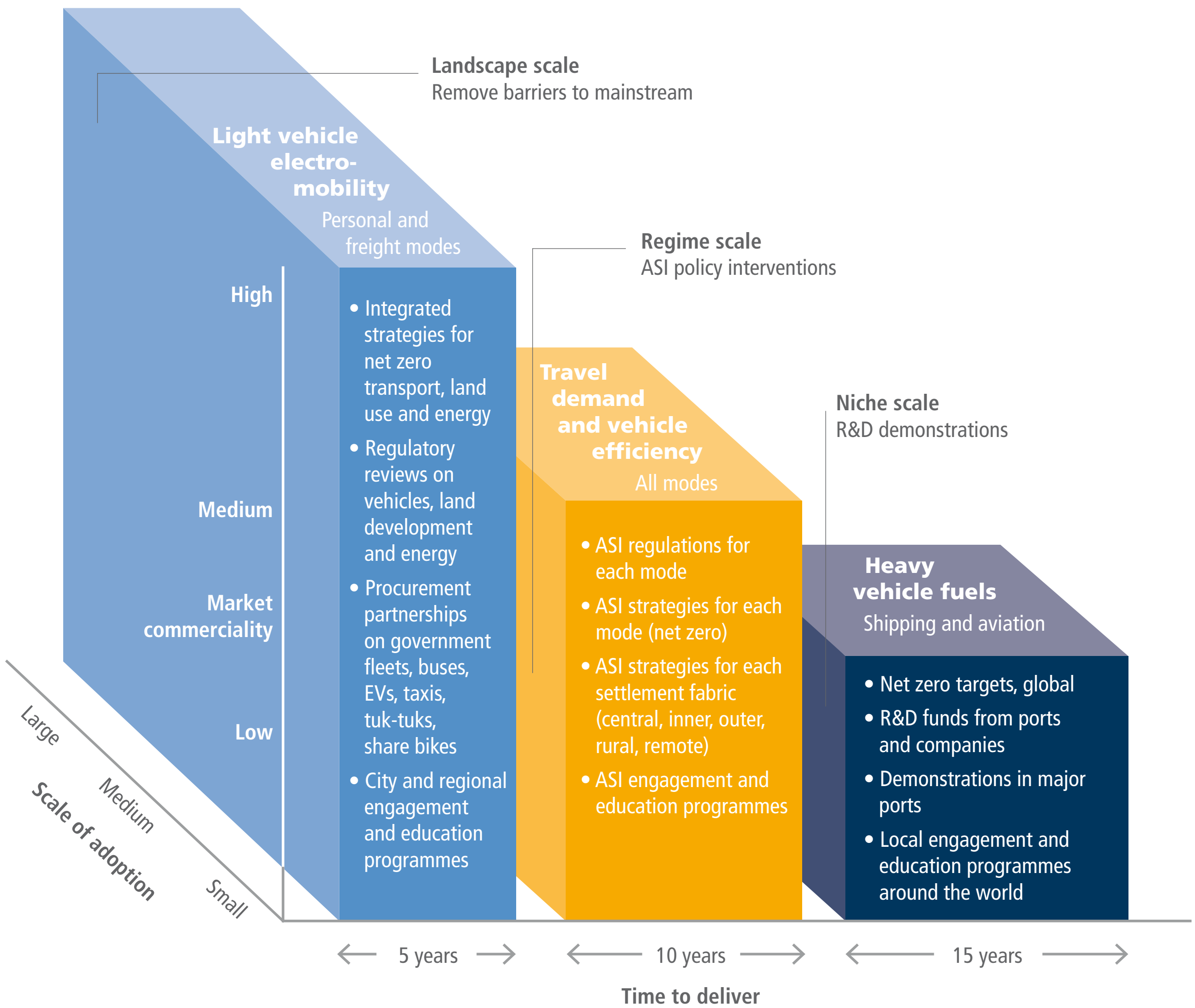


Figure TS.14 | Mitigation options and enabling conditions for transport. 'Niche' scale includes strategies that still require innovation. {Figure 10.22} ASI: Avoid-Shift-Improve; TRL: technology readiness level.

TS.5.4 Buildings

Global GHG emissions from buildings were 12 $GtCO_2$-eq in 2019, equivalent to 21% of global GHG emissions. Of this, 57% (6.8 $GtCO_2$-eq) were indirect emissions from off-site generation of electricity and heat, 24% (2.9 $GtCO_2$-eq) were direct emissions produced on-site and 18% (2.2 $GtCO_2$-eq) were embodied emissions from the production of cement and steel used in buildings (*high confidence*). Most building-sector emissions are CO_2. Final energy demand from buildings reached 128 EJ globally in 2019 (around 31% of global final energy demand), and electricity demand from buildings was slightly above 43 EJ globally (around 18% of global electricity demand). Residential buildings consumed 70% (90 EJ) of the global final energy demand from buildings. Over the period 1990–2019, global CO_2 emissions from buildings increased by 50%, global final energy demand from buildings grew by 38%, and global final electricity demand increased by 161%. {9.3}

In most regions, historical improvements in efficiency have been approximately matched by growth in floor area per capita (*high confidence*). At the global level, building-specific drivers of GHG emissions include: (i) population growth, especially in developing countries; (ii) increasing floor area per capita, driven by the increasing size of dwellings while the size of households kept decreasing, especially in developed countries; (iii) the inefficiency of newly constructed buildings, especially in developing countries, and the low renovation rates and low ambition level in developed countries when existing buildings are renovated; (iv) the increase in use, number and size of appliances and equipment, especially information and communication technologies (ICT) and cooling, driven by income; and, (v) the continued reliance on carbon-intensive electricity and heat. These factors taken together are projected to continue driving increased GHG emissions in the building sector in the future. {9.3, 9.6, 9.9}

Building-sector GHG emissions were assessed using the Sufficiency, Efficiency, Renewable (SER) framework. Sufficiency measures tackle the causes of GHG emissions by limiting the demand for energy and materials over the lifecycle of buildings and appliances (*high confidence*). In Chapter 9 of this report, *sufficiency* differs from *efficiency*: *sufficiency* is about long-term actions driven by non-technological solutions, which consume less energy in absolute terms; *efficiency*, in contrast is about continuous short-term marginal technological improvements. 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. Use of the SER framework aims to reduce the cost of constructing and using buildings without reducing occupants' well-being and comfort. {9.1, 9.4, 9.5, 9.9}

Sufficiency interventions do not consume energy during the use phase of buildings and do not require maintenance nor replacement over the lifetime of buildings. Density, compacity, bioclimatic design to optimise the use of nature-based solutions, multi-functionality of space through shared space and to allow for adjusting the size of buildings to the evolving needs of households, circular use of materials and repurposing unused existing buildings to avoid using virgin materials, optimisation of the use of buildings through lifestyle changes, use of the thermal mass of buildings to reduce thermal needs, and moving from ownership to usership of appliances, are among the sufficiency interventions implemented in leading municipalities (*high confidence*). At a global level, up to 17% of the mitigation potential in the buildings sector could be captured by 2050 through sufficiency interventions (*medium confidence*). (Figure TS.15) {9.2, 9.3, 9.4, 9.5, 9.9}

The potential associated with sufficiency measures, as well as the replacement of appliances, equipment and lights by efficient ones, is below zero cost (*high confidence*). The construction of high-performance buildings is expected to become a business-as-usual technology by 2050 with costs below USD20 tCO_2^{-1} in developed countries and below USD100 tCO_2^{-1} in developing countries (*medium confidence*). For existing buildings, there have been many examples of deep retrofits where additional costs per CO_2 abated are not significantly higher than those of shallow retrofits. However, for the whole building stock they tend to be in cost intervals of USD–200 tCO_2^{-1} and >USD200 tCO_2^{-1} (*medium confidence*). Literature emphasises the critical role of the 2020–2030 decade in accelerating the learning of know-how and skills to reduce the costs and remove feasibility constraints for achieving high-efficiency buildings at scale and set the sector on the pathway to realise its full potential (*high confidence*). {9.3, 9.6, 9.9}.

The development, since AR5, of integrated approaches to the construction and retrofit of buildings has led to increasing the number of zero-energy or zero-carbon buildings in almost all climate zones. The complementarity and interdependency of measures leads to cost reductions, while optimising the mitigation potential achieved and avoiding the lock-in-effect (*medium confidence*). {9.6, 9.9}

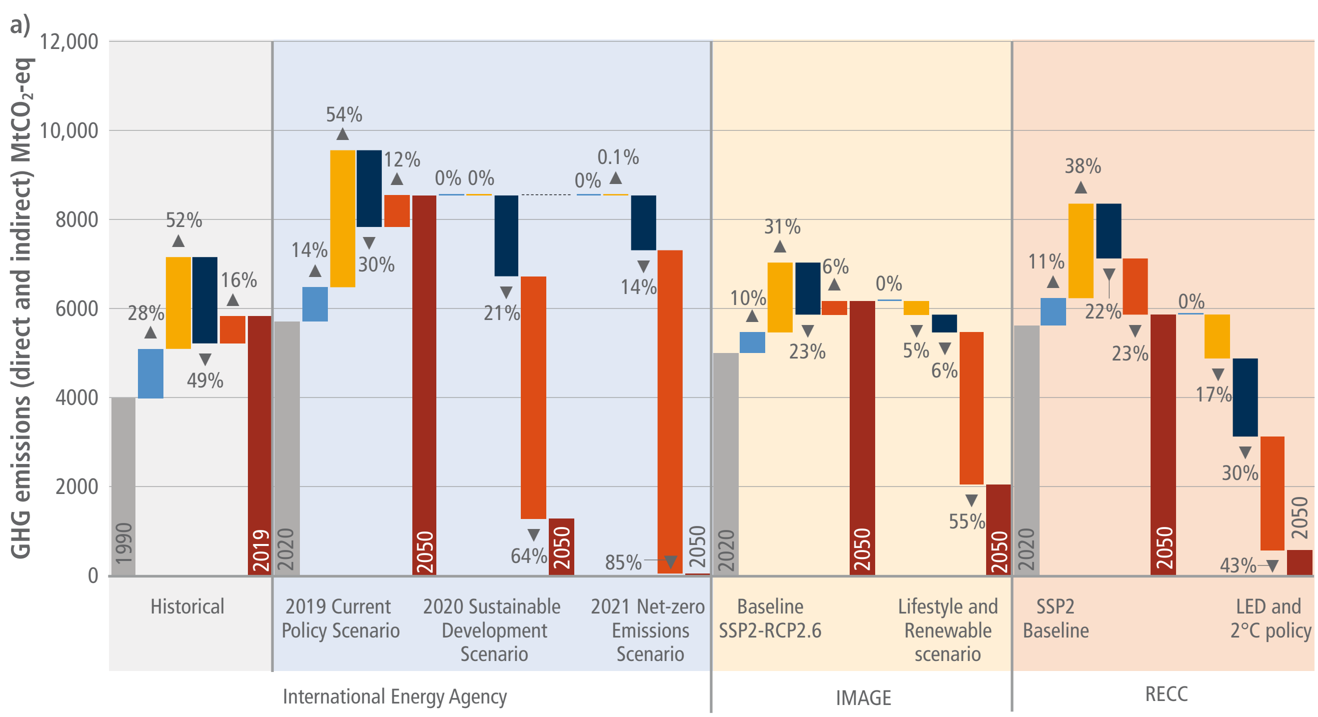


Figure TS.15 | Decompositions of changes in historical residential energy emissions 1990–2019, changes in emissions projected by baseline scenarios for 2020–2050, and differences between scenarios in 2050 using scenarios from three models: IEA, IMAGE, and RECC.

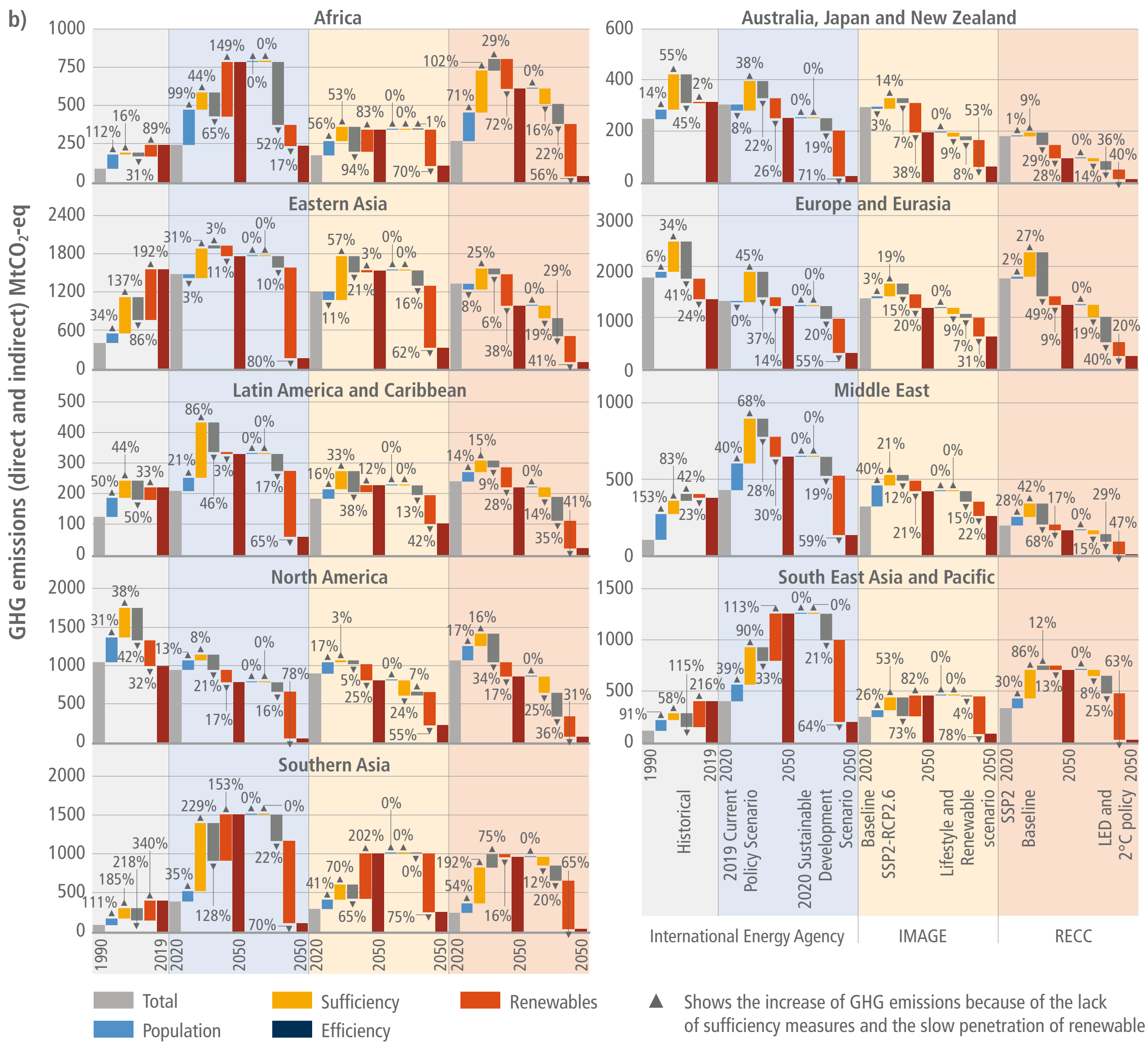


Figure TS.15 (continued): Decompositions of changes in historical residential energy emissions 1990–2019, changes in emissions projected by baseline scenarios for 2020–2050, and differences between scenarios in 2050 using scenarios from three models: IEA, IMAGE, and RECC. RECC-LED data for **(a)** global, and **(b)** for nine world regions, include only space heating and cooling and water heating in residential buildings. Emissions are decomposed using the equation, which shows changes in driver variables of population, sufficiency (floor area per capita), efficiency (final energy per floor area), and renewables (GHG emissions per final energy). 'Renewables' is a summary term describing changes in GHG intensity of energy supply. Emission projections to 2050, and differences between scenarios in 2050, demonstrate mitigation potentials from the dimensions of the SER framework realised in each model scenario. In most regions, historical improvements in efficiency have been approximately matched by growth in floor area per capita. Implementing sufficiency measures that limit growth in floor area per capita, particularly in developed regions, reduces the dependence of climate mitigation on technological solutions. {Figure 9.5, Box 9.2}

The decarbonisation of buildings is constrained by multiple barriers and obstacles as well as limited finance flows (*high confidence*). The lack of institutional capacity, especially in developing countries, and appropriate governance structures slow down the decarbonisation of the global building stock (*medium confidence*). The building sector is highly heterogenous with many different building types, sizes, and operational uses. The sub-segment representing rented property faces principal/agent problems where the tenant benefits from the decarbonisation's investment made by the landlord. The organisational context and the governance structure could trigger or hinder the decarbonisation of buildings. Global investment in the decarbonisation of buildings was estimated at USD164 billion in 2020. However, this is not enough by far to close the investment gap (*high confidence*). {9.9}

Policy packages could grasp the full mitigation potential of the global building stock. Building energy codes represent the main regulatory instrument to reduce emissions from both new and existing buildings (*high confidence*). The most advanced building energy codes include requirements on each of the three pillars of the SER framework in the *use* and *construction* phase of buildings. Building energy codes have proven to be effective if compulsory and combined with other regulatory instruments such as minimum energy performance standard for appliances and equipment, if the performance level is set at the level of the best available technologies in the market (*high confidence*). Market-based instruments such as carbon taxes with recycling of the revenues and personal or building carbon allowances could also contribute to fostering the decarbonisation of the building sector (*medium confidence*). {9.9}

Adapting buildings to future climate while ensuring well-being for all requires action. Expected heatwaves will inevitably increase cooling needs to limit the health impacts of climate change (*medium confidence*). Global warming will impact cooling and heating needs but also the performance, durability and safety of buildings, especially historical and coastal ones, through changes in temperature, humidity, atmospheric concentrations of CO_2 and chloride, and sea level rise. Adaptation measures to cope with climate change may increase the demand for energy and materials leading to an increase in GHG emissions if not mitigated. Sufficiency measures which anticipate climate change, and include natural ventilation, white walls, and nature-based solutions (e.g., green roofs) will decrease the demand for cooling. Shared cooled spaces with highly efficient cooling solutions are among the mitigation strategies which can limit the effect of the expected heatwaves on people's health. {9.7, 9.8}

Figure TS.16 | Contribution of building-sector mitigation policies to meeting Sustainable Development Goals. {Figure 9.18}

Well-designed and effectively implemented mitigation actions in the buildings sector have significant potential to help achieve the SDGs (*high confidence*). As shown in Figure TS.16, the impacts of mitigation actions in the building sector go far beyond the goal of climate action (SDG 13) and contribute to meeting 15 other SDGs. Mitigation actions in the building sector bring health gains through improved indoor air quality and thermal comfort, and have positive significant macro- and micro-economic effects, such as increased productivity of labour, job creation, reduced poverty, especially energy poverty, and improved energy security (*high confidence*). (Figure TS.29) {9.8}

The COVID-19 pandemic emphasised the importance of buildings for human well-being and highlighted the inequalities in access for all to suitable, healthy buildings, which provide natural daylight and clean air to their occupants (*medium confidence*). Recent WHO health recommendations have also emphasise indoor air quality, preventive maintenance of centralised mechanical heating, ventilation, and cooling systems. There are opportunities for repurposing existing non-residential buildings, no longer in use due to the expected spread of teleworking triggered by the health crisis and enabled by digitalisation. (Box TS.14) {9.1}

TS.5.5 Industry

The industry chapter focuses on new developments since AR5 and emphasises the role of the energy-intensive and emissions-intensive basic materials industries in strategies for reaching net zero emissions. The Paris Agreement, the SDGs and the COVID-19 pandemic provide a new context for the evolution of industry and mitigation of industry greenhouse gas (GHG) emissions (*high confidence*). {11.1.1}

Net zero CO_2 industrial-sector emissions are possible but challenging (*high confidence*). Energy efficiency will continue to be important. Reduced materials demand, material efficiency, and circular economy solutions can reduce the need for primary production. Primary production options include switching to new processes that use low-to-zero GHG energy carriers and feedstocks (e.g., electricity, hydrogen, biofuels, and carbon dioxide capture and utilisation (CCU) to provide carbon feedstocks). Carbon capture and storage (CCS) will be required to mitigate remaining CO_2 emissions {11.3}. These options require substantial scaling up of electricity, hydrogen, recycling, CO_2, and other infrastructure, as well as phase-out or conversion of existing industrial plants. While improvements in the GHG intensities of major basic materials have nearly stagnated over the last 30 years, analysis of historical technology shifts and newly available technologies indicate these intensities can be significantly reduced by mid-century. {11.2, 11.3, 11.4}

Industry-sector emissions have been growing faster since 2000 than emissions in any other sector, driven by increased basic materials extraction and production (*high confidence*). GHG emissions attributed to the industrial sector originate from fuel combustion, process emissions, product use and waste, which jointly accounted for 14.1 $GtCO_2$-eq or 24% of all direct anthropogenic emissions in 2019, second behind the energy supply sector. Industry is a leading GHG emitter – 20 $GtCO_2$-eq or 34% of global emissions in 2019 – if indirect emissions from power and heat generation are included. The share of emissions originating from direct fuel combustion is decreasing and was 7 $GtCO_2$-eq, 50% of direct industrial emissions in 2019. {11.2.2}

Global material intensity – the in-use stock of manufactured capital in tonnes per unit of GDP – is increasing (*high confidence*). In-use stock of manufactured capital per capita has been growing faster than GDP per capita since 2000. Total global in-use stock of manufactured capital grew by 3.4% yr^{-1} in 2000–2019. At the same time, per-capita material stocks in several developed countries have stopped growing, showing a decoupling from GDP per capita. {11.2.1, 11.3.1}

The demand for plastic has been growing most strongly since 1970 (*high confidence*). The current >99% reliance on fossil feedstock, very low recycling, and high emissions from petrochemical processes is a challenge for reaching net zero emissions. At the same time, plastics are important for reducing emissions elsewhere, for example, light-weighting vehicles. There are as yet no shared visions for fossil-free plastics, but several possibilities. {11.4.1.3}

Scenario analyses show that significant reductions in global GHG emissions and even close to net zero emissions from GHG intensive industry (e.g., steel, plastics, ammonia, and cement) can be achieved by 2050 by deploying multiple available and emerging options (*medium confidence*). Significant reductions in industry emissions require a reorientation from the historic focus on important but incremental improvements (e.g., energy efficiency) to transformational changes in energy and feedstock sourcing, materials efficiency, and more circular material flows. {11.3, 11.4}

Key mitigation options such as materials efficiency, circular material flows and emerging primary processes, are not well represented in climate change scenario modelling and integrated assessment models (IAMs), albeit with some progress in recent years (*high confidence*). The character of these interventions (e.g., appearing in many forms across complex value chains, making cost estimates difficult) combined with the limited data on new fossil-free primary processes help explain why they are less represented in models than, for example, CCS. As a result, overall mitigation costs and the need for CCS may be overestimated. {11.4.2.1}

Electrification is emerging as a key mitigation option for industry (*high confidence*). Using electricity directly, or indirectly via hydrogen from electrolysis for high temperature and chemical feedstock requirements, offers many options to reduce emissions. It also can provide substantial grid-balancing services, for example, through electrolysis and storage of hydrogen for chemical process use or demand response. (Box TS.9) {11.3.5}

Carbon is a key building block in organic chemicals, fuels and materials and will remain important (*high confidence*). In order to reach net zero CO_2 emissions for the carbon needed in society (e.g., plastics, wood, aviation fuels, solvents, etc.), it is important to

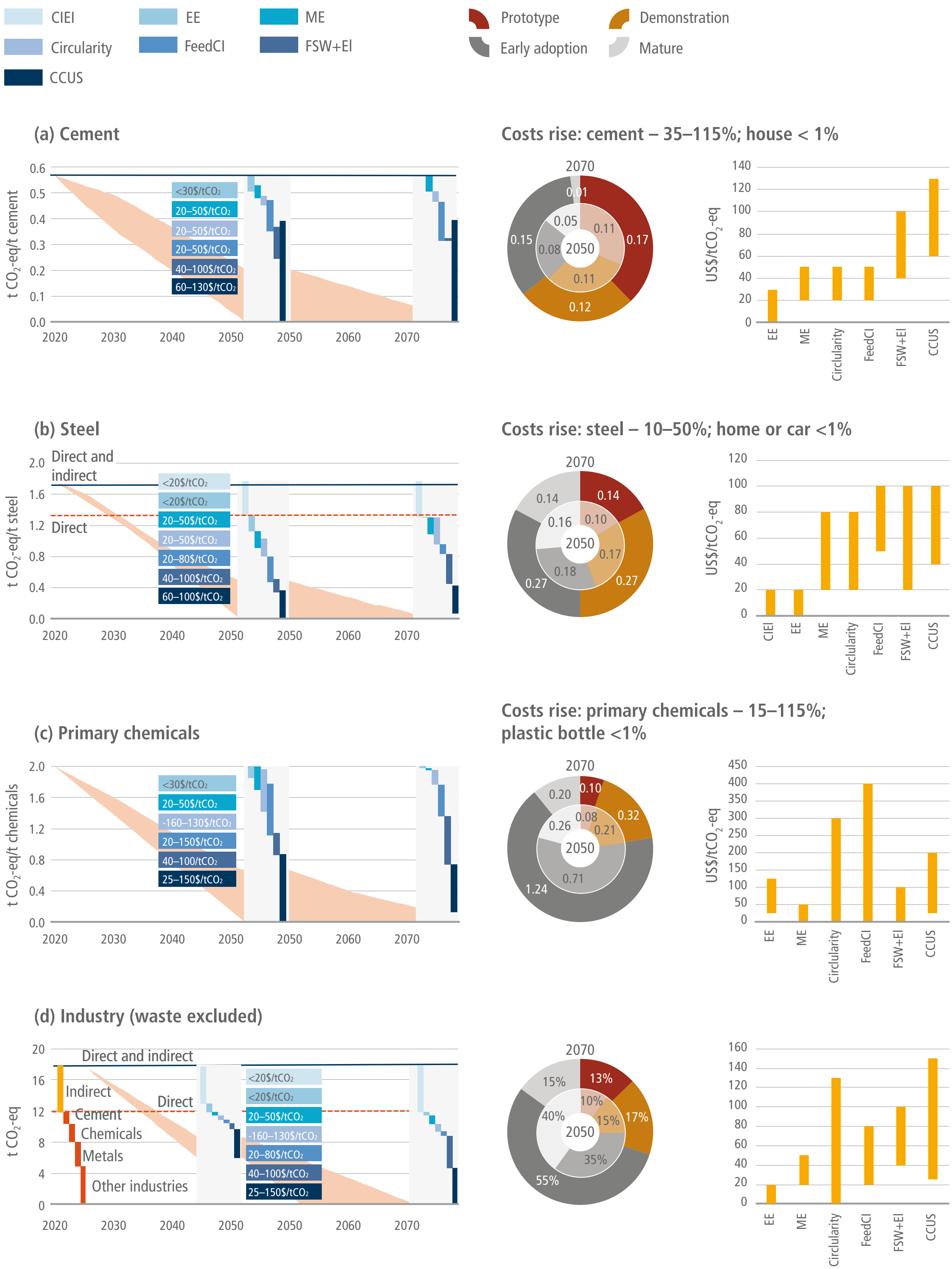


Figure TS.17 | Potentials and costs for zero-carbon mitigation options for industry and basic materials.

Figure TS.17 (continued): Potentials and costs for zero-carbon mitigation options for industry and basic materials. CIEl – carbon intensity of electricity for indirect emissions; EE – energy efficiency; ME – material efficiency; Circularity – material flows (clinker substituted by coal fly ash, blast furnace slag or other by-products and waste, steel scrap, plastic recycling, etc.); FeedCI – feedstock carbon intensity (hydrogen, biomass, novel cement, natural clinker substitutes); FSW+El – fuel switch and processes electrification with low-carbon electricity. Ranges for mitigation options are shown based on bottom-up studies for grouped technologies packages, not for single technologies. In circles, contribution to mitigation from technologies based on their readiness are shown for 2050 (2040) and 2070. Direct emissions include fuel combustion and process emissions. Indirect emissions include emissions attributed to consumed electricity and purchased heat. For basic chemicals, only methanol, ammonia and high-value chemicals are considered. Total for industry does not include emissions from waste. Negative mitigation costs for some options such as Circularity are not reflected. {Figure 11.13}

close the use loops for carbon and carbon dioxide through increased circularity with mechanical and chemical recycling, more efficient use of biomass feedstock with addition of low-GHG hydrogen to increase product yields (e.g., for biomethane and methanol), and potentially direct air capture of CO_2 as a new carbon source. {11.3, 11.4.1}

Production costs for very low to zero emissions basic materials may be high but the cost for final consumers and the general economy will be low (*medium confidence*). Costs and emissions reductions potential in industry, and especially heavy industry, are highly contingent on innovation, commercialisation, and market-uptake policies. Technologies exist to take all industry sectors to very low or zero emissions, but require five to fifteen years of intensive innovation, commercialisation, and policy to ensure uptake. Mitigation costs are in the rough range of USD50–150 $tCO_2\text{-eq}^{-1}$, with wide variation within and outside this band. This affects competitiveness and requires supporting policy. Although production cost increases can be significant, they translate to very small increases in the costs for final products, typically less than a few percent depending on product, assumptions, and system boundaries. (Figure TS.17) {11.4.1.5}

Several technological options exist for very low to zero emissions steel, but their uptake will require integrated material efficiency, recycling, and production decarbonisation policies (*high confidence*). Material efficiency can potentially reduce steel demand by up to 40% based on design for less steel use, long life, reuse, constructability, and low-contamination recycling. Secondary production through high-quality recycling must be maximised. Production decarbonisation will also be required, starting with the retrofitting of existing facilities for partial fuel switching (e.g., to biomass or hydrogen), CCU and CCS, followed by very low and zero emissions production based on high-capture CCS or direct hydrogen, or electrolytic iron-ore reduction followed by an electric arc furnace. {11.3.2, 11.4.1.1}

Several current and emerging options can significantly reduce cement and concrete emissions. Producer, user, and regulator education, as well as innovation and commercialisation policy are needed (*medium confidence*). Cement and concrete are currently overused because they are inexpensive, durable, and ubiquitous, and consumption decisions typically do not give weight to their production emissions. Basic material efficiency efforts to use only well-made concrete thoughtfully and only where needed (e.g., using right-sized, prefabricated components) could reduce emissions by 24–50% through lower demand for clinker. Cementitious material substitution with various materials (e.g., ground limestone and calcined clays) can reduce process calcination emissions by up to 50% and occasionally much more. Until a very low GHG emissions alternative binder to Portland cement is commercialised – which is not anticipated in the near to mid-term – CCS will be essential for eliminating the limestone calcination process emissions for making clinker, which currently represent 60% of GHG emissions in best-available technology plants. {11.3.2, 11.3.6, 11.4.1.2}

While several technological options exist for decarbonising the main industrial feedstock chemicals and their derivatives, the costs vary widely (*high confidence*). Fossil fuel-based feedstocks are inexpensive and still without carbon pricing, and their biomass- and electricity-based replacements are expected to be more expensive. The chemical industry consumes large amounts of hydrogen, ammonia, methanol, carbon monoxide, ethylene, propylene, benzene, toluene, and mixed xylenes and aromatics from fossil feedstock, and from these basic chemicals produces tens of thousands of derivative end-use chemicals. Hydrogen, biogenic or air-capture carbon, and collected plastic waste for the primary feedstocks can greatly reduce total emissions. Biogenic carbon feedstock is expected to be limited due to competing land uses. {11.4.1}

Light industry and manufacturing can be largely decarbonised through switching to low-GHG fuels (e.g., biofuels and hydrogen) and electricity (e.g., for electrothermal heating and heat pumps) (*high confidence*). Most of these technologies are already mature, for example for low-temperature heat, but a major challenge is the current low cost of fossil CH_4 and coal relative to low- and zero-GHG electricity, hydrogen, and biofuels. {11.4.1}

The pulp and paper industry has significant biogenic carbon emissions but relatively small fossil carbon emissions. Pulp mills have access to biomass residues and by-products and in paper mills the use of process heat at low to medium temperatures allows for electrification (*high confidence*). Competition for feedstock will increase if wood substitutes for building materials and petrochemicals feedstock. The pulp and paper industry can also be a source of biogenic carbon dioxide, carbon for organic chemicals feedstock, and for CDR using CCS. {11.4.1}

The geographical distribution of renewable resources has implications for industry (*medium confidence*). The potential for zero-emission electricity and low-cost hydrogen from electrolysis powered by solar and wind, or hydrogen from other very low emission sources, may reshape where currently energy- and emissions-intensive basic materials production is located, how value chains are organised, trade patterns, and what gets transported in international shipping. Regions with bountiful solar and wind resources, or low fugitive CH_4 co-located with CCS geology, may become exporters of hydrogen or hydrogen carriers such as methanol and ammonia, or home to the production of iron and steel, organic platform chemicals, and other energy-intensive basic materials. {11.2, 11.4, Box 11.1}

The level of policy maturity and experience varies widely across the mitigation options (*high confidence*). Energy efficiency is a well-established policy field with decades of experience from voluntary and negotiated agreements, regulations, energy auditing and demand-side management (DSM) programmes. In contrast, materials demand management and efficiency are not well understood and addressed from a policy perspective. Barriers to recycling that policy could address are often specific to the different material loops (e.g., copper contamination for steel and lack of technologies or poor economics for plastics) or waste-management systems. For electrification and fuel switching the focus has so far been mainly on innovation and developing technical supply-side solutions rather than creating market demand. {11.5.2, 11.6}

Industry has so far largely been sheltered from the impacts of climate policy and carbon pricing due to concerns about carbon leakage[26] and reducing competitiveness (*high confidence*). New approaches to industrial development policy are emerging for a transition to net zero GHG emissions. The transition requires a clear direction towards net zero, technology development, market demand for low-carbon materials and products, governance capacity and learning, socially inclusive phase-out plans, as well as international coordination of climate and trade policies (see also TS.6.5). It requires comprehensive and sequential industrial policy strategies leading to immediate action as well as preparedness for future decarbonisation, governance at different levels (from international to local) and integration with other policy domains. {11.6}

TS.5.6 Agriculture, Forestry, Other Land Uses, and Food Systems

TS.5.6.1 Agricultre, Forestry, and Other Land Use (AFOLU)

The agriculture, forestry and other land use (AFOLU)[27] sector encompasses managed ecosystems and offers significant mitigation opportunities while providing food, wood and other renewable resources as well as biodiversity conservation, provided the sector adapts to climate change. Land-based mitigation measures can reduce GHG emissions within the AFOLU sector, deliver CDR and provide biomass thereby enabling emission reductions in other sectors.[28] The rapid deployment of AFOLU measures features in all pathways that limit global warming to 1.5°C. Where carefully and appropriately implemented, AFOLU mitigation measures are positioned to deliver substantial co-benefits and help address many of the wider challenges associated with land management. If AFOLU measures are deployed badly, when taken together with the increasing need to produce sufficient food, feed, fuel and wood, they may exacerbate trade-offs with the conservation of habitats, adaptation, biodiversity and other services. At the same time the capacity of the land to support these functions may be threatened by climate change (*high confidence*). {AR6 WGI Figure SPM.7; AR6 WGII, 7.1, 7.6}

The AFOLU sector, on average, accounted for 13–21% of global total anthropogenic GHG emissions in the period 2010–2019. At the same time managed and natural terrestrial ecosystems were a carbon sink, absorbing around one third of anthropogenic CO_2 emissions (*medium confidence*). Estimated anthropogenic net CO_2 emissions from AFOLU (based on bookkeeping models) result in a net source of +5.9 ± 4.1 $GtCO_2\ yr^{-1}$ between 2010 and 2019 with an unclear trend. Based on FAOSTAT or national GHG inventories, the net CO_2 emissions from AFOLU were 0.0 to +0.8 $GtCO_2\ yr^{-1}$ over the same period. There is a discrepancy in the reported CO_2 AFOLU emissions magnitude because alternative methodological approaches that incorporate different assumptions are used {7.2.2}. If the responses of all managed and natural land to both anthropogenic environmental change and natural climate variability, estimated to be a gross sink of –12.5 ± 3.2 $GtCO_2\ yr^{-1}$ for the period 2010–2019, are added to land-use emissions, then land overall constituted a net sink of –6.6 ± 5.2 $GtCO_2\ yr^{-1}$ in terms of CO_2 emissions (*medium confidence*). (Table TS.4) {7.2, Table 7.1}

Land-use change drives net AFOLU CO_2 emission fluxes. The rate of deforestation, which accounts for 45% of total AFOLU emissions, has generally declined, while global tree cover and global forest-growing stock levels are *likely* increasing (*medium confidence*). There are substantial regional differences, with losses of carbon generally observed in tropical regions and gains in temperate and boreal regions. Agricultural CH_4 and N_2O emissions are estimated to average 157 ± 47.1 $MtCH_4\ yr^{-1}$ and 6.6 ± 4.0 $MtN_2O\ yr^{-1}$ or 4.2 ± 1.3 and 1.8 ± 1.1 $GtCO_2$-eq yr^{-1} (using IPCC AR6 GWP100 values for CH_4 and N_2O) respectively between 2010 and 2019 {7.2.1, 7.2.3}. AFOLU CH_4 emissions continue to increase, the main source of which is enteric fermentation from ruminant animals. Similarly, AFOLU N_2O emissions are increasing, dominated by agriculture, notably from manure application, nitrogen deposition, and nitrogen fertiliser use (*high confidence*). In addition to being a net carbon sink and source of GHG emissions, land plays an important role in climate through albedo effects, evapotranspiration, and aerosol loading through emissions of volatile organic compounds (VOCs). The combined role of CH_4, N_2O and aerosols in total climate forcing, however, is unclear and varies strongly with bioclimatic region and management practice. {2.4.2.5, 7.2, 7.3}

TS

26 See section TS.5.9.

27 AFOLU is a sector in the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. AFOLU anthropogenic greenhouse gas emissions and removals by sinks reported by governments under the UNFCCC are defined as all those occurring on 'managed land'. Managed land is land where human interventions and practices have been applied to perform production, ecological or social functions.

28 For example: in the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, CO_2 emissions from biomass used for energy are reported in the AFOLU sector, calculated as an implicit component of carbon stock changes. In the energy sector, CO_2 emissions from biomass combustion for energy are recorded as an information item that is not included in the sectoral total emissions for the that sector.

Table TS.4 | Net anthropogenic emissions (annual averages for 2010–2019[a]) from agriculture, forestry and other land use (AFOLU). For context, the net flux due to the natural response of land to climate and environmental change is also shown for CO_2 in column E. Positive values represent emissions, negative values represent removals. Due to different approaches to estimate anthropogenic fluxes, AFOLU CO_2 estimates in the table below are not directly comparable to LULUCF in national greenhouse gas inventories (NGHGIs).

Anthropogenic						Natural response	Natural and anthropogenic
Gas	Units	AFOLU net anthropogenic emissions	Non-AFOLU anthropogenic GHG emissions	Total net anthropogenic emissions (AFOLU and non-AFOLU) by gas	AFOLU as a % of total net anthropogenic emissions by gas	Natural land sinks including natural response of land to anthropogenic environmental change and climate variability	Net-land atmosphere CO_2 flux (i.e., anthropogenic AFOLU and natural fluxes across entire land surface)
		A	B	C = A + B	D = (A/C) *100	E	F = A + E
CO_2	$GtCO_2$-eq yr^{-1}	5.9 ± 4.1 (bookkeeping models, managed soils and pasture). 0 to 0.8 (NGHGI/FAOSTAT data)	36.2 ± 2.9	42.0 ± 29.0	14%	–12.5 ± 3.2	–6.6 ± 4.6
CH_4	$MtCH_4$ yr^{-1}	157.0 ± 47.1	207.5 ± 62.2	364.4 ± 109.3			
	$GtCO_2$-eq yr^{-1}	4.2 ± 1.3	5.9 ± 1.8	10.2 ± 3.0	41%		
N_2O	MtN_2O yr^{-1}	6.6 ± 4.0	2.8 ± 1.7	9.4 ± 5.6			
	$GtCO_2$-eq yr^{-1}	1.8 ± 1.1	0.8 ± 0.5	2.6 ± 1.5	69%		
Total	$GtCO_2$-eq yr^{-1}	11.9 ± 4.4 (CO_2 component considers bookkeeping models only)	44 ± 3.4	55.9 ± 6.1	21%		

[a] Estimates are given for 2019 as this is the latest date when data are available for all gases, consistent with Chapter 2 of this report. Positive fluxes are emission from land to the atmosphere. Negative fluxes are removals. For all Table footnotes see Table 7.1. {Table 7.1}

The AFOLU sector offers significant near-term mitigation potential at relatively low cost and can provide 20–30% of the 2050 emissions reduction described in scenarios that limit warming to 2°C (>67%) or lower (*high evidence, medium agreement*). The AFOLU sector can provide 20–30% (interquartile range) of the global mitigation needed for a 1.5°C or 2°C pathway towards 2050, though there are highly variable mitigation strategies for how AFOLU potential can be deployed for achieving climate targets {Illustrative Mitigation Pathways in 7.5}. The estimated economic (<USD100 tCO_2-eq^{-1}) AFOLU sector mitigation potential is 8 to 14 $GtCO_2$-eq yr^{-1} between 2020–2050, with the bottom end of this range representing the mean from IAMs and the upper end representing the mean estimate from global sectoral studies. The economic potential is about half of the technical potential from AFOLU, and about 30–50% could be achieved under USD20 tCO_2-eq^{-1} {7.4}. The implementation of robust measurement, reporting and verification processes is paramount to improving the transparency of changes in land carbon stocks and this can help prevent misleading assumptions or claims on mitigation. {7.1, 7.4, 7.5}

Between 2020 and 2050, mitigation measures in forests and other natural ecosystems provide the largest share of the AFOLU mitigation potential (up to USD100 tCO_2-eq^{-1}), followed by agriculture and demand-side measures (*high confidence*). In the global sectoral studies, the protection, improved management, and restoration of forests, peatlands, coastal wetlands, savannas and grasslands have the potential to reduce emissions and/or sequester 7.3 mean (3.9–13.1) $GtCO_2$-eq yr^{-1}. Agriculture provides the second largest share of the mitigation potential, with 4.1 (1.7–6.7) $GtCO_2$-eq yr^{-1} (up to USD100 tCO_2-eq^{-1}) from cropland and grassland soil carbon management, agroforestry, use of biochar, improved rice cultivation, and livestock and nutrient management. Demand-side measures including shifting to sustainable healthy diets, reducing food waste, building with wood, biochemicals, and bio-textiles, have a mitigation potential of 2.2 (1.1–3.6) $GtCO_2$-eq yr^{-1}. Most mitigation options are available and ready to deploy. Emissions reductions can be achieved relatively quickly, whereas CDR needs upfront investment. Sustainable intensification in agriculture, shifting diets, and reducing food waste could enhance efficiencies and reduce agricultural land needs, and are therefore critical for enabling supply-side measures such as reforestation, restoration, as well as decreasing CH_4 and N_2O emissions from agricultural production. In addition, emerging technologies (e.g., vaccines or CH_4 inhibitors) have the potential to substantially increase the CH_4 mitigation potential beyond current estimates. AFOLU mitigation is not only relevant in countries with large land areas. Many smaller countries and regions, particularly with wetlands, have disproportionately high levels of AFOLU mitigation potential density. {7.4, 7.5}

The economic and political feasibility of implementing AFOLU mitigation measures is hampered by persistent barriers. Assisting countries to overcome barriers will help to achieve

significant short-term mitigation (*medium confidence*). Finance forms a critical barrier to achieving these gains as currently mitigation efforts rely principally on government sources and funding mechanisms which do not provide sufficient resources to enable the economic potential to be realised. Differences in cultural values, governance, accountability and institutional capacity are also important barriers. Climate change itself could reduce the mitigation potential from the AFOLU sector, although an increase in the capacity of natural sinks could occur despite changes in climate (*medium confidence*) {AR6 WGI Figure SPM.7 and Sections 7.4 and 7.6}. The continued loss of biodiversity makes ecosystems less resilient to climate change extremes and this may further jeopardise the achievement of the AFOLU mitigation potentials indicated in this chapter (*high confidence*). (Box TS.15) {7.6}

The provision of biomass for bioenergy (with/without BECCS) and other bio-based products represents an important share of the total mitigation potential associated with the AFOLU sector, though these mitigation effects accrue to other sectors (*high confidence*). Recent estimates of the technical bioenergy potential, when constrained by food security and environmental considerations, are within the ranges 5–50 and 50–250 EJ yr^{-1} by 2050 for residues and dedicated biomass production systems, respectively.[29] (TS.5.7) {7.4, 12.3}

Bioenergy is the most land-intensive energy option, but total land occupation of other renewable energy options can also become significant in high deployment scenarios. While not as closely connected to the AFOLU sector as bioenergy, other renewable energy options can influence AFOLU activities in both synergistic and detrimental ways (*high confidence*). The character of land occupation, and associated impacts, vary considerably among mitigation options and also for the same option depending on geographic location, scale, system design and deployment strategy. Land occupation can be large uniform areas, for example, reservoir hydropower dams and tree plantations, and more distributed occupation that is integrated with other land uses, for example, wind turbines and agroforestry in agriculture landscapes. Deployment can be partly decoupled from additional land use, for example, use of organic waste and residues and integration of solar PV into buildings and other infrastructure (*high confidence*). Wind and solar power can coexist with agriculture in beneficial ways (*medium confidence*). Indirect land occupation includes new agriculture areas following displacement of food production with bioenergy plantations and expansion of mining activities providing minerals required for manufacture of EV batteries, PV, and wind power. {7.4, 12.5}

The deployment of land-based mitigation measures can provide co-benefits, but there are also risks and trade-offs from inappropriate land management (*high confidence*). Such risks can best be managed if AFOLU mitigation is pursued in response to the needs and perspectives of multiple stakeholders to achieve outcomes that maximise synergies while limiting trade-offs (*medium confidence*). The results of implementing AFOLU measures are often variable and highly context-specific. Depending on local conditions (e.g., ecosystem, climate, food system, land ownership) and management strategies (e.g., scale, method), mitigation measures can positively or negatively affect biodiversity, ecosystem functioning, air quality, water availability and quality, soil productivity, rights infringements, food security, and human well-being. The agriculture and forestry sectors can devise management approaches that enable biomass production and use for energy in conjunction with the production of food and timber, thereby reducing the conversion pressure on natural ecosystems (*medium confidence*). Mitigation measures addressing GHGs may also affect other climate forcers such as albedo and evapotranspiration. Integrated responses that contribute to mitigation, adaptation, and other land challenges will have greater likelihood of being successful (*high confidence*); measures which provide additional benefits to biodiversity and human well-being are sometimes described as 'Nature-based Solutions'. {7.1, 7.4, 7.6, 12.4, 12.5}

AFOLU mitigation measures have been well understood for decades but deployment remains slow, and emissions trends indicate unsatisfactory progress despite beneficial contributions to global emissions reduction from forest-related options (*high confidence*). Globally, the AFOLU sector has so far contributed modestly to net mitigation, as past policies have delivered about 0.65 $GtCO_2$ yr^{-1} of mitigation during 2010–2019 or 1.4% of global gross emissions. The majority (>80%) of emission reduction resulted from forestry measures. Although the mitigation potential of AFOLU measures is large from a biophysical and ecological perspective, its feasibility is hampered by lack of institutional support, uncertainty over long-term additionality and trade-offs, weak governance, fragmented land ownership, and uncertain permanence effects. Despite these impediments to change, AFOLU mitigation options are demonstrably effective and with appropriate support can enable rapid emission reductions in most countries. {7.4, 7.6}

Concerted, rapid and sustained effort by all stakeholders, from policymakers and investors to land owners and managers is a pre-requisite for achieving high levels of mitigation in the AFOLU sector (*high confidence*). To date USD0.7 billion yr^{-1} is estimated to have been spent on AFOLU mitigation. This is well short of the more than USD400 billion yr^{-1} that is estimated to be necessary to deliver the up to 30% of global mitigation effort envisaged in deep mitigation scenarios (*medium confidence*). This estimate of the global funding requirement is smaller than current subsidies provided to agriculture and forestry. A gradual redirection of existing agriculture and forestry subsidies would greatly advance mitigation. Effective policy interventions and national (investment) plans as part of NDCs, specific to local circumstances and needs, are urgently needed to accelerate the deployment of AFOLU mitigation options. These interventions are effective when they include funding schemes and long-term consistent support for implementation with governments taking the initiative together with private funders and non-state actors. {7.6}

29 These potentials do not include avoided emissions resulting from bioenergy use associated with BECCS, which depends on energy substitution patterns, conversion efficiencies, and supply chain emissions for both the BECCS and substituted energy systems. Estimates of substitution effects of bioenergy indicate that this additional mitigation would be of the same magnitude as provided through CDR using BECCS. Bio-based products with long service life, for example, construction timber, can also provide mitigation through substitution of steel, concrete, and other products, and through carbon storage in the bio-based product pool. See section TS.5.7 for the CDR potential of BECCS. {7.4, 12.3}

Realising the mitigation potential of the AFOLU sector depends strongly on policies that directly address emissions and drive the deployment of land-based mitigation options, consistent with carbon prices in deep mitigation scenarios (*high confidence*). Examples of successful policies and measures include establishing and respecting tenure rights and community forestry, improved agricultural management and sustainable intensification, biodiversity conservation, payments for ecosystem services, improved forest management and wood-chain usage, bioenergy, voluntary supply chain management efforts, consumer behaviour campaigns, private funding and joint regulatory efforts to avoid, for example, leakage. The efficacy of different policies, however, will depend on numerous region-specific factors. In addition to funding, these factors include governance, institutions, long-term consistent execution of measures, and the specific policy setting. While the governance of land-based mitigation can draw on lessons from previous experience with regulating biofuels and forest carbon, integrating these insights requires governance that goes beyond project-level approaches emphasising integrated land-use planning and management within the frame of the Sustainable Development Goals. {7.4, Box 7.2, 7.6}

Addressing the many knowledge gaps in the development and testing of AFOLU mitigation options can rapidly advance the likelihood of achieving sustained mitigation (*high confidence*). Research priorities include improved quantification of anthropogenic and natural GHG fluxes and emissions modelling, better understanding of the impacts of climate change on the mitigation potential, permanence and additionality of estimated mitigation actions, and improved (real-time and cheap) measurement, reporting and verification. There is a need to include a greater suite of mitigation measures in IAMs, informed by more realistic assessments that take into account local circumstances and socio-economic factors and cross-sector synergies and trade-offs. Finally, there is a critical need for more targeted research to develop appropriate country-level, locally specific, policy and land-management response options. These options could support more specific NDCs with AFOLU measures that enable mitigation while also contributing to biodiversity conservation, ecosystem functioning, livelihoods for millions of farmers and foresters, and many other SDGs. {7.7, Figure 17.1}

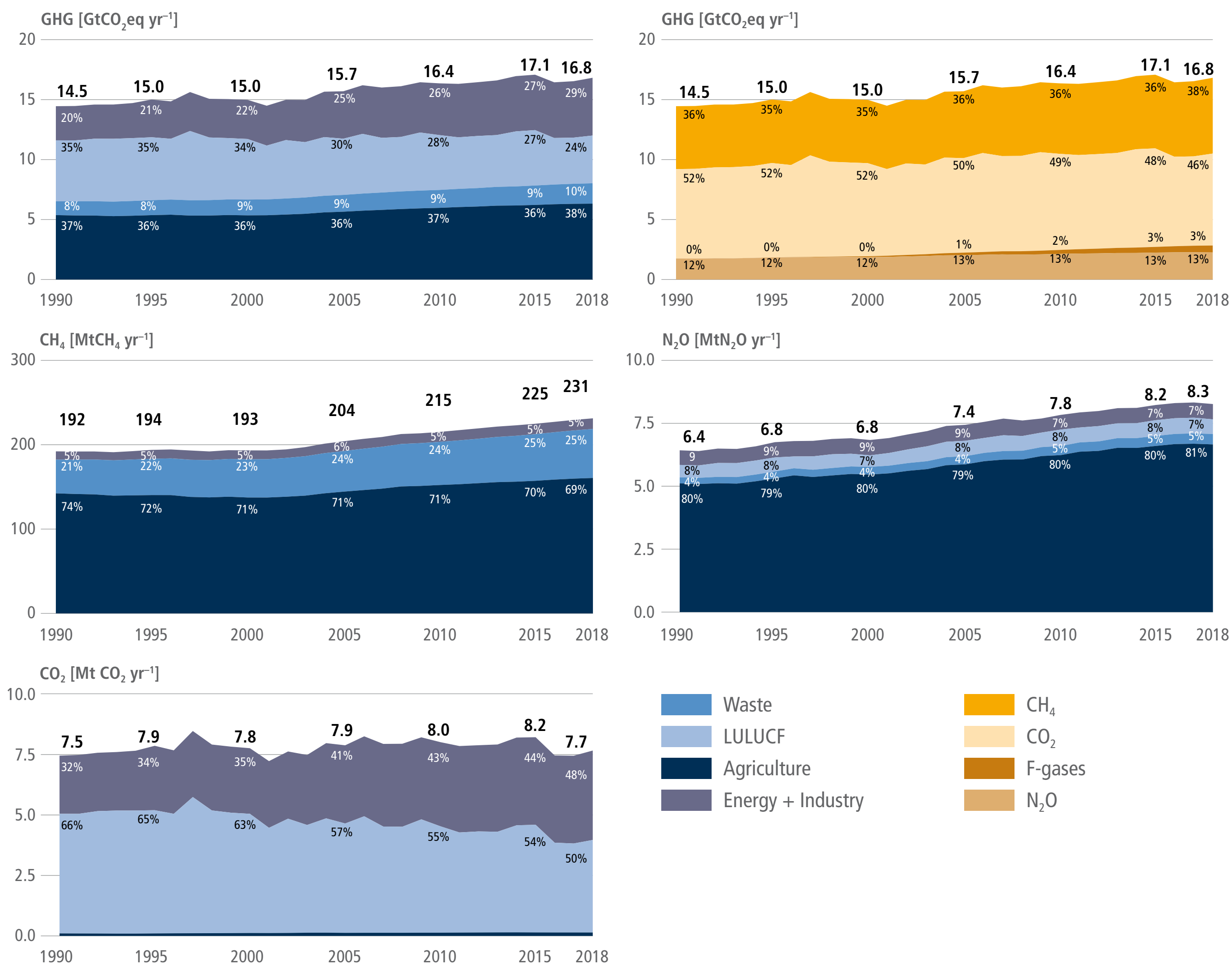


Figure TS.18 | Food-system GHG emissions from the agriculture, and land use, land-use change and forestry (LULUCF), waste, and energy and industry sectors. {Figure 12.5}

TS.5.6.2 Food Systems

Realising the full mitigation potential from the food system requires change at all stages from producer to consumer and waste management, which can be facilitated through integrated policy packages (*high confidence*). Food systems are associated with 23–42% of global GHG emissions, while there is still widespread food insecurity and malnutrition. Absolute GHG emissions from food systems increased from 14 to 17 $GtCO_2$-eq yr^{-1} in the period 1990–2018. Both supply- and demand-side measures are important to reduce the GHG intensity of food systems. Integrated food policy packages based on a combination of market-based, administrative, informative, and behavioural policies can reduce cost compared to uncoordinated interventions, address multiple sustainability goals, and increase acceptance across stakeholders and civil society (*limited evidence*, *medium agreement*). Food systems governance may be pioneered through local food policy initiatives complemented by national and international initiatives, but governance on the national level tends to be fragmented, and thus has limited capacity to address structural issues like inequities in access. (Figure TS.18, Table TS.5, Table TS.6) {7.2, 7.4, 12.4}

Diets high in plant protein and low in meat and dairy are associated with lower GHG emissions (*high confidence*). Ruminant meat shows the highest GHG intensity. Beef from dairy systems has lower emissions intensity than beef from beef herds (8–23 and 17–94 $kgCO_2$-eq (100 g protein)$^{-1}$, respectively) when some emissions are allocated to dairy products. The wide variation in emissions reflects differences in production systems, which range from intensive feedlots with stock raised largely on grains through to rangeland and transhumance production systems. Where appropriate, a shift to diets with a higher share of plant protein, moderate intake of animal-source foods and reduced intake of saturated fats could lead to substantial decreases in GHG emissions. Benefits would also include reduced land

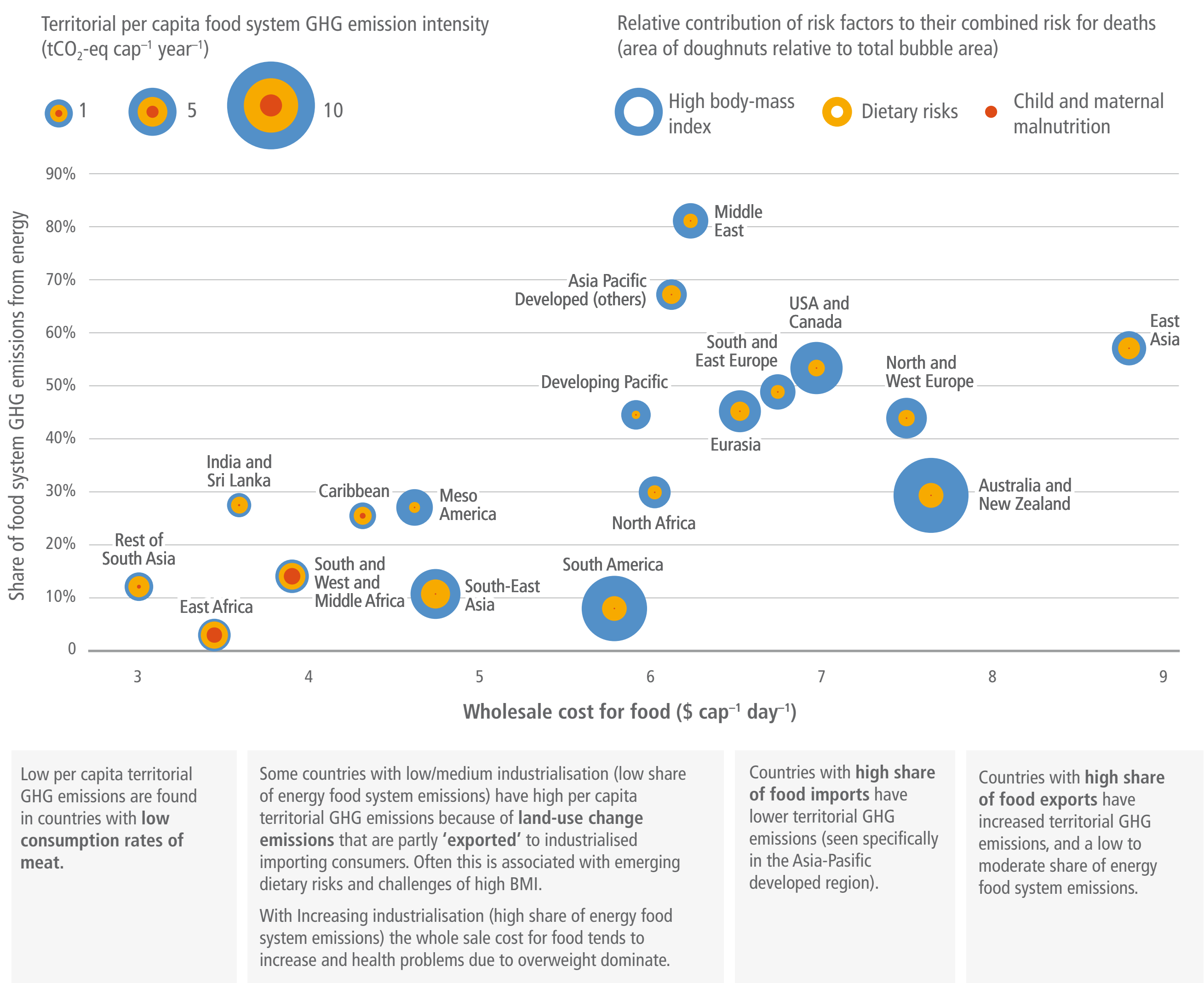


Figure TS.19 | Regional differences in health outcome, territorial per-capita GHG emissions from national food systems, and share of food system GHG emission from energy use. GHG emissions are calculated according to the IPCC Tier 1 approach and are assigned to the country where they occur, not necessarily where the food is consumed. Health outcome is expressed as relative contribution of each of the following risk factors to their combined risk for deaths: Child and maternal malnutrition (red), Dietary risks (yellow) or High body-mass index (blue). {Figure 12.7}

Table TS.5 | Food system mitigation opportunities.

Food system mitigation options (I: incremental; T: transformative)			Direct and indirect effect on GHG mitigation (+/0/–) [a]	Co-benefits/adverse effects [b]
Food from agriculture, aquaculture and fisheries	(I)	Dietary shift, in particular increased share of plant-based protein sources	D+ ↓ GHG footprint	A+ Animal welfare L+ Land sparing H+ Good nutritional properties, potentially ↓ risk from zoonotic diseases, pesticides and antibiotics
	(I/T)	Digital agriculture	D+ ↑ logistics	L+ Land sparing R+ ↑ resource-use efficiencies
	(T)	Gene technology	D+ ↑ productivity or efficiency	H+ ↑ nutritional quality E0 ↓ use of agrochemicals; ↑ probability of off-target impacts
	(I)	Sustainable intensification Land-use optimisation	D+ ↓ GHG footprint E0 Mixed effects	L+ Land sparing R– Might ↑ pollution/biodiversity loss
	(I)	Agroecology	D+ ↓ GHG/area, positive micro-climatic effects E+ ↓ energy, possibly ↓ transport FL+ Circular approaches	E+ Focus on co-benefits/ecosystem services R+ Circular, ↑ nutrient and water use efficiencies
Controlled environment agriculture	(T)	Soil-less agriculture	D+ ↑ productivity, weather independent FL+ Harvest on demand E– Currently ↑ energy demand, but ↓ transport, building spaces can be used for renewable energy	R+ Controlled loops ↑ nutrient- and water-use efficiency L+ Land sparing H+ Crop breeding can be optimised for taste and/or nutritional quality
Emerging food production technologies	(T)	Insects	D0 Good feed conversion efficiency FW+ Can be fed on food waste	H0 Good nutritional qualities but attention to allergies and food safety issues required
	(I/T)	Algae and bivalves	D+ ↓ GHG footprints	A+ Animal welfare L+ Land sparing H+ Good nutritional qualities; risk of heavy-metal and pathogen contamination R+ Biofiltration of nutrient-polluted waters
	(I/T)	Plant-based alternatives to animal-based food products	D+ No emissions from animals, ↓ inputs for feed	A+ Animal welfare L+ Land sparing H+ Potentially ↓ risk from zoonotic diseases, pesticides and antibiotics; but ↑ processing demand
	(T)	Cellular agriculture (including cultured meat, microbial protein)	D+ No emissions from animals, high protein conversion efficiency E– ↑ energy need FLW+ ↓ food loss and waste	A+ Animal welfare R+ ↓ emissions of reactive nitrogen or other pollutants H0 Potentially ↓ risk from zoonotic diseases, pesticides and antibiotics; ↑ research on safety aspects needed
Food processing and packaging	(I)	Valorisation of by-products, FLW logistics and management	M+ Substitution of bio-based materials FL+ ↓ of food losses	
	(I)	Food conservation	FW+ ↓ of food waste E0 ↑ energy demand but also energy savings possible (e.g., refrigeration, transport)	
	(I)	Smart packaging and other technologies	FW+ ↓ of food waste M0 ↑ material demand and ↑ material efficiency E0 ↑ energy demand; energy savings possible	H+ Possibly ↑ freshness/reduced food safety risks
	(I)	Energy efficiency	E+ ↓ energy	
Storage and distribution	(I)	Improved logistics	D+ ↓ transport emissions FL+ ↓ losses in transport FW– Easier access to food could ↑ food waste	
	(I)	Specific measures to reduce food waste in retail and food catering	FW+ ↓ of food waste E+ ↓ downstream energy demand M+ ↓ downstream material demand	
	(I)	Alternative fuels/transport modes	D+ ↓ emissions from transport	
	(I)	Energy efficiency	E+ ↓ energy in refrigeration, lightening, climatisation	
	(I)	Replacing refrigerants	D+ ↓ emissions from the cold chain	

[a] Direct and indirect GHG effects: D – direct emissions except emissions from energy use, E – energy demand, M – material demand, FL – food losses, FW – food waste; direction of effect on GHG mitigation: (+) increased mitigation, (0) neutral, (–) decreased mitigation.

[b] Co-benefits/adverse effects: H – health aspects, A – animal welfare, R – resource use, L – land demand, E – ecosystem services; (+) co-benefits, (–) adverse effects. {Table 12.8}

occupation and nutrient losses to the surrounding environment, while at the same time providing health benefits and reducing mortality from diet-related non-communicable diseases. (Figure TS.19) {7.4.5, 12.4}

Emerging food technologies such as cellular fermentation, cultured meat, plant-based alternatives to animal-based food products, and controlled environment agriculture, can bring substantial reduction in direct GHG emissions from food production (*limited evidence, high agreement*). These technologies have lower land, water, and nutrient footprints, and address concerns over animal welfare. Realising the full mitigation potential depends on access to low-carbon energy as some emerging technologies are relatively more energy intensive. This also holds for deployment of cold-chain and packaging technologies, which can help reduce food loss and waste, but increase energy and materials use in the food system. (Table TS.5) {11.4.1.3, 12.4}

TS.5.7 Carbon Dioxide Removal (CDR)

CDR is a key element in scenarios that limit warming to 2°C (>67%) or 1.5°C (>50%) by 2100 (*high confidence*). Implementation strategies need to reflect that CDR methods differ in terms of removal process, timescale of carbon storage, technological maturity, mitigation potential, cost, co-benefits, adverse side effects, and governance requirements. (Box TS.10)

Table TS.6 | Assessment of food system policies targeting (post-farm gate) food-chain actors and consumers.

	Level G: global/multinational; N: national; L: local	Transformative potential	Environmental effectiveness	Feasibility	Distributional effects	Cost	Co-benefits[a] and adverse side effect	Implications for coordination, coherence and consistency in policy package[b]
Integrated food policy packages	**NL**				**can be controlled**	**cost efficient**	**+ balanced, addresses multiple sustainability goals**	Reduces cost of uncoordinated interventions; increases acceptance across stakeholders and civil society (*robust evidence*, *high agreement*)
Taxes on food products	GN				regressive	low[#1]	– unintended substitution effects	High enforcing effect on other food policies; higher acceptance if compensation or hypothecated taxes (*medium evidence*, *high agreement*)
GHG taxes on food	GN				regressive	low[#2]	– unintended substitution effects + high spillover effect	Supportive, enabling effect on other food policies, agricultural/fishery policies; requires changes in power distribution and trade agreements (*medium evidence*, *medium agreement*)
Trade policies	G				impacts global distribution	complex effects	+ counters leakage effects +/– effects on market structure and jobs	Requires changes in existing trade agreements (*medium evidence*, *high agreement*)
Investment into research and innovation	GN				none	medium	+ high spillover effect + converging with digital society	Can fill targeted gaps for coordinated policy packages (e.g., monitoring methods) (*robust evidence*, *high agreement*)
Food and marketing regulations	N					low		Can be supportive; might be supportive to realise innovation; voluntary standards might be less effective (*medium evidence*, *medium agreement*)
Organisational-level procurement policies	NL					low	+ can address multiple sustainability goals	Enabling effect on other food policies; reaches large share of population (*medium evidence*, *high agreement*)
Sustainable food-based dietary guidelines	GNL				none	low	+ can address multiple sustainability goals	Little attention so far on environmental aspects; can serve as benchmark for other policies (labels, food formulation standards, etc.) (*medium evidence*, *medium agreement*)
Food labels/ information	GNL				education level relevant	low	+ empowers citizens + increases awareness + multiple objectives	Effective mainly as part of a policy package; incorporation of other objectives (e.g., animal welfare, fair trade); higher effect if mandatory (*medium evidence*, *medium agreement*)
Nudges	NL				none	low	+ possibly counteracting information deficits in population subgroups	High enabling effect on other food policies (*medium evidence*, *high agreement*)

Effect of measures: negative; none/unclear; slightly positive; positive

Notes: [#1] Minimum level to be effective 20% price increase; [#2] Minimum level to be effective USD50–80 tCO_2-eq. [a] In addition, all interventions are assumed to address health and climate change mitigation. [b] Requires coordination between policy areas, participation of stakeholders, transparent methods and indicators to manage trade-offs and prioritisation between possibly conflicting objectives; and suitable indicators for monitoring and evaluation against objectives.

All the illustrative mitigation pathways (IMPs) assessed in this report use land-based biological CDR (primarily afforestation/reforestation (A/R)) and/or bioenergy with carbon capture and storage (BECCS). Some also include direct air CO_2 capture and storage (DACCS) (*high confidence*). Across the scenarios limiting warming to 2°C (>67%) or below, cumulative volumes[30] of BECCS reach 328 (168–763) $GtCO_2$, CO_2 removal from AFOLU (mainly A/R) reaches 252 (20–418) $GtCO_2$, and DACCS reaches 29 (0–339) $GtCO_2$, for the 2020–2100 period. Annual volumes in 2050 are 2.75 (0.52–9.45) $GtCO_2\ yr^{-1}$ for BECCS, 2.98 (0.23–6.38) $GtCO_2\ yr^{-1}$ for the CO_2 removal from AFOLU (mainly A/R), and 0.02 (0–1.74) $GtCO_2\ yr^{-1}$ for DACCS. (Box TS.10) {12.3, Cross-Chapter Box 8 in Chapter 12}

Despite limited current deployment, estimated mitigation potentials for DACCS, enhanced weathering (EW) and ocean-based CDR methods (including ocean alkalinity enhancement and ocean fertilisation) are moderate to large (*medium confidence*). The potential for DACCS (5–40 $GtCO_2\ yr^{-1}$) is limited mainly by requirements for low-carbon energy and by cost (100–300 (full range: 84–386) USD tCO_2^{-1}). DACCS is currently at a medium technology readiness level. EW has the potential to remove 2–4 (full range: <1 to around 100) $GtCO_2\ yr^{-1}$, at costs ranging from 50 to 200 (full range: 24–578) USD tCO_2^{-1}. Ocean-based methods have a combined potential to remove 1–100 $GtCO_2\ yr^{-1}$ at costs of USD40–500 tCO_2^{-1}, but their feasibility is uncertain due to possible side effects on the marine environment. EW and ocean-based methods are currently at a low technology readiness level. {12.3}

CDR governance and policymaking can draw on widespread experience with emissions reduction measures (*high confidence*). Additionally, to accelerate research, development, and demonstration, and to incentivise CDR deployment, a political commitment to formal integration into existing climate policy frameworks is required, including reliable measurement, reporting and verification (MRV) of carbon flows. {12.3.3, 12.4, 12.5}

Box TS.10 | Carbon Dioxide Removal (CDR)

Carbon Dioxide Removal (CDR) is necessary to achieve net zero CO_2 and GHG emissions both globally and nationally, counterbalancing 'hard-to-abate' residual emissions. CDR is also an essential element of scenarios that limit warming to 1.5°C or below 2°C (>67%) by 2100, regardless of whether global emissions reach near zero, net zero or net negative levels. While national mitigation portfolios aiming at net zero emissions or lower will need to include some level of CDR, the choice of methods and the scale and timing of their deployment will depend on the achievement of gross emission reductions, and managing multiple sustainability and feasibility constraints, including political preferences and social acceptability.

CDR refers to 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, geochemical or chemical CO_2 sinks, but excludes natural CO_2 uptake not directly caused by human activities (Annex I). Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) applied to fossil CO_2 do not count as removal technologies. CCS and CCU can only be part of CDR methods if the CO_2 is biogenic or directly captured from ambient air, and stored durably in geological reservoirs or products. {12.3}

There is a great variety of CDR methods and respective implementation options {Cross-Chapter Box 8, Figure 1 in Chapter 12}. Some of these methods (like afforestation and soil carbon sequestration) have been practiced for decades to millennia, although not necessarily with the intention to remove carbon from the atmosphere. Conversely, for methods such as DACCS and BECCS, experience is growing but still limited in scale. A categorisation of CDR methods can be based on several criteria, depending on the highlighted characteristics. In this report, the categorisation is focused on the role of CDR methods in the carbon cycle, that is on the removal process (*land-based biological*; *ocean-based biological*; *geochemical*; *chemical*) and on the time scale of storage (*decades to centuries*; *centuries to millennia*; *10,000 years or longer*), the latter being closely linked to different carbon storage media. Within one category (e.g., ocean-based biological CDR) options often differ with respect to other dynamic or context-specific dimensions such as mitigation potential, cost, potential for co-benefits and adverse side effects, and technology readiness level. (Table TS.7, TS.5.6, TS. 5.7) {12.3}

It is useful to distinguish between CO_2 removal from the atmosphere as the outcome of deliberate activities implementing CDR options, and the net emissions outcome achieved with the help of CDR deployment (i.e., gross emissions minus gross removals). As part of ambitious mitigation strategies at global or national levels, gross CDR can fulfil three different roles in complementing emissions abatement: (i) lowering net CO_2 or GHG emissions in the near term; (ii) counterbalancing 'hard-to-abate' residual emissions such as CO_2 from industrial activities and long-distance transport, or CH_4 and nitrous oxide from agriculture, in order to help reach net zero CO_2 or GHG emissions in the mid-term; (iii) achieving net negative CO_2 or GHG emissions in the long term if deployed at levels exceeding annual residual emissions {2.7, 3.3, 3.4, 3.5}. These roles of CDR are not mutually exclusive: for example, achieving net zero CO_2 or GHG emissions globally might involve individual developed countries attaining net negative CO_2 emissions at the time of global net zero, thereby allowing developing countries a smoother transition. {Cross-Chapter Box 8, Figure 2 in Chapter 12}

30 As a median value [5–95th percentile range].

Table TS.7 | Summary of status, costs, potentials, risk and impacts, co-benefits, trade-offs and spillover effects and the role in mitigation pathways for CDR methods {12.3.2, 7.4}. (TRL = technology readiness level.)

CDR method	Status (TRL)	Cost[1] (USD tCO_2^{-1})	Mitigation potential[1] ($GtCO_2\ yr^{-1}$)	Risk and impacts	Co-benefits	Trade-offs and spillover effects	Role in mitigation pathways	Section
Afforestation/ reforestation	8–9	0–240	0.5–10	Reversal of carbon removal through wildfire, disease, pests may occur. Reduced catchment water yield and lower groundwater level if species and biome are inappropriate.	Enhanced employment and local livelihoods, improved biodiversity, improved renewable wood products provision, soil carbon and nutrient cycling. Possibly less pressure on primary forest.	Inappropriate deployment at large scale can lead to competition for land with biodiversity conservation and food production.	Substantial contribution in IAMs and also in bottom-up sectoral studies.	{7.4}
Soil carbon sequestration in croplands and grasslands	8–9	–45–100	0.6–9.3	Risk of increased nitrous oxide emissions due to higher levels of organic nitrogen in the soil; risk of reversal of carbon sequestration.	Improved soil quality, resilience and agricultural productivity.	Attempts to increase carbon sequestration potential at the expense of production. Net addition per hectare is very small; hard to monitor.	In development – not yet in global mitigation pathways simulated by IAMs in bottom-up studies: with medium contribution.	{7.4}
Peatland and coastal wetland restoration	8–9	Insufficient data	0.5–2.1	Reversal of carbon removal in drought or future disturbance. Risk of increased CH_4 emissions.	Enhanced employment and local livelihoods, increased productivity of fisheries, improved biodiversity, soil carbon and nutrient cycling.	Competition for land for food production on some peatlands used for food production.	Not in IAMs but some bottom-up studies with medium contribution.	{7.4}
Agroforestry	8–9	Insufficient data	0.3–9.4	Risk that some land area lost from food production; requires very high skills.	Enhanced employment and local livelihoods, variety of products improved soil quality, more resilient systems.	Some trade-off with agricultural crop production, but enhanced biodiversity, and resilience of system.	No data from IAMs, but in bottom-up sectoral studies with medium contribution.	{7.4}
Improved forest management	8–9	Insufficient data	0.1–2.1	If improved management is understood as merely intensification involving increased fertiliser use and introduced species, then it could reduce biodiversity and increase eutrophication.	In case of sustainable forest management, it leads to enhanced employment and local livelihoods, enhanced biodiversity, improved productivity.	If it involves increased fertiliser use and introduced species it could reduce biodiversity and increase eutrophication and upstream GHG emissions.	No data from IAMs, but in bottom-up sectoral studies with medium contribution.	{7.4}
Biochar	6–7	10–345	0.3–6.6	Particulate and GHG emissions from production; biodiversity and carbon stock loss from unsustainable biomass harvest.	Increased crop yields and reduced non-CO_2 emissions from soil; and resilience to drought.	Environmental impacts associated particulate matter; competition for biomass resource.	In development – not yet in global mitigation pathways simulated by IAMs.	{7.4}
Direct air carbon capture and storage (DACCS)	6	100–300 (84–386)	5–40	Increased energy and water use.	Water produced (solid sorbent DAC designs only).	Potentially increased emissions from water supply and energy generation.	In a few IAMs; DACCS complements other CDR methods.	{12.3}
Bioenergy with carbon capture and storage (BECCS)	5–6	15–400	0.5–11	Inappropriate deployment at very large scale leads to additional land and water use to grow biomass feedstock. Biodiversity and carbon stock loss if from unsustainable biomass harvest.	Reduction of air pollutants, fuel security, optimal use of residues, additional income, health benefits, and if implemented well, it can enhance biodiversity.	Competition for land with biodiversity conservation and food production.	Substantial contribution in IAMs and bottom-up sectoral studies. Note – mitigation through avoided GHG emissions resulting from bioenergy use is of the same magnitude as the mitigation from CDR (TS.5.6).	{7.4}
Enhanced weathering (EW)	3–4	50–200 (24–578)	2–4 (<1–95)	Mining impacts; air quality impacts of rock dust when spreading on soil.	Enhanced plant growth, reduced erosion, enhanced soil carbon, reduced soil acidity, enhanced soil water retention.	Potentially increased emissions from water supply and energy generation.	In a few IAMs; EW complements other CDR methods.	{12.3}

Table TS.7 (continued):

CDR method	Status (TRL)	Cost[1] (USD tCO_2^{-1})	Mitigation potential[1] ($GtCO_2\ yr^{-1}$)	Risk and impacts	Co-benefits	Trade-offs and spillover effects	Role in mitigation pathways	Section
'Blue carbon management' in coastal wetlands	2–3	Insufficient data	<1	If degraded or lost, coastal blue carbon ecosystems are expected to release most of their carbon back to the atmosphere; potential for sediment contaminants, toxicity, bioaccumulation and biomagnification in organisms; issues related to altering degradability of coastal plants; use of sub-tidal areas for tidal wetland carbon removal; effect of shoreline modifications on sediment redeposition and natural marsh accretion; abusive use of coastal blue carbon as means to reclaim land for purposes that degrade capacity for carbon removal.	Provide many non-climatic benefits and can contribute to ecosystem-based adaptation, coastal protection, increased biodiversity, reduced upper ocean acidification; could potentially benefit human nutrition or produce fertiliser for terrestrial agriculture, anti-methanogenic feed additive, or as an industrial or materials feedstock.	If degraded or lost, coastal blue carbon ecosystems are likely to release most of their carbon back to the atmosphere. The full delivery of the benefits at their maximum global capacity will require years to decades to be achieved.	Not incorporated in IAMs, but in some bottom-up studies: small contribution.	{7.4, 12.3.1}
Ocean fertilisation	1–2	50–500	1–3	Nutrient redistribution, restructuring of the ecosystem, enhanced oxygen consumption and acidification in deeper waters, potential for decadal-to-millennial-scale return to the atmosphere of nearly all the extra carbon removed, risks of unintended side effects.	Increased productivity and fisheries, reduced upper-ocean acidification.	Sub-surface ocean acidification, deoxygenation; altered meridional supply of macro-nutrients as they are utilised in the iron-fertilised region and become unavailable for transport to, and utilisation in other regions, fundamental alteration of food webs, biodiversity.	No data.	{12.3.1}
Ocean alkalinity enhancement (OAE)	1–2	40–260	1–100	Increased seawater pH and saturation states and may impact marine biota. Possible release of nutritive or toxic elements and compounds. Mining impacts.	Limiting ocean acidification.	Potentially increased emissions of CO_2 and dust from mining, transport and deployment operations.	No data.	{12.3.1}

[1] Range based on authors' estimates (as assessed from literature) are shown, with full literature ranges shown in ( ) brackets.

TS.5.8 Demand-side Aspects of Mitigation

The assessment of the social science literature and regional case studies reveals how social norms, culture, and individual choices interact with infrastructure and other structural changes over time. This provides new insight into climate change mitigation strategies, and how economic and social activity might be organised across sectors to support emission reductions. To enhance well-being, people demand services and not primary energy and physical resources per se. Focusing on demand for services and the different social and political roles people play broadens the participation in climate action. (Box TS.11)

Demand-side mitigation and new ways of providing services can help *Avoid* and *Shift* final service demands and *Improve* service delivery. Rapid and deep changes in demand make it easier for every sector to reduce GHG emissions in the near and mid-term (*high confidence*). {5.2, 5.3}

The indicative potential of demand-side strategies to reduce emissions of direct and indirect CO_2 and non-CO_2 GHG emissions in three end-use sectors (buildings, land transport, and food) is 40–70% globally by 2050 (*high confidence*). Technical mitigation potentials compared to the 2050 emissions projection of two scenarios consistent with policies announced by national governments until 2020 amount to 6.8 $GtCO_2$ for building use and construction, 4.6 $GtCO_2$ for land transport and 8.0 $GtCO_2$-eq for food demand, and amount to 4.4 $GtCO_2$ for industry. Mitigation strategies can be classified as *Avoid-Shift-Improve* (ASI) options, that reflect opportunities for socio-cultural, infrastructural, and technological change. The greatest *Avoid* potential comes from reducing long-haul aviation and providing short-distance low-carbon urban infrastructures. The greatest *Shift* potential would come from switching to plant-based diets. The greatest *Improve* potential comes from within the building sector, and in particular increased use of energy-efficient end-use technologies and passive housing. (Figures TS.20 and TS.21) {5.3.1, 5.3.2, Figures 5.7 and 5.8, Table 5.1 and Table SM.5.2}

Socio-cultural and lifestyle changes can accelerate climate change mitigation (*medium confidence*). Among 60 identified actions that could change individual consumption, individual mobility choices have the largest potential to reduce carbon footprints. Prioritising car-free mobility by walking and cycling and adoption of electric mobility could save 2 tCO_2-eq cap^{-1} yr^{-1}. Other options with high mitigation potential include reducing air travel, cooling setpoint adjustments, reduced appliance use, shifts to public transit, and shifting consumption towards plant-based diets. {5.3.1, 5.3.1.2, Figure 5.8}

Box TS.11 | A New Chapter in AR6 WGIII Focusing on the Social Science of Demand, and Social Aspects of Mitigation

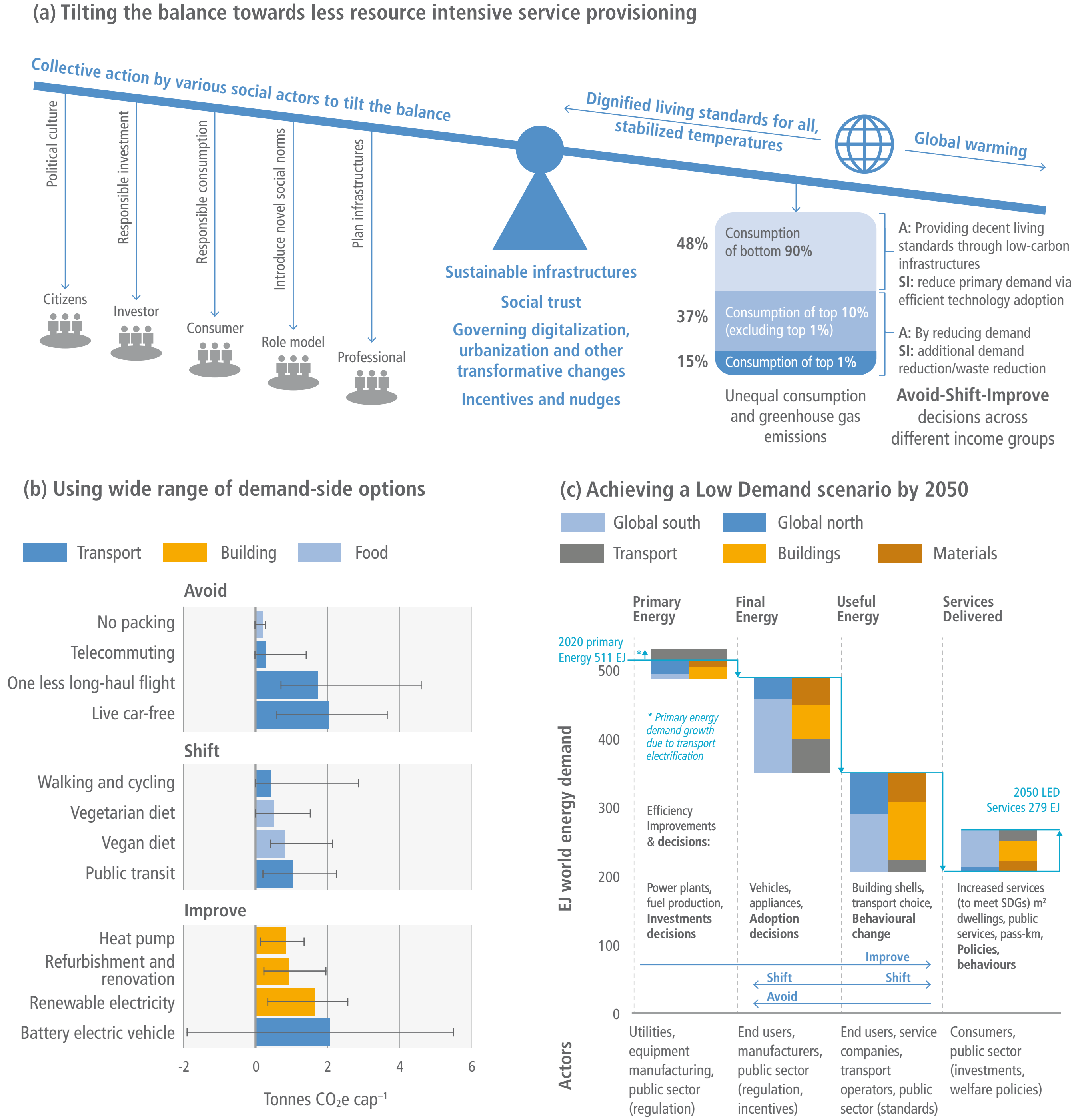
The WGIII contribution to the Sixth Assessment Report of the IPCC (AR6) features a distinct chapter on demand, services and social aspects of mitigation {5}. The scope, theories, and evidence for such an assessment are addressed in Sections 5.1 and 5.4 within Chapter 5 and a Social Science Primer as an Appendix to Chapter 5.

The literature on social science – from sociology, psychology, gender studies and political science for example – and climate change mitigation is growing rapidly. A bibliometric search of the literature identified 99,065 peer-reviewed academic papers, based on 34 search queries with content relevant to Chapter 5. This literature is expanding by 15% per year, with twice as many publications in the AR6 period (2014–2020) as in all previous years.

The models of stakeholders' decisions assessed by IPCC have continuously evolved. From AR1 to AR4, rational choice was the implicit assumption: agents with perfect information and unlimited processing capacity maximising self-focused expected utility and differing only in wealth, risk attitude, and time discount rate. The AR5 introduced a broader range of goals (material, social, and psychological) and decision processes (calculation-based, affect-based, and rule-based processes). However, its perspective was still individual- and agency-focused, neglecting structural, cultural, and institutional constraints and the influence of physical and social context.

A social science perspective is important in two ways. By adding new actors and perspectives, it (i) provides more options for climate mitigation; and (ii) helps to identify and address important social and cultural barriers and opportunities to socio-economic, technological, and institutional change. Demand-side mitigation involves five sets of social actors: individuals (e.g., consumption choices, habits), groups and collectives (e.g., social movements, values), corporate actors (e.g., investments, advertising), institutions (e.g., political agency, regulations), and infrastructure actors (e.g., very long-term investments and financing). Actors either contribute to the status-quo of global high-carbon consumption, and a GDP growth-oriented economy, or help generate the desired change to a low-carbon energy-services, well-being, and equity-oriented economy. Each set of actors has novel implications for the design and implementation of both demand- and supply-side mitigation policies. They show important synergies, making energy demand mitigation a dynamic problem where the packaging and/or sequencing of different policies play a role in their effectiveness {5.5, 5.6}. Incremental interventions change social practices, simultaneously affecting emissions and well-being. The transformative change requires coordinated action across all five sets of actors (Table 5.4), using social science insights about intersection of behaviour, culture, institutional and infrastructural changes for policy design and implementation. *Avoid*, *Shift*, and *Improve* choices by individuals, households and communities support mitigation {5.3.1.1, Table 5.1}. They are instigated by role models, changing social norms driven by policies and social movements. They also require appropriate infrastructures designed by urban planners and building and transport professionals, corresponding investments, and a political culture supportive of demand-side mitigation action.

Demand side mitigation is about more than behavioural change. Reconfiguring the way services are provided while simultaneously changing social norms and preferences will help reduce emissions and access. Transformation happens through societal, technological and institutional changes.

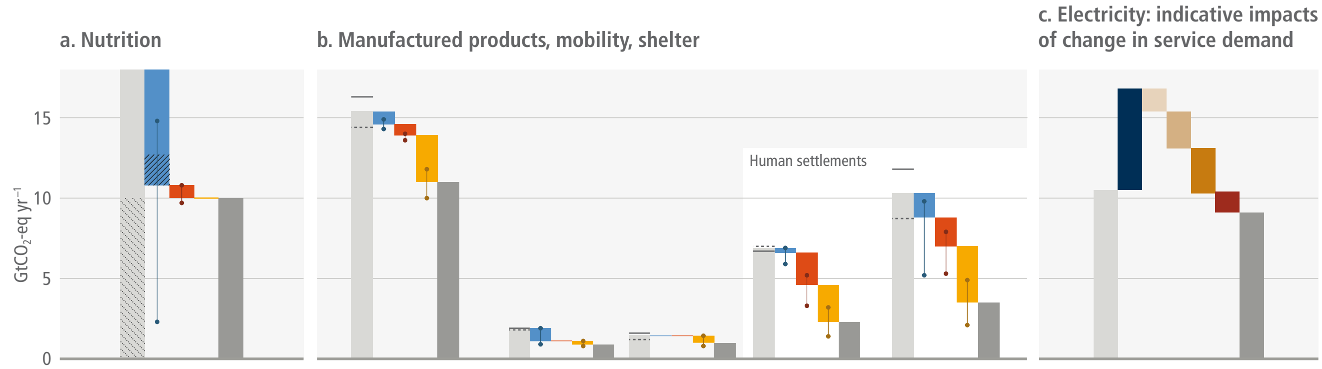


Low-carbon lifestyle transition can be classified into Avoid, Shift, and Improve options. Individual potential to reduce emissions is highest in mobility systems.

Improved service provisioning systems enable increases in service levels and at the same time a reduction in upstream energy demand by 45%.

Figure TS.20 | Demand-side strategies for mitigation. Demand-side mitigation is about more than behavioural change and transformation happens through societal, technological and institutional changes. {Figure 5.10, Figure 5.14}

Demand-side mitigation can be achieved through changes in socio-cultural factors, infrastructure design and use, and end-use technology adoption by 2050.



End-use sectors	Food	Industry	Aviation	Shipping	Land transport	Buildings	Electricity
Services for well-being	Nutrition	Manufactured products	Mobility			Shelter	
	Socio-cultural factors	Socio-cultural factors					Additional electrification (+60%)
	Dietary shift (shifting to balanced, sustainable healthy diets), avoidance of food waste and over-consumption	Shift in demand towards sustainable consumption, such as intensive use of longer-lived repairable products	Avoid long-haul flights; shift to trains wherever possible	Currently not applicable	Teleworking or telecommuting; active mobility through walking and cycling	Social practices resulting in energy saving; lifestyle and behavioural changes	Additional emissions from increased electricity generation to enable the end-use sectors' substitution of electricity for fossil fuels, e.g. via heat pumps and electric cars {Table SM5.3; 6.6}
	Infrastructure use	Infrastructure use					
	Choice architecture[1] and information to guide dietary choices; financial incentives; waste management; recycling infrastructure	Networks established for recycling, repurposing, remanufacturing and reuse of metals, plastics and glass; labelling low-emissions materials and products	Currently not applicable	Currently not applicable	Public transport; shared mobility; compact cities; spatial planning	Compact cities; rationalisation of living floor space; architectural design; urban planning (e.g., green roof, cool roof, urban green spaces etc.)	Industry; Land transport; Buildings; Load management[2] – Demand-side measures −73%
	End-use technology adoption	End-use technology adoption					
	Currently estimates are not available (for lab-based meat and similar options – no quantitative literature available, overall potential considered in socio-cultural factors)	Green procurement to access material-efficient products and services; access to energy-efficient and CO_2 neutral materials	Adoption of energy-efficient technologies; technologies with improved aerodynamics	Adoption of energy-efficient technology/ systems	Electric vehicles; shift to more efficient vehicles	Energy-efficient building envelopes and appliances; shift to renewables	Reduced emissions through demand-side mitigation options (in end-use sectors: buildings, industry and land transport) which has potential to reduce electricity demand[3]

Total emissions 2050: Mean ---- IEA-STEPS — IP_ModAct

AFOLU
Direct reduction of food related emissions, excluding reforestation of freed up land

Total emissions 2050
Socio-cultural factors
Infrastructure use
End-use technology adoption

Emissions that cannot be avoided or reduced through demand-side options are assumed to be addressed by supply-side options

Add. electrification
Industry
Land transport
Buildings
Load management

[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 TS.21 | Demand-side mitigation can be achieved through changes in socio-cultural factors, infrastructure design and use, and technology adoption. Mitigation response options related to demand for services have been categorised into three domains: 'socio-cultural factors', related to social norms, culture, and individual choices and behaviour; 'infrastructure use', related to the provision and use of supporting infrastructure that enables individual choices and behaviour; and 'technology adoption', which refers to the uptake of technologies by end users. Potentials in 2050 are estimated using the International Energy Agency's 2020 World Energy Outlook STEPS (Stated Policy Scenarios) as a baseline. This scenario is based on a sector-by-sector assessment of specific policies in place, as well as those that have been announced by countries by mid-2020. This scenario was selected due to the detailed representation of options across sectors and sub-sectors. The heights of the coloured columns represent the potentials on which there is a high level of agreement in the literature, based on a range of case studies. The range shown by the dots connected by dotted lines represents the highest and lowest potentials reported in the literature which have low to medium levels of agreement. The demand-side potential of socio-cultural factors in the food system has two parts. The economic potential of direct emissions (mostly non-CO_2) demand reduction through socio-cultural factors alone is 1.9 $GtCO_2$-eq without considering land-use change by diversion of agricultural land from food production to carbon sequestration. If further changes in land use enabled by this change in demand are considered, the indicative potential could reach 7 $GtCO_2$-eq. The electricity panel presents separately the mitigation potential from changes in electricity demand and changes associated with enhanced electrification in end-use sectors. Electrification increases electricity demand, while it is avoided though demand-side mitigation strategies. Load management refers to demand-side flexibility that can be achieved through incentive design such as time-of-use pricing/monitoring by artificial intelligence, diversification of storage facilities, and so on. NZE (IEA Net-Zero Emissions by 2050 scenario) is used to compute the impact of end-use sector electrification, while the impact of demand-side response options is based on bottom-up assessments. Dark grey columns show the emissions that cannot be avoided through demand-side mitigation options. The table indicates which demand-side mitigation options are included. Options are categorised according to: socio-cultural factors, infrastructure use, and technology adoption. Figure SPM.7 covers potential of demand-side options for the year 2050. Figure SPM.8 covers both supply- and demand-side options and their potentials for the year 2030. {5.3, Figure 5.7, 5.SM.II}

Leveraging improvements in end-use service delivery through behavioural and technological innovations, and innovations in market organisation, leads to large reductions in upstream resource use (*high confidence*). Analysis of indicative potentials range from a factor 10- to 20-fold improvement in the case of available energy (exergy) analysis, with the highest improvement potentials at the end-user and service-provisioning levels. Realisable service level efficiency improvements could reduce upstream energy demand by 45% in 2050. (Figure TS.20) {5.3.2, Figure 5.10}

***Decent living standards* (DLS) and *well-being for all* (SDG 3) are achievable if high-efficiency low-demand mitigation pathways are followed (*medium confidence*).** Minimum requirements of energy use consistent with enabling *well-being for all* is between 20 and 50 GJ cap^{-1} yr^{-1} depending on the context. (Figure TS.22) {5.2.2.1, 5.2.2.2, Box 5.3}

Alternative service provision systems, for example, those enabled through digitalisation, sharing economy initiatives and circular economy initiatives, have to date made a limited contribution to climate change mitigation (*medium confidence*). While digitalisation through specific new products and applications holds potential for improvement in service-level efficiencies, without public policies and regulations, it also has the potential to increase consumption and energy use. Reducing the energy use of data centres, networks, and connected devices is possible in managing low-carbon digitalisation. Claims on the benefits of the circular economy for sustainability and climate change mitigation have limited evidence. (Box TS.12, Box TS.14) {5.3.4, Figures 5.12 and 5.13}

Box TS.12 | Circular Economy (CE)

In AR6, the circular economy (CE) concept {Annex I} is highlighted as an increasingly important mitigation approach that can help deliver human well-being by minimising waste of energy and resources. While definitions of CE vary, its essence is to shift away from linear 'make and dispose' economic models to those that emphasise product longevity, reuse, refurbishment, recycling, and material efficiency, thereby enabling more circular material systems that reduce embodied energy and emissions. {5.3.4, 8.4, 8.5, 9.5, 11.3.3}

Whereas IPCC AR4 {WGIII, Chapter 10} included a separate chapter on waste-sector emissions and waste-management practices, and AR5 {WGIII, Chapter 10} reviewed the importance of 'reduce, reuse, recycle' and related policies, AR6 focuses on how CE can reduce waste in materials production and consumption by optimising materials' end-use service utility. Specific examples of CE implementations, policies, and mitigation potentials are included in Chapters 5, 8, 9, 11 and 12. {5.3, 8.4, 9.5, 11.3, 12.6}

CE is shown to empower new social actors in mitigation actions, given that it relies on the synergistic actions of producers, sellers, and consumers {11.3.3}. As an energy and resource demand-reduction strategy, it is consistent with high levels of human well-being {5.3.4.3} and ensures better environmental quality (Figure TS.22) {5.2.1}. It also creates jobs through increased sharing, reuse, refurbishment, and recycling activities. Therefore, CE contributes to several SDGs, including clean water and sanitation (SDG 6), affordable energy and clean energy (SDG 7), decent work and economic growth (SDG 8), responsible production and consumption (SDG 12) and climate action (SDG 13). {11.5.3.2}

Emissions savings derive from reduced primary material production and transport. For example, in buildings, lifetime extension, material efficiency, and reusable components reduce embodied emissions by avoiding demand for structural materials {9.3, 9.5}. At regional scales, urban/industrial symbiosis reduce primary material demand through by-product exchange networks {11.3.3}. CE strategies also exhibit enabling effects, such as material-efficient and circular vehicle designs that also improve fuel economy {10.2.2.2}. There is growing interest in 'circular bioeconomy' concepts applied to bio-based materials {Box 12.2} and even a 'circular carbon economy', wherein carbon captured via CCU {11.3.6} or CDR {3.4.6} is converted into reusable materials, which is especially relevant for the transitions of economies dependent on fossil fuel revenue. {12.6}

While there are many recycling policies, CE-oriented policies for more efficient material use with higher value retention are comparatively far fewer; these policy gaps have been attributed to institutional failures, lack of coordination, and lack of strong advocates {5.3, 9.5.3.6, Boxes 11.5 and 12.2}. Reviews of mitigation potentials reveal unevenness in the savings of CE applications and potential risks of rebound effects {5.3}. Therefore, CE policies that identify system determinants maximise potential emissions reductions, which vary by material, location, and application.

There are knowledge gaps for assessing CE opportunities within mitigation models due to CE's many cross-sectoral linkages and data gaps related to its nascent state {3.4.4}. Opportunity exists to bridge knowledge from the industrial ecology field, which has historically studied CE, to the mitigation modelling community for improved analysis of interventions and policies for AR7. For instance, a global CE knowledge-sharing platform is helpful for CE performance measurement, reporting and accounting. {5.3, 9.5, 11.7}

Providing better services with less energy and resource input has high technical potential and is consistent with providing well-being for all (*medium confidence*). The assessment of 19 demand-side mitigation options and 18 different constituents of well-being showed that positive impacts on well-being outweigh negative ones by a factor of 11. {5.2, 5.2.3, Figure 5.6}

Demand-side mitigation options bring multiple interacting benefits (*high confidence*). Energy services to meet human needs for nutrition, shelter, health, and so on, are met in many different ways with different emissions implications that depend on local contexts, cultures, geography, available technologies, and social preferences. In the near term, many less-developed countries, and poor people everywhere, require better access to safe and low-emissions energy sources to ensure decent living standards and increase energy savings from service improvements by about 20–25%. (Figure TS.22) {5.2, 5.4.5, Figures 5.3, 5.4, 5.5 and 5.6, Boxes 5.2 and 5.3}

Granular technologies and decentralised energy end-use, characterised by modularity, small unit sizes and small unit costs, diffuse faster into markets and are associated with faster technological learning benefits, greater efficiency, more opportunities to escape technological lock-in, and greater employment (*high confidence*). Examples include solar PV systems, batteries, and thermal heat pumps. {5.3, 5.5, 5.5.3}

Wealthy individuals contribute disproportionately to higher emissions and have a high potential for emissions reductions while maintaining decent living standards and well-being (*high confidence*). Individuals with high socio-economic status are capable of reducing their GHG emissions by becoming role models of low-carbon lifestyles, investing in low-carbon businesses, and advocating for stringent climate policies. {5.4.1, 5.4.3, 5.4.4, Figure 5.14}

Demand-side solutions require both motivation and capacity for change (*high confidence*). Motivation by individuals or households worldwide to change energy consumption behaviour is generally low. Individual behavioural change is insufficient for climate change mitigation unless embedded in structural and cultural change. Different factors influence individual motivation and capacity for change in different demographics and geographies. These factors go beyond traditional socio-demographic and economic predictors and include psychological variables such as awareness, perceived risk, subjective and social norms, values, and perceived behavioural control. Behavioural nudges promote easy behaviour change, for example, '*Improve*' actions such as making investments in energy efficiency, but fail to motivate harder lifestyle changes (*high confidence*). {5.4}

Behavioural interventions, including the way choices are presented to end users (an intervention practice known as choice architecture), work synergistically with price signals, making the combination more effective (*medium confidence*). Behavioural interventions through nudges, and alternative ways of redesigning and motivating decisions, alone provide small to medium contributions to reduce energy consumption and GHG emissions. Green defaults, such as automatic enrolment in 'green energy' provision, are highly effective. Judicious labelling, framing, and communication of social norms can also increase the effect of mandates, subsidies, or taxes. {5.4, 5.4.1, Table 5.3, 5.3}

Cultural change, in combination with new or adapted infrastructure, is necessary to enable and realise many *Avoid* and *Shift* options (*medium confidence*). By drawing support from diverse actors, narratives of change can enable coalitions to form, providing the basis for social movements to campaign in favour of (or against) societal transformations. People act and contribute to climate change mitigation in their diverse capacities as consumers, citizens, professionals, role models, investors, and policymakers. {5.4, 5.5, 5.6}

Collective action as part of social or lifestyle movements underpins system change (*high confidence*). Collective action and social organising are crucial to shift the possibility space of public policy on climate change mitigation. For example, climate strikes have given voice to youth in more than 180 countries. In other instances, mitigation policies allow the active participation of all stakeholders, resulting in building social trust, new coalitions, legitimising change, and thus initiate a positive cycle in climate governance capacity and policies. {5.4.2, Figure 5.14}

Transition pathways and changes in social norms often start with pilot experiments led by dedicated individuals and niche groups (*high confidence*). Collectively, such initiatives can find entry points to prompt policy, infrastructure, and policy reconfigurations, supporting the further uptake of technological and lifestyle innovations. Individuals' agency is central as social change agents and narrators of meaning. These bottom-up socio-cultural forces catalyse a supportive policy environment, which enables changes. {5.5.2}

The current effects of climate change, as well as some mitigation strategies, are threatening the viability of existing business practices, while some corporate efforts also delay mitigation action (*medium confidence*). Policy packages that include job creation programmes can help to preserve social trust, livelihoods, respect, and dignity of all workers and employees involved. Business models that protect rent-extracting behaviour may sometimes delay political action. Corporate advertisement and brand-building strategies may also attempt to deflect corporate responsibility to individuals or aim to appropriate climate-care sentiments in their own brand–building. {5.4.3, 5.6.4}

Middle actors – professionals, experts, and regulators – play a crucial, albeit underestimated and underutilised, role in establishing low-carbon standards and practices (*medium confidence*). Building managers, landlords, energy-efficiency advisers, technology installers, and car dealers influence patterns of mobility and energy consumption by acting as middle actors or intermediaries in the provision of building or mobility services and need greater capacity and motivation to play this role. (Figure TS.20a) {5.4.3}

Figure TS.22 | Demand-side mitigation options, well-being and SDGs. {Figure 5.6}

SDGs	2	6	7,11	3	6	7	11	11	4		1,2,8,10	5,10,16	5,16	10,16	11,16	8	9,12
Mitigation strategies/ Well-being dimensions	Food	Water	Air	Health	Sanitation	Energy	Shelter	Mobility	Education	Communication	Social protection	Participation	Personal Security	Social cohesion	Political stability	Economic stability	Material provision
Sufficiency (adequate floor space, etc.)	[+1] •••	[+2] ••••	[+2] •••••	[+3] •••••	[+1] •	[+3] ••••	[+1] •	[+1] ••	[+1] ••	[+2] •••	[+1] ••	[+1] ••		[+2] •••••		[+2] ••••	[+2] ••••
Efficiency	[+2] •	[+2] ••••	[+3/–1] ••••	[+3/–1] •••••	[+1] •	[+3] ••••	[+2] ••••		[+1] •••	[+1] •••		[+1] ••••	[+1] •••	[+2/–1] ••••		[+2] •••••	[+2/–1] ••••
Lower carbon and renewable energy	[+2/–1] •••	[+2/–1] ••••	[+3] •••••	[+3] •••••		[+3] ••••	[+1] •••	[+1] •••	[+1] •••	[+2] •••		[+1] •••	[+1] •••	[+2/–1] ••••		[+2/–1] •••••	[+2] ••••
Food waste	[+1] •••	[+2] ••••	[+2] ••••	[+2] •••	[+1] ••	[+1] ••••				[+1] ••	[–1/+1] •••	[+1] •••			[+1] •	[+1] ••	
Over-consumption	[+1] •	[+1/–1] •	[+1/–1] •	[+3] ••••		[+1/–1] •						[+2] ••••			[+1] •		
Plant based diets	[+2] •••	[+2] ••••	[+3] •••••	[+3] •••						[–1] •••	[+3] •••••	[+1] ••••		[–1] •	[+2] •		
Teleworking and online education system	[+1] ••		[+3] ••••	[+2] ••••		[+2] ••••	[+1] ••	[+2] ••••	[–1] •••	[+2] ••••	[+1] ••••	[+2] ••••	[+1/–1] ••••	[+2] ••••	[+2] •••	[+2] •••	
Non-motorised transport	[+2] ••	[+1] ••	[+1] •••••	[+3] •••••		[+2] ••••		[+3] •••••	[+1] ••••	[+3] •••	[+1] •••	[+1] ••	[+2] ••••	[+2] •••	[+2] ••	[+2] •••	
Shared mobility	[+1] ••		[+3] •••	[+2] ••••		[+1] •••		[+2] ••••		[+1] •••	[+2] •••	[+1] •••	[+1/–1] •••	[+1/–1] ••••	[–1] ••••	[+2] ••••	[+2] ••••
Electric vehicles (EVs)	[+1] •••		[+2] ••••	[+1] ••••	[+1] ••••	[+3] ••••		[+2] ••••			[+3] •••••	[+2] •••				[+2] ••••	[–1] ••
Compact city	[+2/–1] •••	[+1] ••	[+2/–1] •••	[+3/–1] ••••	[+1] ••	[+3/–1] •••••	[–1] •••••	[+3] •••••	[+1] •••••	[+1/–1] •••	[+2] ••	[+1] ••	[+1] ••••	[+1/–1] •••••		[+1] ••••	[+1] ••
Circular and shared economy	[+2] ••••	[+1] •••	[+2] •••	[+2] •••		[+3] •••	[+2/–1] •••	[+3] •••••	[+1] ••••	[+1] ••••	[+1] •••	[+1] •••	[+2] ••••	[+1] ••	[+1] ••	[+2] ••	[+3] •••
Systems approach in urban policy and practice	[+1] •••	[+2] •••	[+2] •••	[+3] •••	[+1] •••	[+3] •••	[+2] •••	[+3] •••		[+1] ••	[–1] ••	[+1] •••	[+2] •	[+1] ••		[+1] ••	[+3] •••••
Nature-Based Solutions	[+2] •••	[+1/–1] •••••	[+3/–1] ••••	[+3] •••••	[+1] •••	[+3] •••	[+1/–1] •••	[+1] •••	[+2] ••••		[+2] ••	[+3] ••	[+1] •••	[+2/–2] •••		[+3] ••••	[+1] ••
Using less material by design	[+2] ••	[+2] •••	[+3] •••	[+2] ••	[+2] •••	[+3] ••••	[+2] ••••	[+2] ••••	[+1] ••	[+2] •••	[+1] ••	[+1] •••	[+1] ••	[+1] ••	[+1] ••	[+2] •••	[+3] ••
Product life extension	[+2] ••	[+2] •••	[+3] •••	[+2] ••	[+2] •••	[+3] ••••	[+2] ••••	[+2] ••••	[+1] ••	[+2] •••	[+1] ••	[–1] ••••	[+1] ••	[+1] ••	[+1] ••	[+2] •••	[+3] ••
Energy efficiency	[+2] ••	[+2] •••	[+3] •••	[+1] ••	[+2] •••	[+3] ••••	[+2] ••••	[+2] ••••	[+1] ••	[+2] •••	[+2] ••••	[+2] •••	[+1] ••		[+1] ••	[+2] •••	[+2] ••
Circular economy	[+2] •••	[+2] •••	[+3] •••	[+1] ••	[+2] •••	[+3] ••••	[+2] ••••	[+2] ••••	[+1] ••	[+2] •••	[+1] ••	[+1] •••	[+2] ••	[+1] ••		[+2] •••	[+3] ••

- High positive impact [+3]
- Medium positive impact [+2]
- Low positive impact [+1]
- Overall neutral
- No impact
- Low negative impact [–1]
- Medium negative impact [–2]
- ● Confidence level

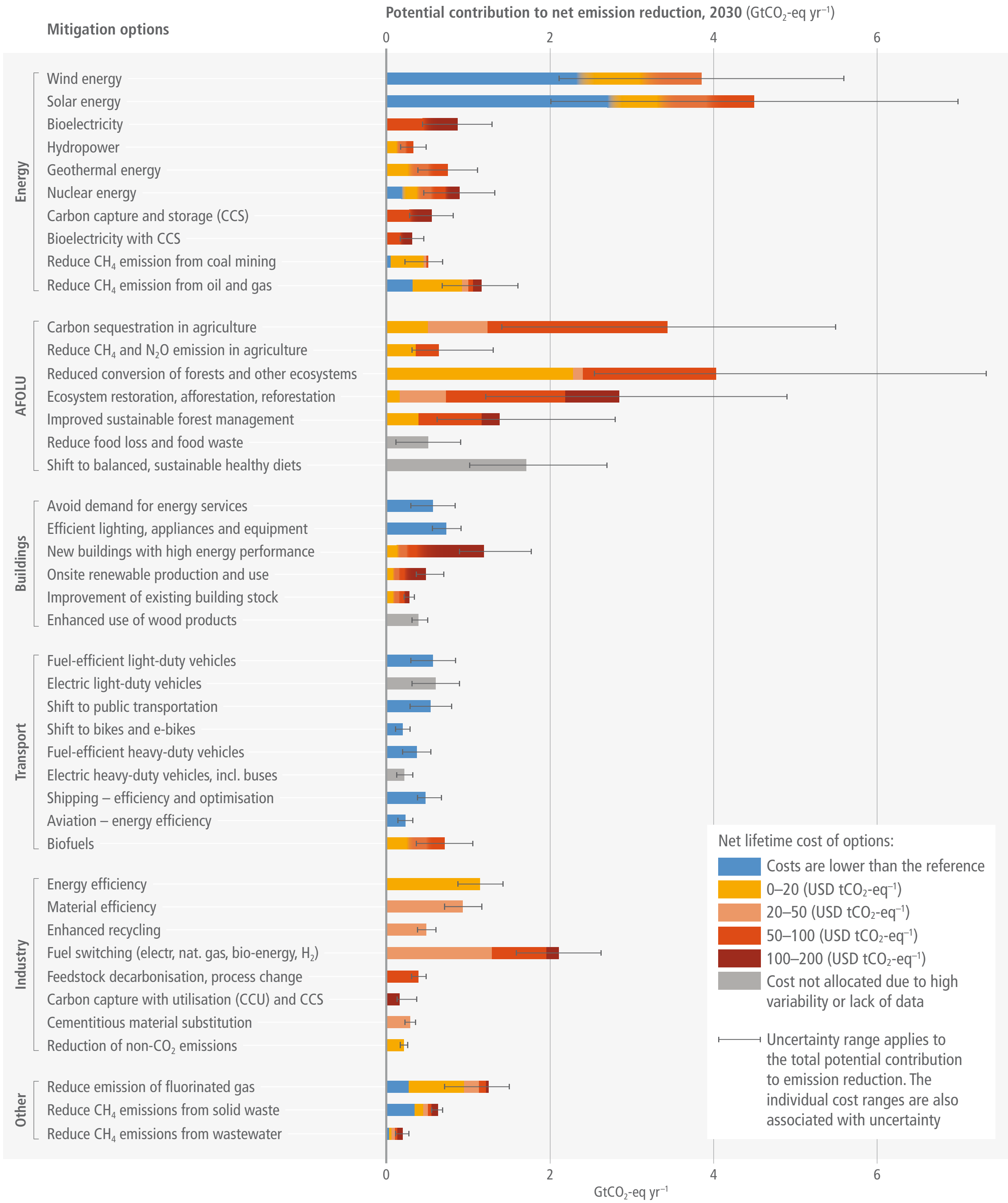


Figure TS.23 | Overview of emission mitigation options and their cost and potential for the year 2030. The mitigation potential of each option is the quantity of net greenhouse gas emission reductions that can be achieved by a given mitigation option relative to specified emission baselines that reflects what would be considered current policies in the period 2015–2019. Mitigation options may overlap or interact and cannot simply be summed together. The potential for each option is broken down into cost categories (see legend). Only monetary costs and revenues are considered. If costs are less than zero, lifetime monetary revenues are higher than lifetime monetary costs. For wind energy, for example, negative cost indicates that the cost is lower than that of fossil-based electricity production. The error bars refer to the total potential for each option. The breakdown into cost categories is subject to uncertainty. Where a smooth colour transition is shown, the breakdown of the potential into cost categories is not well researched, and the colours indicate only into which cost category the potential can predominantly be found in the literature. {Figure SPM.8, 6.4, Table 7.3, Supplementary Material Table 9.SM.2, Supplementary Material Table 9.SM.3, 10.6, 11.4, Figure 11.13, 12.2, Supplementary Material 12.SM.1.2.3}

Social influencers and thought leaders can increase the adoption of low-carbon technologies, behaviours, and lifestyles (*high confidence*). Preferences are malleable and can align with a cultural shift. The modelling of such shifts by salient and respected community members can help bring about changes in different service provisioning systems. Between 10% and 30% of committed individuals are required to set new social norms. {5.2.1, 5.4}

TS.5.9 Mitigation Potential Across Sectors and Systems

The total emission mitigation potential achievable by the year 2030, calculated based on sectoral assessments, is sufficient to reduce global greenhouse gas (GHG) emissions to half of the current (2019) level or less (*high confidence*). This potential – 31–44 $GtCO_2$-eq – requires the implementation of a wide range of mitigation options. Options with mitigation costs lower than USD20 tCO_2^{-1} make up more than half of this potential and are available for all sectors. The market benefits of some options exceed their costs. (Figure TS.23) {12.2, Table 12.3}

Cross-sectoral considerations in mitigation finance are critical for the effectiveness of mitigation action as well as for balancing the often conflicting social, developmental, and environmental policy goals at the sectoral level (*medium confidence*). True resource mobilisation plans that properly address mitigation costs and benefits at sectoral level cannot be developed in isolation of their cross-sectoral implications. There is an urgent need for multilateral financing institutions to align their frameworks and delivery mechanisms, including the use of blended financing to facilitate cross-sectoral solutions as opposed to causing competition for resources among sectors. {12.6.4}

Carbon leakage is a cross-sectoral and cross-country consequence of differentiated climate policy (*robust evidence, medium agreement*). Carbon leakage occurs when mitigation measures implemented in one country/sector leads to increased emissions in other countries/sectors. Global commodity value chains and associated international transport are important mechanisms through which carbon leakage occurs. Reducing emissions from the value chain and transportation can offer opportunities to mitigate three elements of cross-sectoral spillovers and related leakage: (i) domestic cross-sectoral spillovers within the same country; (ii) international spillovers within a single sector resulting from substitution of domestic production of carbon-intensive goods with their imports from abroad; and (iii) international cross-sectoral spillovers among sectors in different countries. {12.6.3}

TS.6 Implementation and Enabling Conditions

Chapters 13 to 16 address the enabling conditions that can accelerate or impede rapid progress on mitigation. Chapters 13 and 14 focus on policy, governance and institutional capacity, and international cooperation, respectively taking a national and international perspective; Chapter 15 focuses on investment and finance; and Chapter 16 focuses on innovation and technology. The assessment of social aspects of mitigation draws on material assessed in Chapter 5.

TS.6.1 Policy and Institutions

Long-term deep emission reductions, including the reduction of emissions to net zero, is best achieved through institutions and governance that nurture new mitigation policies, while at the same time reconsidering existing policies that support the continued emission of GHGs (*high confidence*). To do so effectively, the scope of climate governance needs to include both direct efforts to target GHG emissions and indirect opportunities to tackle GHG emissions that result from efforts directed towards other policy objectives. {13.2, 13.5, 13.6, 13.7, 13.9}

Institutions and governance underpin mitigation by providing the legal basis for action. This includes setting up implementing organisations and the frameworks through which diverse actors interact (*medium evidence, high agreement*). Institutions can create mitigation and sectoral policy instruments; policy packages for low-carbon system transition; and economy-wide measures for systemic restructuring. {13.2, 13.7, 13.9}

Policies have had a discernible impact on mitigation for specific countries, sectors, and technologies (*high confidence*), avoiding emissions of several $GtCO_2$-eq yr^{-1} (*medium confidence*). Both market-based and regulatory policies have distinct but complementary roles. The share of global GHG emissions subject to mitigation policy has increased rapidly in recent years, but big gaps remain in policy coverage, and the stringency of many policies falls short of what is needed to achieve the desired mitigation outcomes. (Box TS.13) {13.6, Cross-Chapter Box 10 in Chapter 14}

Climate laws enable mitigation action by signalling the direction of travel, setting targets, mainstreaming mitigation into sector policies, enhancing regulatory certainty, creating law-backed agencies, creating focal points for social mobilisation, and attracting international finance (*medium evidence, high agreement*). By 2020, 'direct' climate laws primarily focused on GHG reductions were present in 56 countries covering 53% of global emissions (Figure TS.24). More than 690 laws, including 'indirect' laws, however, may also have an effect on mitigation. Among direct laws, 'framework' laws set an overarching legal basis for mitigation either by pursuing a target and implementation approach, or by seeking to mainstream climate objectives through sectoral plans and integrative institutions. (Figure TS.24) {13.2}

Institutions can enable improved governance by coordinating across sectors, scales and actors, building consensus for action, and setting strategies (*medium evidence, high agreement*). Institutions are more stable and effective when they are congruent with national contexts, leading to mitigation-focused institutions in some countries and the pursuit of multiple objectives in others. Sub-national institutions play a complementary role to national institutions by developing locally relevant visions and plans, addressing policy gaps or limits in national institutions, building local administrative structures and convening actors for place-based decarbonisation. {13.2}

Mitigation strategies, instruments and policies that fit with dominant ideas, values and belief systems within a country or within a sector are more easily adopted and implemented (*medium confidence*). Ideas, values and beliefs may change over time. Policies that bring perceived direct benefits, such as subsidies, usually receive greater support. The awareness of co-benefits for the public increases support of climate policies (*high confidence*). {13.2, 13.3, 13.4}

Climate governance is constrained and enabled by domestic structural factors, but it is still possible for actors to make substantial changes (*medium evidence, high agreement*). Key structural factors are domestic material endowments (such as fossil fuels and land-based resources); domestic political systems; and prevalent ideas, values and belief systems. Developing Countries face additional material constraints in climate governance due to development challenges and scarce economic or natural resources. A broad group of actors influence how climate governance develop over time, including a range of civic organisations, encompassing both pro- and anti-climate action groups. {13.3, 13.4}

Sub-national actors are important for mitigation because municipalities and regional governments have jurisdiction over climate-relevant sectors such as land use, waste and urban policy. They are able to experiment with climate solutions and can forge partnerships with the private sector and internationally to leverage enhanced climate action (*high confidence*). More than 10,500 cities and nearly 250 regions representing more than 2 billion people have pledged largely voluntary action to reduce emissions. Indirect gains include innovation, establishing norms and developing capacity. However, sub-national actors often lack national support, funding, and capacity to mobilise finance and human resources, and create new institutional competences. {13.5}

Climate litigation is growing and can affect the outcome and ambition of climate governance (*medium evidence, high agreement*). Since 2015, at least 37 systemic cases have been initiated against states that challenge the overall effort of a state to mitigate or adapt to climate change. If successful, such cases can lead to an increase in a country's overall ambition to tackle climate change. Climate litigation has also successfully challenged governments' authorisations of high-emitting projects, setting precedents in favour of climate action. Climate litigation against private sector and financial institutions is also on the rise. {13.4}

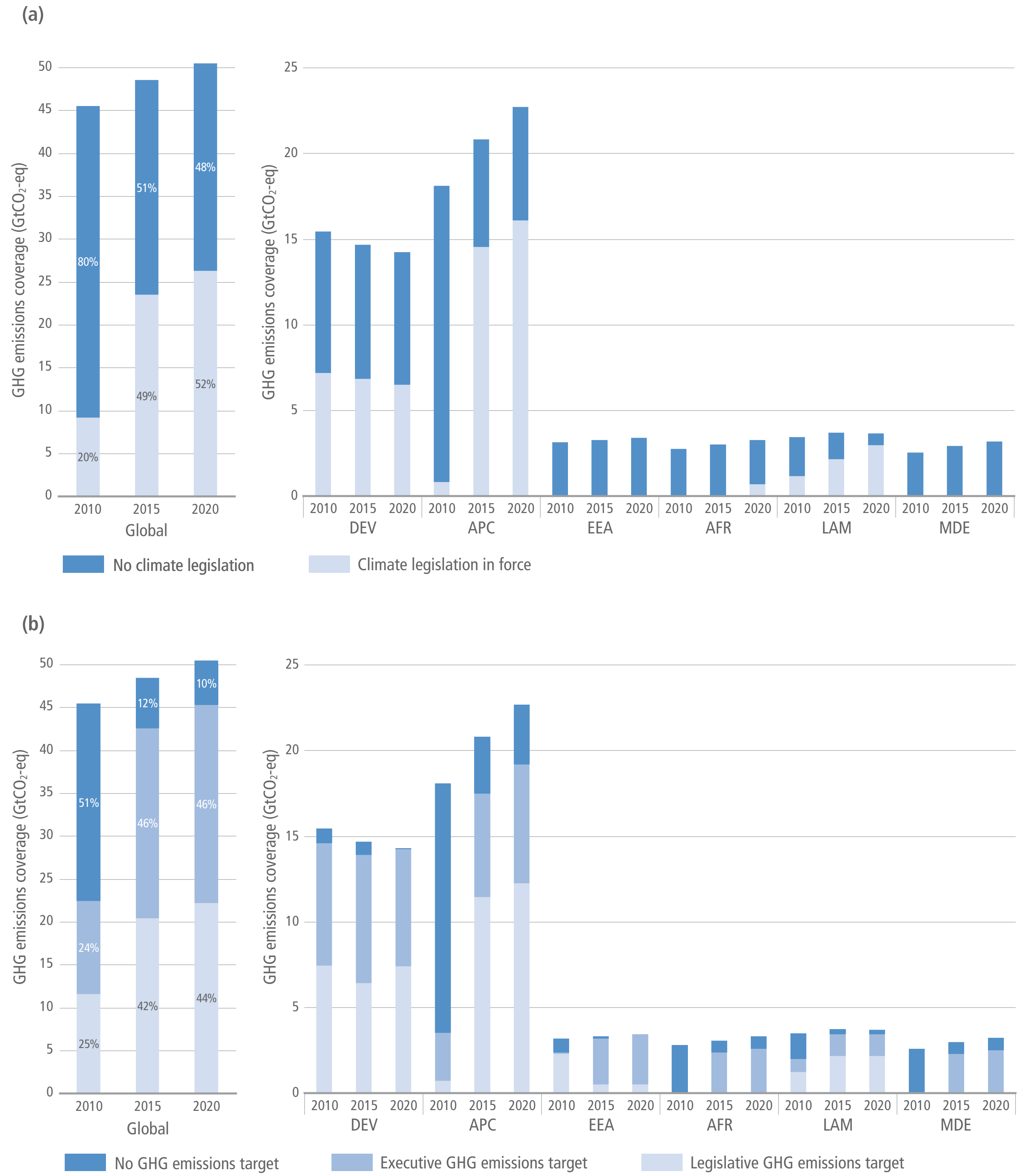


Figure TS.24 | Prevalence of legislation and emissions targets across regions. Panel (a): shares of global GHG emissions under national climate change legislations – in 2010, 2015 and 2020. Climate legislation is defined as an act passed by a parliament that includes the reduction of GHGs in its title or objectives. **Panel (b):** shares of global GHG emissions under national climate emission targets – in 2010, 2015 and 2020. Emissions reductions targets were taken into account as a legislative target when they were defined in a law or as part of a country's submission under the Kyoto Protocol, or as an executive target when they were included in a national policy or official submissions under the UNFCCC. Targets were included if they were economy-wide or included at least the energy sector. The proportion of national emissions covered are scaled to reflect coverage and whether targets are in GHG or CO_2 terms. Emissions data used are for 2019. 2020 data was excluded as emissions shares across regions deviated from past patterns due to COVID-19. AR6 regions: DEV = Developed countries; APC = Asia and Pacific; EEA = Eastern Europe and West Central Asia; AFR = Africa; LAM = Latin America and the Caribbean; ME = Middle East. {Figure 13.1 and 13.2}

The media shapes the public discourse about climate mitigation. This can usefully build public support to accelerate mitigation action but may also be used to impede decarbonisation (*medium evidence, high agreement*). Global media coverage (across a study of 59 countries) has been growing, from about 47,000 articles in 2016–17 to about 87,000 in 2020–21. Generally, the media representation of climate science has increased and become more accurate over time. On occasion, the propagation of scientifically misleading information by organised counter-movements has fuelled polarisation, with negative implications for climate policy. {13.4}

Explicit attention to equity and justice is salient to both social acceptance and fair and effective policymaking for mitigation (*high confidence*). Distributional implications of alternative climate policy choices can be usefully evaluated at city, local and national scales as an input to policymaking. It is anticipated that institutions and governance frameworks that enable consideration of justice and Just Transitions can build broader support for climate policymaking. {13.2, 13.6, 13.8, 13.9}

Carbon pricing is effective in promoting implementation of low-cost emissions reductions (*high confidence*). While the coverage of emissions trading and carbon taxes has risen to over 20 percent of global CO_2 emissions, both coverage and price are lower than is needed for deep reductions. Market mechanisms ideally are designed to be effective as well as efficient, balance distributional goals and find social acceptance. Practical experience has driven progress in market mechanism design, especially of emissions trading schemes. Carbon pricing is limited in its effect on adoption of higher-cost mitigation options, and where decisions are often not sensitive to price incentives, such as in energy efficiency, urban planning, and infrastructure (*robust evidence*, *medium agreement*). Subsidies have been used to improve energy efficiency, encourage the uptake of renewable energy and other sector-specific emissions-saving options. {13.6}

Carbon pricing is most effective if revenues are redistributed or used impartially (*high confidence*). A carbon levy earmarked for green infrastructures or saliently returned to taxpayers corresponding to widely accepted notions of fairness increases the political acceptability of carbon pricing. {5.6, Box 5.11}

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 (using alternative methodologies) 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} {13.6}

Regulatory instruments play an important role in achieving specific mitigation outcomes in sectoral applications (*high confidence*). Regulation is effective in particular applications and often enjoys greater political support, but tends to be more economically costly than pricing instruments (*robust evidence*, *medium agreement*). Flexible forms of regulation (e.g., performance standards) have achieved aggregate goals for renewable energy generation, vehicle efficiency and fuel standards, and energy efficiency in buildings and industry. Infrastructure investment decisions are significant for mitigation because they lock-in high- or low-emissions trajectories over long periods. Information and voluntary programs can contribute to overall mitigation outcomes (*medium evidence*, *high agreement*). Designing for overlap and interactions among mitigation policies enhances their effectiveness. {13.6}

National mitigation policies interact internationally with effects that both support and hinder mitigation action (*medium evidence, high agreement*). Reductions in demand for fossil fuels tend to negatively affect fossil fuel-exporting countries. Creation of markets for emission reduction credits tends to benefit countries able to supply credits. Policies to support technology development and diffusion tend to have positive spillover effects. There is no consistent evidence of significant emissions leakage or competitiveness effects between countries, including for emissions-intensive trade-exposed industries covered by emission-trading systems (*medium confidence*). {13.6}

Policy packages are better able to support socio-technical transitions and shifts in development pathways toward low-carbon futures than are individual policies (*high confidence*). For best effect, they need to be harnessed to a clear vision for change and designed with attention to local governance context. Comprehensiveness in coverage, coherence to ensure complementarity, and consistency of policies with the overarching vision and its objectives are important design criteria. Integration across objectives occurs when a policy package is informed by a clear problem framing and identification of the full range of relevant policy subsystems. The climate policy landscape is outlined in Table TS.8, which maps framings of desired national policy outcomes to policymaking approaches. {13.7, Figure 13.6}

Table TS.8 | Mapping the landscape of climate policy. {Figure 13.6}

Approach to policymaking	Framing of outcome	
	Enhancing mitigation	**Addressing multiple objectives of mitigation and development**
Shifting incentives	'Direct mitigation focus' *{2.8, 13.6}* **Objective:** reduce GHG emissions now. **Literature:** how to design and implement policy instruments, with attention to distributional and other concerns. **Examples:** carbon tax, cap and trade, border carbon adjustment (BCA), disclosure policies.	'Co-benefits' *{5.6.2, 12.4.4, 17.3}* **Objective:** synergies between mitigation and development. **Literature:** scope for and policies to realise synergies and avoid trade-offs across climate and development objectives. **Examples:** appliance standards, fuel taxes, community forest management, sustainable dietary guidelines, green building codes, packages for air pollution, packages for public transport.
Enabling transition	'Socio-technical transitions' *{1.7.3, 5.5, 6.7, 10.8, Cross-Chapter Box 12 in Chapter 16}* **Objective:** accelerate low-carbon shifts in socio-technical systems. **Literature:** understand socio-technical transition processes, integrated policies for different stages of a technology 'S curve' and explore structural, social and political elements of transitions. **Examples:** packages for renewable-energy transition and coal phase-out; diffusion of electric vehicles, process and fuel switching in key industries.	'System transitions to shift development pathways' *{7.4.5, 11.6.6, 13.9, 17.3.3, Cross-Chapter Box 5 in Chapter 4, Cross-Chapter Box 12 in Chapter 16}* **Objective:** accelerate system transitions and shift development pathways to expand mitigation options and meet other development goals. **Literature:** examines how structural development patterns and broad cross-sector and economy-wide measures drive ability to mitigate while achieving development goals through integrated policies and aligning enabling conditions. **Examples:** packages for sustainable urbanisation, land-energy-water nexus approaches, green industrial policy, regional Just Transition plans.

The co-benefits and trade-offs of integrating adaptation and mitigation are most usefully identified and assessed prior to policymaking rather than being accidentally discovered (*high confidence*). This requires strengthening relevant national institutions to reduce silos and overlaps, increasing knowledge exchange at the country and regional levels, and supporting engagement with bilateral and multilateral funding partners. Local governments are well placed to develop policies that generate social and environmental co-benefits but to do so require legal backing and adequate capacity and resources. {13.8}

Climate change mitigation is accelerated when attention is given to integrated policy and economy-wide approaches, and when enabling conditions (*governance, institutions, behaviour and lifestyle, innovation, policy,* and *finance*), are present (*robust evidence, medium agreement*). Accelerating climate mitigation includes simultaneously weakening high-carbon systems and encouraging low-carbon systems; ensuring interaction between adjacent systems (e.g., energy and agriculture); overcoming resistance to policies (e.g., from incumbents in high-carbon-emitting industries), including by providing transitional support to the vulnerable and negatively affected by distributional impacts; inducing changes in consumer practices and routines; providing transition support; and addressing coordination challenges in policy and governance. Table TS.9 elucidates the complexity of policymaking in driving sectoral transitions by summarising case studies of sectoral transitions from Chapters 5 to 12. These real-world sectoral transitions reinforce critical lessons on policy integration. (Table TS.9) {13.7, 13.9}

Economy-wide packages, including economic-stimulus packages, can contribute to shifting sustainable development pathways and achieving net zero outcomes whilst meeting short-term economic goals (*medium evidence, high agreement*). The 2008–9 global recession showed that policies for sustained economic recovery go beyond short-term fiscal stimulus to include long-term commitments of public spending on the low-carbon economy, pricing reform, addressing affordability, and minimising distributional impacts. COVID-19 spurred stimulus packages and multi-objective recovery policies may also have potential to meet short-term economic goals while enabling longer-term sustainability goals. (Table TS.8) {13.9}

Table TS.9 | Case studies of integrated policymaking for sectoral transitions. Real-world sectoral transitions reinforce critical lessons on policy integration: a high-level strategic goal (column A), the need for a clear sectoral outcome framing (column B), a carefully coordinated mix of policy instruments and governance actions (column C), and the importance of context-specific governance factors (column D). Illustrative examples, drawn from sectors, help elucidate the complexity of policymaking in driving sectoral transitions. {Cross-Chapter Box 9 in Chapter 13, Table 1}

A. Illustrative case	B. Objective	C. Policy mix	D. Governance context	
			Enablers	Barriers
Shift in mobility service provision in Kolkata, India {Box 5.8}	– Improve system efficiency, sustainability and comfort – Shift public perceptions of public transport	– Strengthen coordination between modes – Formalise and green auto-rickshaws – Procure fuel-efficient, comfortable low-floor AC buses – Ban cycling on busy roads – Deploy policy actors as change-agents, mediating between interest groups	– Cultural norms around informal transport-sharing, linked to high levels of social trust – Historically crucial role of buses in transit – App-cab companies shifting norms and formalising mobility-sharing – Digitalisation and safety on board	– Complexity: multiple modes with separate networks and meanings – Accommodating and addressing legitimate concerns from social movements about the exclusionary effects of 'premium' fares, cycling bans on busy roads
LPG subsidy ('Zero Kero') programme, Indonesia {Box 6.3}	– Decrease fiscal expenditures on kerosene subsidies for cooking	– Subsidise provision of liquefied petroleum gas (LPG) cylinders and initial equipment – Convert existing kerosene suppliers to LPG suppliers	– Provincial government and industry support in targeting beneficiaries and implementation – Synergies in kerosene and LPG distribution infrastructures	– Continued user preference for traditional solid fuels – Reduced GHG benefits as subsidy shifted between fossil fuels
Action Plan for Prevention and Control of Deforestation in the Legal Amazon, Brazil {Box 7.9}	– Control deforestation and promote sustainable development	– Expand protected areas; homologation of indigenous lands – Improve inspections, satellite-based monitoring – Restrict public credit for enterprises and municipalities with high deforestation rates – Set up a REDD+ mechanism (Amazon Fund)	– Participatory agenda-setting process – Cross-sectoral consultations on conservation guidelines – Mainstreaming of deforestation in government programmes and projects	– Political polarisation leading to erosion of environmental governance – Reduced representation and independence of civil society in decision-making bodies – Lack of clarity around land ownership
Climate smart cocoa (CSC) production, Ghana {Box 7.12}	– Promote sustainable intensification of cocoa production – Reduce deforestation – Enhance incomes and adaptive capacities	– Distribute shade tree seedlings – Provide access to agronomic information and agrochemical inputs – Design a multi-stakeholder program including MNCs, farmers and NGOs	– Local resource governance mechanisms ensuring voice for smallholders – Community governance allowed adapting to local context – Private-sector role in popularising CSC	– Lack of secure tenure (tree rights) – Bureaucratic and legal hurdles to register trees – State monopoly on cocoa marketing, export
Coordination mechanism for joining fragmented urban policymaking in Shanghai, China {Box 8.3}	– Integrate policymaking across objectives, towards low-carbon urban development	– Combine central targets and evaluation with local flexibility for initiating varied policy experiments – Establish a local leadership team for coordinating cross-sectoral policies involving multiple institutions – Create a direct programme fund for implementation and capacity-building	– Strong vertical linkages between central and local levels – Mandate for policy learning to inform national policy – Experience with mainstreaming mitigation in related areas (e.g., air pollution)	– Challenging starting point – low share of renewable energy, high dependency on fossil fuels – Continued need for high investments in a developing context
Policy package for building energy efficiency, EU {Box SM.9.1}	– Reduce energy consumption, integrating renewable energy and mitigating GHG emissions from buildings	– Energy performance standards, set at nearly zero energy for new buildings – Energy performance standards for appliances – Energy performance certificates shown during sale – Long-term renovation strategies	– Binding EU-level targets, directives and sectoral effort-sharing regulations – Supportive urban policies, coordinated through city partnerships – Funds raised from allowances auctioned under the Emissions Trading Scheme (ETS)	– Inadequate local technical capacity to implement multiple instruments – Complex governance structure leading to uneven stringency

Table TS.9 (continued):

A. Illustrative case	B. Objective	C. Policy mix	D. Governance context	
			Enablers	Barriers
African electromobility – trackless trams with solar in Bulawayo and e-motorbikes in Kampala {Box 10.4}	– Leapfrog into a decarbonised transport future – Achieve multiple social benefits beyond mobility provision	– Develop urban centres with solar at station precincts – Public-private partnerships for financing – Sanction demonstration projects for new electric transit and new electric motorbikes (for freight)	– 'Achieving SDGs' was an enabling policy framing – Multi-objective policy process for mobility, mitigation and manufacturing – Potential for funding through climate finance – Co-benefits such as local employment generation	– Economic decline in the first decade of the 21st century – Limited fiscal capacity for public funding of infrastructure – Inadequate charging infrastructure for e-motorbikes
Initiative for a climate-friendly industry in North Rhine Westphalia (NRW), Germany {Box 11.3}	– Collaboratively develop innovative strategies towards a net zero GHG industrial sector, while securing competitiveness	– Build platform to bring together industry, scientists and government in self-organised innovation teams – Intensive cross-branch cooperation to articulate policy/infrastructure needs	– NRW is Germany's industrial heartland, with an export-oriented industrial base – Established government-industry ties – Active discourse between industry and public	– Compliance rules preventing in-depth co-operation
Food2030 strategy, Finland {Box 12.2}	– Local, organic and climate-friendly food production – Responsible and healthy food consumption – A competitive food supply chain	– Target funding and knowledge support for innovations – Apply administrative means (legislation, guidance) to increase organic food production and procurement – Use education and information instruments to shift behaviour (media campaigns, websites)	– Year-long deliberative stakeholder engagement process across sectors – Institutional structures for agenda-setting, guiding policy implementation and reflexive discussions	– Weak role of integrated impact assessments (IAMs) to inform agenda-setting – Monitoring and evaluation close to ministry in charge – Lack of standardised indicators of food system sustainability

Box TS.13 | Policy Attribution: Methodologies For – and Estimations of – the Macro-level Impact of Mitigation Policies on Indices of GHG Mitigation

Policy attribution examines the extent to which *GHG emission reductions*, the *proximate drivers of emissions*, and the deployment of *technologies that reduce emissions* may be reasonably attributed to policies implemented prior to the observed changes. Such policies include regulatory instruments such as energy-efficiency programmes or technical standards and codes, carbon pricing, financial support for low-carbon energy technologies and efficiency, voluntary agreements, and regulation of land-use practices.

The vast majority of literature reviewed for this report examines the effect of particular instruments in particular contexts {13.6, 14.3, 16.4}, and only a small number directly or plausibly infer global impacts of policies. Policies also differ in design, scope, and stringency, may change over time as they require amendments or new laws, and often partially overlap with other instruments. These factors complicate analysis, because they give rise to the potential for double counting emissions reductions that have been observed. These lines of evidence on the impact of polices include:

- **GHG Emissions.** Evidence from econometric assessments of the impact of policies in countries which took on Kyoto Protocol targets; decomposition analyses that identify policy-related, absolute reductions from historical levels in particular countries. {13.6.2, 14.3.3, Cross-Chapter Box 10 in Chapter 14}
- **Proximate emission drivers.** Trends in the factors that drive emissions including reduced rates of deforestation {7.6.2}, industrial energy efficiency {Box 16.3}, buildings energy efficiency {Figure 2.22}, and the policy-driven displacement of fossil fuel combustion by renewable energy. (Box TS.13, Table 1; Box TS.13, Figure 1) {Chapters 2 and 6, Cross-Chapter Box 10 in Chapter 14}
- **Technologies.** The literature indicates unambiguously that the rapid expansion of low-carbon energy technologies is substantially attributable to policy. {6.7.5, 16.5}

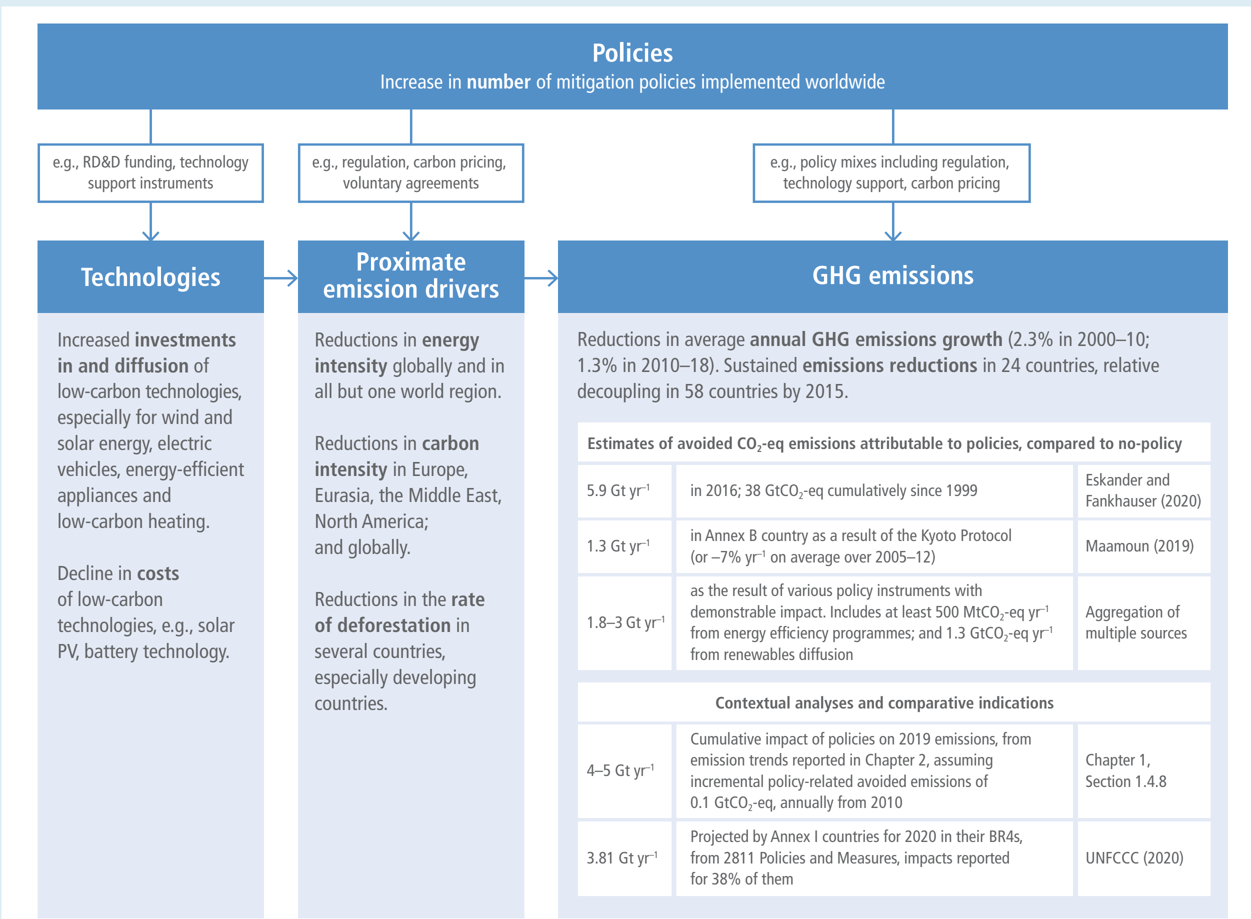
As illustrated in Box TS.13, Figure 1, these multiple lines of evidence point to policies having had a discernible impact on mitigation for specific countries, sectors, and technologies (*high confidence*), avoiding emissions of several $GtCO_2$-eq yr^{-1} globally (*medium confidence*).

Box TS.13 (continued)

Box TS.13, Table 1 | The effects of policy on GHG emissions, drivers of emissions, and technology deployment.

Sector	Effects on emissions	Effects on immediate drivers	Effects on low-carbon technology
Energy supply {Chapter 6}	Carbon pricing, emissions standards, and technology support have led to declining emissions associated with the supply of energy.	Carbon pricing and technology support have led to improvements in the efficiency of energy conversion.	A variety of market-based instruments, especially technology-support policies have led to high diffusion rates and cost reductions for renewable energy technologies.
AFOLU {Chapter 7}	Regulation of land-use rights and practices have led to falling aggregate AFOLU-sector emissions.	Regulation of land-use rights and practices, payments for ecosystem service, and offsets, have led to decreasing rates of deforestation (*medium confidence*).	
Buildings {Chapter 9}	Regulatory standards have led to reduced emissions from new buildings.	Regulatory standards, financial support for building renovation and market-based instruments have led to improvements in building and building-system efficiencies.	Technology support and regulatory standards have led to adoption of low-carbon heating systems and high-efficiency appliances.
Transport {Chapter 10}	Vehicle standards, land-use planning, and carbon pricing have led to avoided emissions in ground transportation.	Vehicle standard, carbon pricing, and support for electrification have led to automobile efficiency improvements.	Technology support and emissions standards have increased diffusion rates and cost reductions for electric vehicles.
Industry {Chapter 11}		Carbon pricing has led to efficiency improvements in industrial facilities.	

Note: statements describe the effects of policies across those countries where policies are in place. Unless otherwise noted, all findings are of *high confidence*.



Box TS.13, Figure 1 | Policy impacts on key outcome indices: GHG emissions, proximate emission drivers, and technologies, including several lines of evidence on GHG abatement attributable to policies. {Cross-Chapter Box 10, Figure 1 in Chapter 14}

TS.6.2 International Cooperation

International cooperation is having positive and measurable results (*high confidence*). The Kyoto Protocol led to measurable and substantial avoided emissions, including in 20 countries with Kyoto first-commitment period targets that have experienced a decade of declining absolute emissions. It also built national capacity for GHG accounting, catalysed the creation of GHG markets, and increased investments in low-carbon technologies. Other international agreements and institutions have led to avoided CO_2 emissions from land-use practices, as well as avoided emissions of some non-CO_2 greenhouse gases (*medium confidence*). {14.3, 14.5, 14.6}

New forms of international cooperation have emerged since AR5 in line with an evolving understanding of effective mitigation policies, processes, and institutions. Both new and pre-existing forms of cooperation are vital for achieving climate mitigation goals in the context of sustainable development (*high confidence*). While previous IPCC assessments have noted important synergies between the outcomes of climate mitigation and achieving sustainable development objectives, there now appear to be synergies between the two processes themselves (*medium confidence*). Since AR5, international cooperation has shifted towards facilitating national-level mitigation action through numerous channels, including though processes established under the UNFCCC regime and through regional and sectoral agreements and organisations. {14.2, 14.3, 14.5, 14.6}

Participation in international agreements and transboundary networks is associated with the adoption of climate policies at the national and sub-national levels, as well as by non-state actors (*high confidence*). International cooperation helps countries achieve long-term mitigation targets when it supports development and diffusion of low-carbon technologies, often at the level of individual sectors, which can simultaneously lead to significant benefits in the areas of sustainable development and equity (*medium confidence*). {14.2, 14.3, 14.5, 14.6}

International cooperation under the UN climate regime took an important new direction with the entry into force of the 2015 Paris Agreement, which strengthened the objective of the UN climate regime, including its long-term temperature goal, while adopting a different architecture to that of the Kyoto Protocol (*high confidence*). The core national commitments under the Kyoto Protocol were legally binding quantified emission targets for developed countries tied to well-defined mechanisms for monitoring and enforcement. By contrast, the commitments under the Paris Agreement are primarily procedural, extend to all parties, and are designed to trigger domestic policies and measures, enhance transparency, and stimulate climate investments, particularly in developing countries, and to lead iteratively to rising levels of ambition across all countries. Issues of equity remain of central importance in the UN climate regime, notwithstanding shifts in the operationalisation of 'common but differentiated responsibilities and respective capabilities' from Kyoto to Paris. {14.3}

There are conflicting views on whether the Paris Agreement's commitments and mechanisms will lead to the attainment of its stated goals (*medium confidence*). Arguments in support of the Paris Agreement are that the processes it initiates and supports will in multiple ways lead, and indeed have already led, to rising levels of ambition over time. The recent proliferation of national mid-century net zero GHG targets can be attributed in part to the Paris Agreement. Moreover, its processes and commitments will enhance countries' abilities to achieve their stated level of ambition, particularly among developing countries. Arguments against the Paris Agreement are that it lacks a mechanism to review the adequacy of individual Parties' Nationally Determined Contributions (NDCs), that collectively current NDCs are inconsistent in their level of ambition with achieving the Paris Agreement's long-term temperature goal, that its processes will not lead to sufficiently rising levels of ambition in the NDCs, and that NDCs will not be achieved because the targets, policies and measures they contain are not legally binding at the international level. To some extent, arguments on both sides are aligned with different analytic frameworks, including assumptions about the main barriers to mitigation that international cooperation can help overcome. The extent to which countries increase the ambition of their NDCs and ensure they are effectively implemented will depend in part on the successful implementation of the support mechanisms in the Paris Agreement, and in turn will determine whether the goals of the Paris Agreement are met (*high confidence*). {14.2, 14.3, 14.4}

International cooperation outside the UNFCCC processes and agreements provides critical support for mitigation in particular regions, sectors and industries, for particular types of emissions, and at the sub- and trans-national levels (*high confidence*). Agreements addressing ozone depletion, transboundary air pollution, and release of mercury are all leading to reductions in the emissions of specific greenhouse gases. Cooperation is occurring at multiple governance levels including cities. Transnational partnerships and alliances involving non-state and sub-national actors are also playing a growing role in stimulating low-carbon technology diffusion and emissions reductions (*medium confidence*). Such transnational efforts include those focused on climate litigation; the impacts of these are unclear but promising. Climate change is being addressed in a growing number of international agreements operating at sectoral levels, as well as within the practices of many multilateral organisations and institutions. Sub-global and regional cooperation, often described as climate clubs, can play an important role in accelerating mitigation, including the potential for reducing mitigation costs through linking national carbon markets, although actual examples of these remain limited. {14.2, 14.4, 14.5, 14.6}

International cooperation will need to be strengthened in several key respects in order to support mitigation action consistent with limiting temperature rise to well below 2°C in the context of sustainable development and equity (*high confidence*). Many developing countries' NDCs have components or additional actions that are conditional on receiving assistance with respect to finance, technology development and transfer, and capacity-building, greater than what has been provided to date. Sectoral and sub-global cooperation is providing critical support, and yet there is room for further progress. In some cases, notably with respect to aviation and shipping, sectoral agreements have adopted climate mitigation goals that fall far short of what would be required to achieve the long-term temperature goal of the Paris Agreement. Moreover, there are cases where international cooperation may be hindering mitigation efforts, namely evidence that trade and investment agreements, as well as agreements within the energy sector, impede national mitigation efforts (*medium confidence*). International cooperation is emerging but so far fails to fully address transboundary issues associated with solar radiation modification (SRM) and carbon dioxide removal (CDR). {14.2, 14.3, 14.4, 14.5, 14.6, Cross-Working Group Box 4 in Chapter 14}

TS.6.3 Societal Aspects of Mitigation

Social equity reinforces capacity and motivation for mitigating climate change (*medium confidence*). Impartial governance such as fair treatment by law-and-order institutions, fair treatment by gender, and income equity, increases social trust, thus enabling demand-side climate policies. High-status (often high-carbon) item consumption may be reduced by taxing absolute wealth without compromising well-being. {5.2, 5.4.2, 5.6}

Policies that increase the political access and participation of women, racialised, and marginalised groups, increase the democratic impetus for climate action (*high confidence*). Including more differently situated knowledge and diverse perspectives makes climate mitigation policies more effective. {5.2, 5.6}

Greater contextualisation and granularity in policy approaches better addresses the challenges of rapid transitions towards zero-carbon systems (*high confidence*). Larger systems take more time to evolve, grow, and change compared to smaller ones. Creating and scaling up entirely new systems takes longer than replacing existing technologies and practices. Late adopters tend to adopt faster than early pioneers. Obstacles and feasibility barriers are high in the early transition phases. Barriers decrease as a result of technical and social learning processes, network building, scale economies, cultural debates, and institutional adjustments. {5.5, 5.6}

Mitigation policies that integrate and communicate with the values people hold are more successful (*high confidence*). Values differ between cultures. Measures that support autonomy, energy security and safety, equity and environmental protection, and fairness resonate well in many communities and social groups. Changing from a commercialised, individualised, entrepreneurial training model to an education cognisant of planetary health and human well-being can accelerate climate change awareness and action. {5.4.1, 5.4.2}

Changes in consumption choices that are supported by structural changes and political action enable the uptake of low-carbon choices (*high confidence*). Policy instruments applied in coordination can help to accelerate change in a consistent desired direction. Targeted technological change, regulation, and public policy can help in steering digitalisation, the sharing economy, and circular economy towards climate change mitigation. (Boxes TS.12 and TS.14) {5.3, 5.6}

Complementarity in policies helps in the design of an optimal demand-side policy mix (*medium confidence*). In the case of energy efficiency, for example, this may involve CO_2 pricing, standards and norms, and information feedback. {5.3, 5.4, 5.6}

TS.6.4 Investment and Finance

Finance to reduce net GHG emissions and enhance resilience to climate impacts is a critical enabling factor for the low-carbon transition. Fundamental inequities in access to finance as well as finance terms and conditions, and countries' exposure to physical impacts of climate change overall, result in a worsening outlook for a global Just Transition (*high confidence*). Decarbonising the economy requires global action to address fundamental economic inequities and overcome the climate investment trap that exists for many developing countries. For these countries the costs and risks of financing often represent a significant challenge for stakeholders at all levels. This challenge is exacerbated by these countries' general economic vulnerability and indebtedness. The rising public fiscal costs of mitigation, and of adapting to climate shocks, is affecting many countries and worsening public indebtedness and country credit ratings at a time when there were already significant stresses on public finances. The COVID-19 pandemic has made these stresses worse and tightened public finances still further. Other major challenges for commercial climate finance include: the mismatch between capital and investment needs, home bias[31] considerations, differences in risk perceptions for regions, as well as limited institutional capacity to ensure safeguards are effective (*high confidence*). {15.2, 15.6.3}

Investors, central banks, and financial regulators are driving increased awareness of climate risk. This increased awareness can support climate policy development and implementation (*high confidence*) {15.2, 15.6}. Climate-related financial risks arise from physical impacts of climate change (already relevant in the short term), and from a disorderly transition to a low-carbon economy. Awareness of these risks is increasing, leading also to concerns about financial stability. Financial regulators and institutions have responded with multiple regulatory and voluntary initiatives to assess and address these risks. Yet despite these initiatives, climate-related financial risks remain greatly underestimated by financial institutions and markets, limiting the capital reallocation needed for the low-carbon transition. Moreover, risks relating to national and international inequity – which act as a barrier to the transformation – are not yet reflected in decisions by the financial community. Stronger steering by regulators and policymakers has the potential to close this gap. Despite the increasing attention of investors to climate change, there is limited evidence that this attention has directly impacted emission reductions. This leaves high uncertainty, both near term (2021–30) and longer term (2021–50), on the feasibility of an alignment of financial flows with the Paris Agreement goals (*high confidence*). {15.2, 15.6}

Progress on the alignment of financial flows with low-GHG emissions pathways remains slow. There is a climate financing

31 Most of climate finance stays within national borders, especially private climate flows (over 90%). The reasons for this range from national policy support, differences in regulatory standards, exchange rate, political and governance risks, to information market failures.

gap which reflects a persistent misallocation of global capital (*high confidence*) {15.2, 15.3}. Persistently high levels of both public and private fossil fuel-related financing continue to be of major concern despite promising recent commitments. This reflects policy misalignment, the current perceived risk-return profile of fossil fuel-related investments, and political economy constraints (*high confidence*). Estimates of climate finance flows[32] exhibit highly divergent patterns across regions and sectors and a slowing growth {15.3}. When the perceived risks are too high, the misallocation of abundant savings persists and investors refrain from investing in infrastructure and industry in search of safer financial assets, even earning low or negative real returns (*high confidence*). {15.2, 15.3}

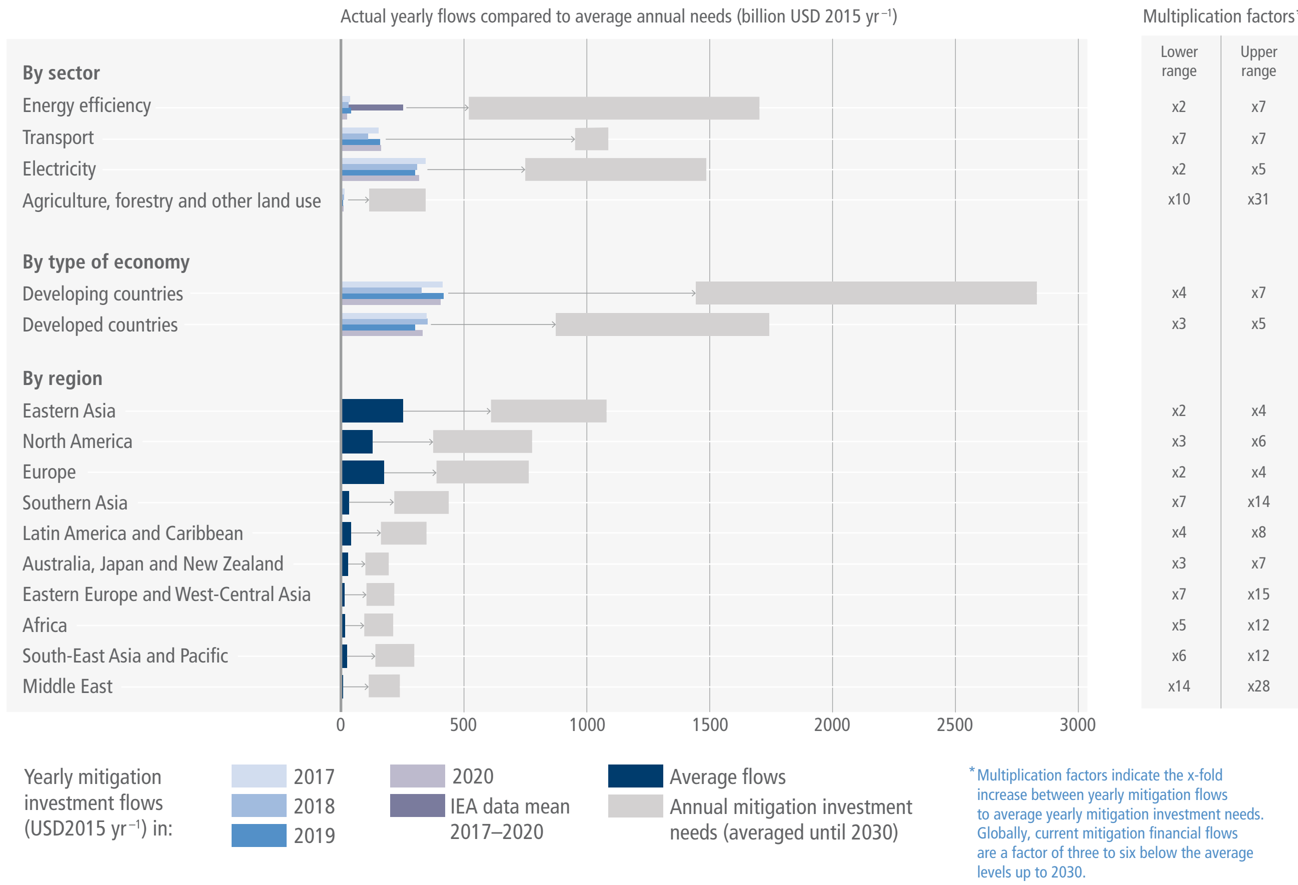


Figure TS.25 | Breakdown of recent average (downstream) mitigation investments and model-based investment requirements for 2020–2030 (USD billion) in scenarios that likely limit warming to 2°C or lower. Mitigation investment flows and model-based investment requirements by sector / segment (energy efficiency in buildings and industry, transport including efficiency, electricity generation, transmission and distribution including electrification, and agriculture, forestry and other land use), by type of economy, and by region (see Annex II Part I Section 1: By region is based on intermediate level (R10) classification scheme. By type of economy is based on intermediate level (R10) classification scheme, which considers 'North America', 'Europe', and 'Australia, Japan and New Zealand' as developed countries, and the other seven regions as developing countries). Breakdown by sector / segment may differ slightly from sectoral analysis in other contexts due to the availability of investment needs data. The granularity of the models assessed in Chapter 3, and other studies, do not allow for a robust assessment of the specific investment needs of LDCs or SIDSs. Investment requirements in developing countries might be underestimated due to missing data points as well as underestimated technology costs. In modelled pathways, regional investments are projected to occur when and where they are cost 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. Investment requirements and flows covering downstream / mitigation technology deployment only. Data includes investments with a direct mitigation effect, and in the case of electricity, additional transmission and distribution investments. See section 15.4.2 Quantitative assessment of financing needs for detailed data on investment requirements. Data on mitigation investment flows are based on a single series of reports (Climate Policy Initiative, CPI) which assembles data from multiple sources. Investment flows for energy efficiency are adjusted based on data from the International Energy Agency (IEA). Data on mitigation investments do not include technical assistance (i.e., policy and national budget support or capacity building), other non-technology deployment financing. Adaptation only flows are also excluded. Data on mitigation investment requirements for electricity are based on emission pathways C1, C2 and C3 (Table SPM.1). For electricity investment requirements, the upper end refers to the mean of C1 pathways and the lower end to the mean of C3 pathways. Data points for energy efficiency, transport and AFOLU cannot always be linked to C1–C3 scenarios. Data do not include needs for adaptation or general infrastructure investment or investment related to meeting the SDGs other than mitigation, which may be at least partially required to facilitate mitigation. The multiplication factors show the ratio of average annual model-based mitigation investment requirements (2020–2030) and most recent annual mitigation investments (averaged for 2017–2020). The lower and upper multiplication factors refer to the lower and upper ends of the range of investment needs.

Given the multiple sources and lack of harmonised methodologies, the data can only be indicative of the size and pattern of investment gaps. The gap between most recent flows and required investments is only a single indicator. A more comprehensive (and qualitative) assessment is required in order to understand the magnitude of the challenge of scaling up investment in sectors and regions. The analysis also does not consider the effects of misaligned flows. {15.3, 15.4, 15.5, Table 15.2, Table 15.3, Table 15.4}

32 Climate finance flows refers to local, national, or transnational financing from public, private, and alternative sources, to support mitigation and adaptation actions addressing climate change.

Global climate finance is heavily focused on mitigation (more than 90% on average between 2017–2020) (*high confidence*) {15.4, 15.5}. This is despite the significant economic effects of climate change's expected physical impacts, and the increasing awareness of these effects on financial stability. To meet the needs for rapid deployment of mitigation options, global mitigation investments are expected to need to increase by the factor of three to six (*high confidence*). The gaps represent a major challenge for developing countries, especially Least-Developed Countries (LDCs), where flows have to increase by the factor of four to seven for specific sectors such as AFOLU, and for specific groups with limited access to, and high costs of, climate finance (*high confidence*) (Figure TS.25) {15.4, 15.5}. The actual size of sectoral and regional climate financing gaps is only one component driving the magnitude of the challenge. Financial and economic viability, access to capital markets, appropriate regulatory frameworks, and institutional capacity to attract and facilitate investments and ensure safeguards are decisive to scaling-up funding. Soft costs for regulatory environment and institutional capacity, upstream funding needs as well as R&D and venture capital for development of new technologies and business models are often overlooked despite their critical role to facilitate the deployment of scaled-up climate finance (*high confidence*). {15.4.1, 15.5.2}

The relatively slow implementation of commitments by countries and stakeholders in the financial sector to scale up climate finance reflects neither the urgent need for ambitious climate action, nor the economic rationale for ambitious climate action (*high confidence*). Delayed climate investments and financing – and limited alignment of investment activity with the Paris Agreement – will result in significant carbon lock-ins, stranded assets, and other additional costs. This will particularly impact urban infrastructure and the energy and transport sectors (*high confidence*). A common understanding of debt sustainability and debt transparency, including negative implications of deferred climate investments on future GDP, and how stranded assets and resources may be compensated, has not yet been developed (*medium confidence*). {15.6}

There is a mismatch between capital availability in the developed world and the future emissions expected in developing countries (*high confidence*). This emphasises the need to recognise the explicit and positive social value of global cross-border mitigation financing. A significant push for international climate finance access for vulnerable and poor countries is particularly important given these countries' high costs of financing, debt stress and the impacts of ongoing climate change (*high confidence*). {15.2, 15.3.2.3, 15.5.2, 15.6.1, 15.6.7}

Innovative financing approaches could help reduce the systemic under-pricing of climate risk in markets and foster demand for investment opportunities aligned with the Paris Agreement goals. Approaches include de-risking investments, robust 'green' labelling and disclosure schemes, in addition to a regulatory focus on transparency and reforming international monetary system financial sector regulations (*medium confidence*). Green bond markets and markets for sustainable finance products have grown significantly since AR5 and the landscape continues to evolve. Underpinning this evolution is investors' preference for scalable and identifiable low-carbon investment opportunities. These relatively new labelled financial products will help by allowing a smooth integration into existing asset allocation models (*high confidence*). Green bond markets and markets for sustainable finance products have also increased significantly since AR5, but challenges nevertheless remain, in particular, there are concerns about 'greenwashing' and the limited application of these markets to developing countries (*high confidence*). {15.6.2, 15.6.6}

New business models (e.g., pay-as-you-go) can facilitate the aggregation of small-scale financing needs and provide scalable investment opportunities with more attractive risk-return profiles (*high confidence*). Support and guidance for enhancing transparency can promote capital markets' climate financing by providing quality information to price climate risks and opportunities. Examples include SDG and environmental, social and governance (ESG) disclosure, scenario analysis and climate risk assessments, including the Task Force on Climate-related Financial Disclosures (TCFD). The outcome of these market-correcting approaches on capital flows cannot be taken for granted, however, without appropriate fiscal, monetary and financial policies. Mitigation policies will be required to enhance the risk-weighted return of low-emission and climate-resilient options, accelerate the emergence and support for financial products based on real projects, such as green bonds, and phase-out fossil fuel subsidies. Greater public-private cooperation can also encourage the private sector to increase and broaden investments, within a context of safeguards and standards, and this can be integrated into national climate change policies and plans (*high confidence*). {15.1, 15.2.4, 15.3.1, 15.3.2, 15.3.3, 15.5.2, 15.6.1, 15.6.2, 15.6.6, 15.6.7, 15.6.8}

Ambitious global climate policy coordination and stepped-up public climate financing over the next decade (2021–2030) can help redirect capital markets and overcome challenges relating to the need for parallel investments in mitigation. It can also help address macroeconomic uncertainty and alleviate developing countries' debt burden post-COVID-19 (*high confidence*). Providing strong climate policy signals helps guide investment decisions. Credible signalling by governments and the international community can reduce uncertainty for financial decision-makers and help reduce transition risk. In addition to indirect and direct subsidies, the public sector's role in addressing market failures, barriers, provision of information, and risk-sharing can encourage the efficient mobilisation of private sector finance (*high confidence*) {15.2, 15.6.1, 15.6.2}. The mutual benefits of coordinated support for climate mitigation and adaptation in the next decade for both developed and developing regions could potentially be very high in the post-COVID era. Climate-compatible stimulus packages could significantly reduce the macro-financial uncertainty generated by the pandemic and increase the sustainability of the world economic recovery {15.2, 15.3.2.3, 15.5.2, 15.6.1, 15.6.7}. Political leadership and intervention remain central to addressing uncertainty, which is a fundamental barrier for the redirection of financial flows. Existing policy misalignments – for example, in fossil fuel subsidies – undermine the credibility of public commitments, reduce perceived transition risks and limit financial sector action (*high confidence*). {15.2, 15.3.3, 15.6.1, 15.6.2, 15.6.3}

The greater the urgency of action to remain on a 1.5°C pathway, the greater need for parallel investment decisions in upstream and downstream parts of the value chain (*high confidence*). Greater urgency also reduces the lead times to build trust in regulatory frameworks. Consequently, many investment decisions will need to be made based on the long-term global goals. This highlights the importance of trust in political leadership which, in turn, affects risk perception and ultimately financing costs (*high confidence*). {15.6.1, 15.6.2}

Accelerated international cooperation on finance is a critical enabler of a low-carbon and Just Transition (*very high confidence*). Scaled-up public grants for adaptation and mitigation, and funding for low-income and vulnerable regions, especially in Sub-Saharan Africa, may have the highest returns. Key options include: increased public finance flows from developed to developing countries beyond USD100 billion a year; shifting from a direct lending modality towards public guarantees to reduce risks and greatly leverage private flows at lower cost; local capital markets development; and, changing the enabling operational definitions. A coordinated effort to green the post-pandemic recovery is also essential in countries facing much higher debt costs (*high confidence*). {15.2, 15.6}

TS.6.5 Innovation, Technology Development and Transfer

Innovation in climate mitigation technologies has seen enormous activity and significant progress in recent years. Innovation has also led to, and exacerbated, trade-offs in relation to sustainable development. Innovation can leverage action to mitigate climate change by reinforcing other interventions. In conjunction with other enabling conditions, innovation can support system transitions to limit warming and help shift development pathways. The currently widespread implementation of solar PV and LED lighting, for instance, could not have happened without technological innovation. Technological innovation can also bring about new and improved ways of delivering services that are essential to human well-being (*high confidence*) {16.1, 16.3, 16.4, 16.6}. At the same time as delivering benefits, innovation can result in trade-offs that undermine both progress on mitigation and progress towards other Sustainable Development Goals (SDGs). Trade-offs include negative externalities' – for instance, greater environmental pollution and social inequalities – rebound effects leading to lower net emission reductions or even increases in emissions, and increased dependency on foreign knowledge and providers (*high confidence*). Effective governance and policy have the potential to avoid and minimise such misalignments (*medium evidence*, *high agreement*). {16.2, 16.3, 16.4, 16.5.1, 16.6}

A systemic view of innovation to direct and organise the processes has grown over the last decade. This systemic view of innovation takes into account the role of actors, institutions, and their interactions, and can inform how innovation systems that vary across technologies, sectors and countries, can be strengthened (*high confidence*) {16.2, 16.3, 16.5}. Where a systemic view of innovation has been taken, it has enabled the development and implementation of indicators that are better able to provide insights in innovation processes. This, in turn, has enabled the analysis and strengthening of innovation systems. Traditional quantitative innovation indicators mainly include R&D investments and patents. Figure TS.26 illustrates that energy-related research, development and demonstration (RD&D) has risen slowly in the last

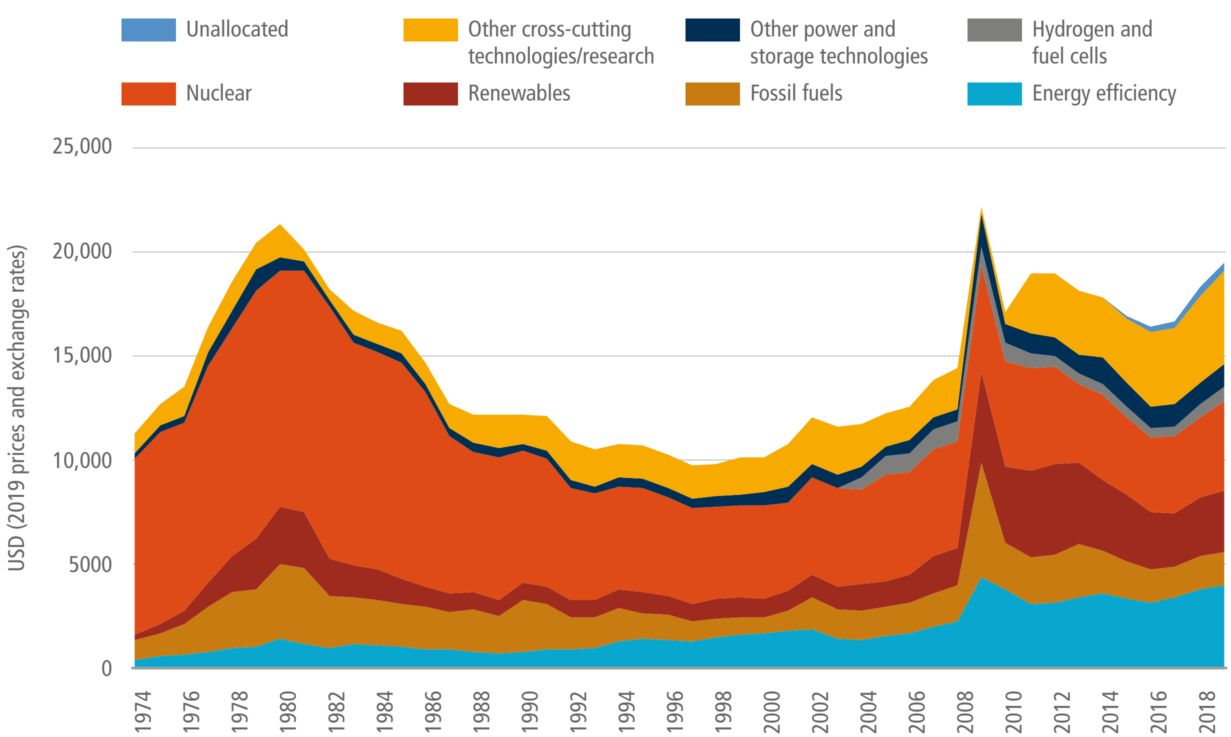


Figure TS.26 | Fraction of public energy research, development and demonstration (RD&D) spending by technology over time for IEA (largely OECD) countries between 1974 and 2018. {Box 16.3, Figure 1}

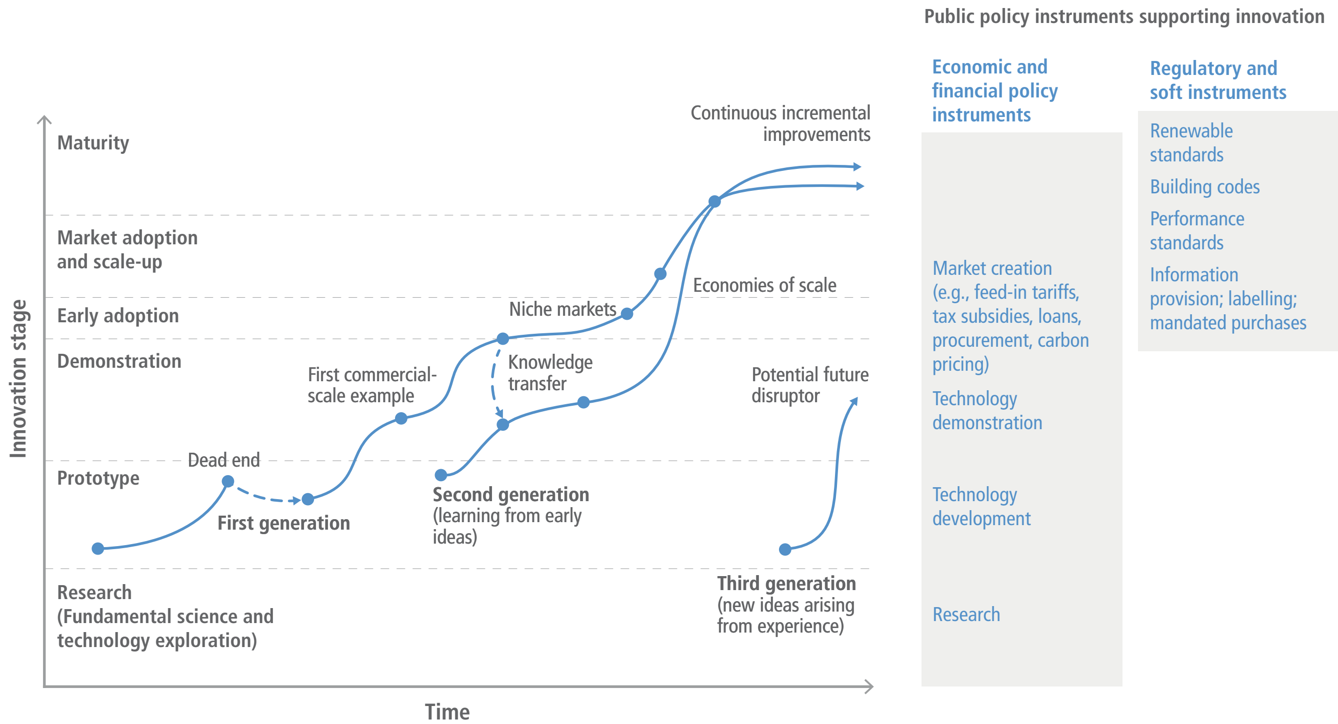


Figure TS.27 | Technology innovation process and the (illustrative) roles of different public policy instruments (on the right-hand side). {Figure 16.1} Note that demand-pull instruments in the regulatory instrument category, for instance, can also shape the early stages of the innovation process. Their position in the latter stages is highlighted in this figure because typically these instruments have been introduced in latter stages of the development of the technology. {16.4.4}

two decades, and that there has been a reorientation of the portfolio of funded energy technologies. Systemic indicators of innovation, however, go well beyond these approaches. They include structural innovation system elements including actors and networks, as well as indicators for how innovation systems function, such as access to finance, employment in relevant sectors, and lobbying activities {16.3.4, Table 16.7}. For example, in Latin America, monitoring systemic innovation indicators for the effectiveness of agroecological mitigation approaches has provided insights on the appropriateness and social alignment of new technologies and practices {Box 16.5}. Climate-energy-economy models, including integrated assessment models (IAMs), generally employ a stylised and necessarily incomplete view of innovation, and have yet to incorporate a systemic representation of innovation systems. {16.2.4, Box 16.1}

A systemic perspective on technological change can provide insights to policymakers supporting their selection of effective innovation policy instruments (*high confidence*) {16.4, 16.5}. A combination of scaled-up innovation investments with demand-pull interventions can achieve faster technology unit cost reductions and more rapid scale-up than either approach in isolation. These innovation policy instruments would nonetheless have to be tailored to local development priorities, to the specific context of different countries, and to the technology being supported. The timing of interventions and any trade-offs with sustainable development also need to be addressed. Public R&D funding and support, as well as innovation procurement, have shown to be valuable for fostering innovation in small-to-medium clean-tech firms (Figure TS.27) {16.4.4.3}. Innovation outcomes of policy instruments not necessarily aimed at innovation, such as feed-in tariffs, auctions, emissions trading schemes, taxes and renewable portfolio standards, vary from negligible to positive for climate change mitigation. Some specific designs of environmental taxation can also result in negative distributional outcomes {16.4.4}. Most of the available literature and evidence on innovation systems come from industrialised countries and larger developing countries. However, there is a growing body of evidence from developing countries and Small Island Developing States (SIDS). {16.4, 16.5, 16.7}

Experience and analyses show that technological change is inhibited if technological innovation system functions are not adequately fulfilled; this inhibition occurs more often in developing countries (*high confidence*). Examples of such functions are knowledge development, resource mobilisation, and activities that shape the needs, requirements and expectations of actors within the innovation system (guidance of the search). Capabilities play a key role in these functions, the buildup of which can be enhanced by domestic measures, but also by international cooperation. For instance, innovation cooperation on wind energy has contributed to the accelerated global spread of this technology. As another example, the policy guidance by the Indian government, which also promoted development of data, testing capabilities and knowledge within the private sector, has been a key determinant of the success of an energy-efficiency programme for air conditioners and refrigerators in India. {16.3, 16.5, 16.6, Cross-Chapter Box 12 in Chapter 16, Box 16.3}

Consistent with innovation system approaches, the sharing of knowledge and experiences between developed and developing countries can contribute to addressing global climate and the SDGs. The effectiveness of such international cooperation arrangements, however, depends on the way they are developed and implemented (*high confidence*). The effectiveness and sustainable development benefits of technology sharing under market conditions appears to be determined primarily by the complexity of technologies, local capabilities and the policy regime. This suggests that the development of planning and innovation capabilities remains necessary, especially in Least-Developed Countries (LDCs) and SIDS. International diffusion of low-emission technologies is also facilitated by knowledge spillovers from regions engaged in clean R&D (*medium confidence*). {16.2}

The evidence on the role of intellectual property rights (IPR) in innovation is mixed. Some literature suggests that it is a barrier while other sources suggests that it is an enabler to the diffusion of climate-related technologies (*medium confidence*). There is agreement that countries with well-developed institutional capacity may benefit from a strengthened IPR regime, but that countries with limited capabilities might face greater barriers to innovation as a consequence. This enhances the continued need for capacity-building. Ideas to improve the alignment of the global IPR regime and addressing climate change include specific arrangements for LDCs, case-by-case decision-making and patent-pooling institutions. {16.2.3, 16.5, Box 16.10}

Although some initiatives have mobilised investments in developing countries, gaps in innovation cooperation remain, including in the Paris Agreement instruments. These gaps could be filled by enhancing financial support for international technology cooperation, by strengthening cooperative approaches, and by helping build suitable capacity in developing countries across all technological innovation system functions (*high confidence*). The implementation of current arrangements of international cooperation for technology development and transfer, as well as capacity-building, are insufficient to meet climate objectives and contribute to sustainable development. For example, despite building a large market for mitigation technologies in developing countries, the lack of a systemic perspective in the implementation of the Clean Development Mechanism (CDM), operational since the mid-2000s, has only led to some technology transfer, especially to larger developing countries, but limited capacity building and minimal technology development (*medium confidence*). In the current climate regime, a more systemic approach to innovation cooperation could be introduced by linking technology institutions, such as the Technology Mechanism, and financial actors, such as the Financial Mechanism. {16.5.3}

Countries are exposed to sustainable development challenges in parallel with the challenges that relate to climate change. Addressing both sets of challenges simultaneously presents multiple and recurrent obstacles that systemic approaches to technological change could help resolve, provided they are well managed (*high confidence*). Obstacles include both entrenched power relations dominated by vested interests that control and benefit from existing technologies, and governance structures that continue to reproduce unsustainable patterns of production and consumption (*medium confidence*). Studies also highlight the potential of cultural factors to strongly influence the pace and direction of technological change. Sustainable solutions require adoption and mainstreaming of locally novel technologies that can meet local needs, and simultaneously address the SDGs. Acknowledging the systemic nature of technological innovation – which involve many levels of actors, stages of innovation and scales – can lead to new opportunities to shift development pathways towards sustainability. {16.4, 16.5, 16.6}

Strategies for climate change mitigation can be most effective in accelerating transformative change when actions taken to strengthen one set of enabling conditions also reinforce and strengthen the effectiveness of other enabling conditions (*medium confidence*). Applying transition or system dynamics to decisions can help policymakers take advantage of such high-leverage intervention points, address the specific characteristics of technological stages, and respond to societal dynamics. Inspiration can be drawn from the global unit-cost reductions of solar PV, which were accelerated by a combination of factors interacting in a mutually reinforcing way across a limited group of countries (*high confidence*) {Box 16.2, Cross-Chapter Box 12 in Chapter 16}. Transitions can be accelerated by policies appropriately targeted, which may be grouped in different 'pillars of policy'. The relative importance of different 'pillars' differs according to the stage of the transition. (Figure TS.28) {1.2.3}

Better and more comprehensive data on innovation indicators can provide timely insights for policymakers and policy design locally, nationally and internationally, especially for developing countries, where such insights are often missing. Data needed include those that can show the strength of technological, sectoral and national innovation systems. It is also necessary to validate current results and generate insights from theoretical frameworks and empirical studies for developing countries' contexts. Innovation studies on adaptation and mitigation other than energy and *ex-post* assessments of the effectiveness of various innovation-related policies and interventions, including R&D, would also provide benefits. Furthermore, methodological developments to improve the ability of IAMs to capture energy innovation system dynamics and the relevant institutions and policies (including design and implementation), would allow for more realistic assessment. {16.2, 16.3, 16.7}

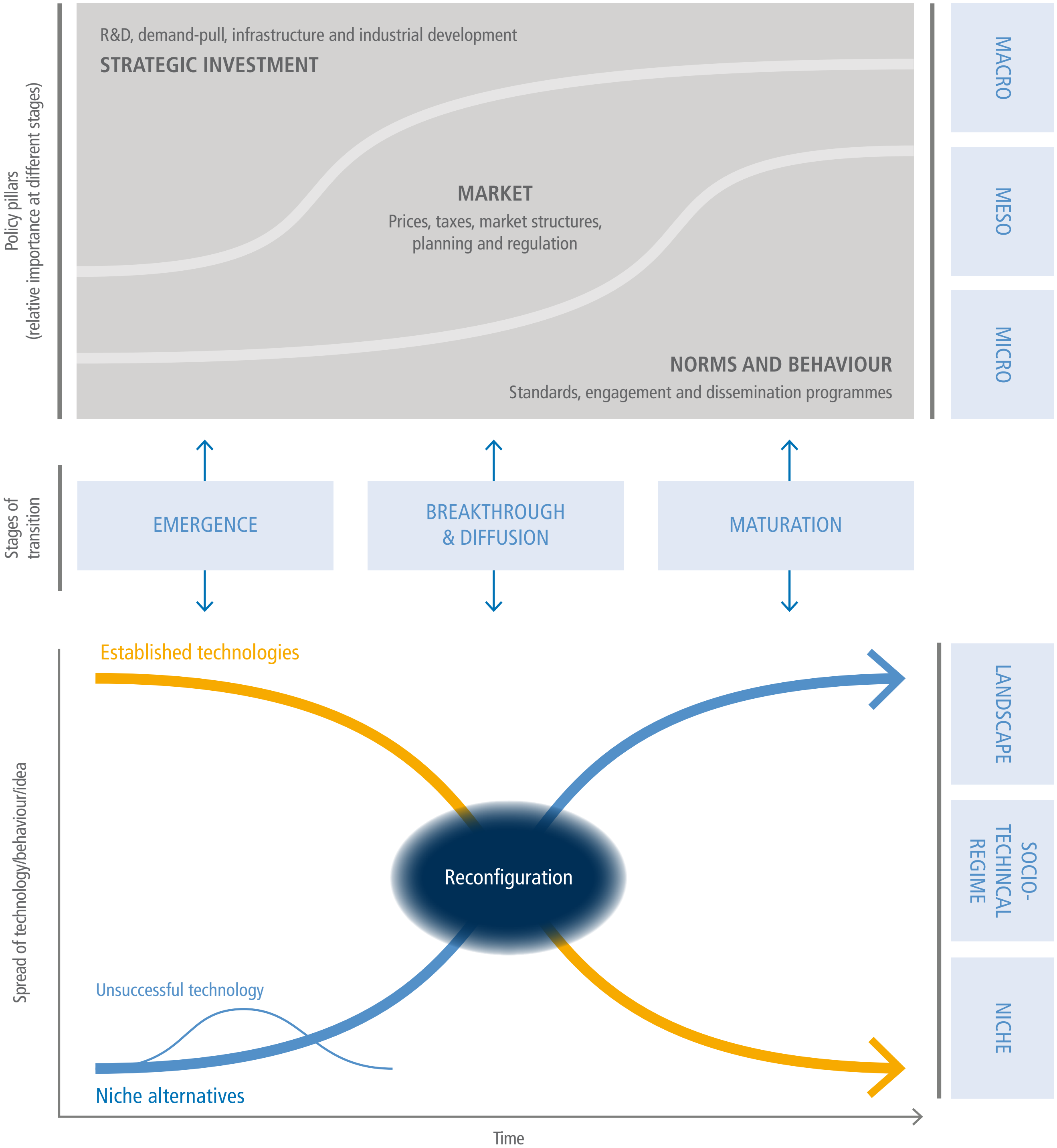


Figure TS.28 | Transition dynamics: levels, policies and processes. {Figure 1.7} The relative importance of different 'pillars of policy' differs according to the stage of the transition. The lower panel illustrates growth of innovative technologies or practices, which if successful, emerge from niches into an S-shaped dynamic of exponential growth. The diffusion stage often involves new infrastructure and reconfiguration of existing market and regulatory structures. During the phase of more widespread diffusion, growth levels off to linear, then slows as the industry and market matures. The processes displace incumbent technologies/practices which decline, initially slowly, but then at an accelerating pace. Many related literatures identify three main levels with different characteristics, most generally termed *micro, meso* and *macro*.

Box TS.14 | Digitalisation

Digital technologies can promote large increases in energy efficiency through coordination and an economic shift to services, but they can also greatly increase energy demand because of the energy used in digital devices (*high confidence*). {Cross-Chapter Box 11 in Chapter 16, 16.2}

Digital devices, including servers, increase pressure on the environment due to the demand for rare metals and end-of-life disposal. The absence of adequate governance in many countries can lead to harsh working conditions and unregulated disposal of electronic waste. Digitalisation also affects firms' competitiveness, the demand for skills, and the distribution of, and access to resources. The existing digital divide, especially in developing countries, and the lack of appropriate governance of the digital revolution can hamper the role that digitalisation could play in supporting the achievement of stringent mitigation targets. At present, the understanding of both the direct and indirect impacts of digitalisation on energy use, carbon emissions and potential mitigation is limited (*medium confidence*).

The digital transformation is a megatrend that is fundamentally changing all economies and societies, albeit in very different ways depending on the level of development of a given country and on the nature of its economic system. Digital technologies have significant potential to contribute to decarbonisation due to their ability to increase energy and material efficiency, make transport and building systems less wasteful, and improve the access to services for consumers and citizens. Yet, if left unmanaged, the digital transformation will probably increase energy demand, exacerbate inequities and the concentration of power, leaving developing economies with less access to digital technologies behind, raise ethical issues, reduce labour demand and compromise citizens' welfare. Appropriate governance of the digital transformation can ensure that digitalisation works as an enabler, rather than as a barrier and further strain in decarbonisation pathways. Governance can ensure that digitalisation not only reduces GHG emissions intensity but also contributes to reducing absolute GHG emission, constraining run-away consumption. {Cross-Chapter Box 11 in Chapter 16, 16.2}

Digital technologies have the potential to reduce energy demand in all end-use sectors through steep improvements in energy efficiency. This includes material input savings and increased coordination as they allow the use of fewer inputs to perform a given task. Smart appliances and energy management, supported by choice architectures, economic incentives and social norms, effectively reduce energy demand and associated GHG emissions by 5–10% while maintaining equal service levels. Data centres can also play a role in energy-system management, for example by waste-heat utilisation where district heat systems are close by; temporal and spatial scheduling of electricity demand can provide about 6% of the total potential demand response. {5.5, Cross-Chapter Box 11, Table 1 in Chapter 16}

Digital technologies, analytics and connectivity consume large amounts of energy, implying higher direct energy demand and related carbon emissions. Global energy demand from digital appliances reached 7.14 EJ in 2018. The demand for computing services increased by 550% between 2010 and 2018 and is now estimated at 1% of global electricity consumption. Due to efficiency improvements, the associated energy demand increased only modestly, by about 6% from 2000 to 2018. {Box 9.5}

System-wide effects endanger energy and GHG-emission savings. Rising demand can diminish energy savings, and also produce run-away effects associated with additional consumption and GHG emissions if left unregulated. Savings are varied in smart and shared mobility systems, as ride-hailing increases GHG emissions due to deadheading, whereas shared pooled mobility and shared cycling reduce GHG emissions, as occupancy levels and/or weight per person kilometre transported improve. Systemic effects have wider boundaries of analysis and are more difficult to quantify and investigate but are nonetheless very relevant. Systemic effects tend to have negative impacts, but policies and adequate infrastructures and choice architectures can help manage and contain these. {5.3, 5.4, 5.6}

TS.7 Mitigation in the Context of Sustainable Development

Accelerating climate mitigation *in the context of sustainable development* involves not only expediting the pace of change but also addressing the underlying drivers of vulnerability and emissions. Addressing these drivers can enable diverse communities, sectors, stakeholders, regions and cultures to participate in just, equitable and inclusive processes that improve the health and well-being of people and the planet. Looking at climate change from a justice perspective also means placing the emphasis on: (i) the protection of vulnerable populations from the impacts of climate change, (ii) mitigating the effects of low-carbon transformations, and (iii) ensuring an equitable decarbonised world (*high confidence*). {17.1}

The SDG framework[33] can serve as a template to evaluate the long-term implications of mitigation on sustainable development and vice versa (*high confidence*). Understanding the co-benefits and trade-offs associated with mitigation is key to understanding how societies prioritise among the various sectoral policy options (*medium confidence*). Areas with anticipated trade-offs include food and biodiversity, energy affordability/access, and mineral-resource extraction. Areas with anticipated co-benefits include health, especially regarding air pollution, clean energy access and water availability. The possible implementation of the different sectoral mitigation options therefore depends on how societies prioritise mitigation versus other products and services: not least, how societies prioritise food, material well-being, nature conservation and biodiversity protection, as well as considerations such as their future dependence on CDR. Figure TS.29 summarises the assessment of where key synergies and trade-offs exist between mitigation options and the SDGs. (Figures TS.29 and TS.31, Table TS.7) {12.3, 12.4, 12.5, 12.6.1, Figures 3.39 and 17.1}

The beneficial and adverse impacts of deploying climate-change mitigation and adaptation responses are highly context-specific and scale-dependent. There are synergies and trade-offs between adaptation and mitigation as well as synergies and trade-offs with sustainable development (*high confidence*). Strong links also exist between sustainable development, vulnerability and climate risks, as limited economic, social and institutional resources often result in low adaptive capacities and high vulnerability, especially in developing countries. Resource limitations in these countries can similarly weaken the capacity for climate mitigation and adaptation. The move towards climate-resilient societies requires transformational or deep systemic change. This has important implications for countries' sustainable development pathways (*medium evidence*, *high agreement*). (Box TS.3, Figure TS.29) {4.5, Figure 4.9, 17.3.3}

Many of the potential trade-offs between mitigation and other sustainable development outcomes depend on policy design and can be compensated or avoided with additional policies and investments, or through policies that integrate mitigation with other SDGs (*high confidence*). Targeted SDG policies and investments, for example, in the areas of healthy nutrition, sustainable consumption and production, and international collaboration, can support climate change mitigation policies and resolve or alleviate trade-offs. Trade-offs can also be addressed by complementary policies and investments, as well as through the design of cross-sectoral policies integrating mitigation with the SDGs, and in particular: good health and well-being (SDG 3), zero hunger and nutrition (SDG 2), responsible consumption and production (SDG 12), reduced inequalities (SDG 10), and life on land (SDG 15). (Figures TS.29 and TS.30) {3.7}

***Decent living standards*, which encompasses many SDG dimensions, are achievable at lower energy use than previously thought (*high confidence*).** Mitigation strategies that focus on lowering demand for energy and land-based resources exhibit reduced trade-offs and negative consequences for sustainable development relative to pathways involving either high emissions and climate impacts or pathways with high consumption and emissions that are ultimately compensated by large quantities of BECCS. Figure TS.30 illustrates how, in the case of pathways limiting warming to 1.5°C (>67%), sustainable development policies can lead to overall benefits compared to mitigation policies alone. (Figures TS.22 and TS.30) {3.7, 5.2}

The timing of mitigation actions and their effectiveness will have significant consequences for broader sustainable development outcomes in the longer term (*high confidence*). Ambitious mitigation can be considered a precondition for achieving the SDGs. {3.7}

Adopting coordinated cross-sectoral approaches to climate mitigation can target synergies and minimise trade-offs, both between sectors and between sustainable development objectives (*high confidence*). This requires integrated planning using multiple-objective-multiple-impact policy frameworks. Strong inter-dependencies and cross-sectoral linkages create both opportunities for synergies and need to address trade-offs related to mitigation options and technologies. This can only be done if coordinated sectoral approaches to climate change mitigation policies are adopted that mainstream these interactions and ensure local people are involved in the development of new products, as well as production and consumption practices. For instance, there can be many synergies in urban areas between mitigation policies and the SDGs but capturing these depends on the overall planning of urban structures and on local integrated policies such as combining affordable housing and spatial planning with walkable urban areas, green electrification and clean renewable energy (*medium confidence*). Integrated planning and cross-sectoral alignment of climate change policies are also particularly evident in developing countries' NDCs under the Paris Agreement, where key priority sectors such as agriculture and energy are closely aligned with the proposed mitigation and adaptation actions and the SDGs. {12.6.2, Supplementary Material Table 17.SM.1, 17.3.3}

33 The 17 SDGs are at the heart of the UN 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015.

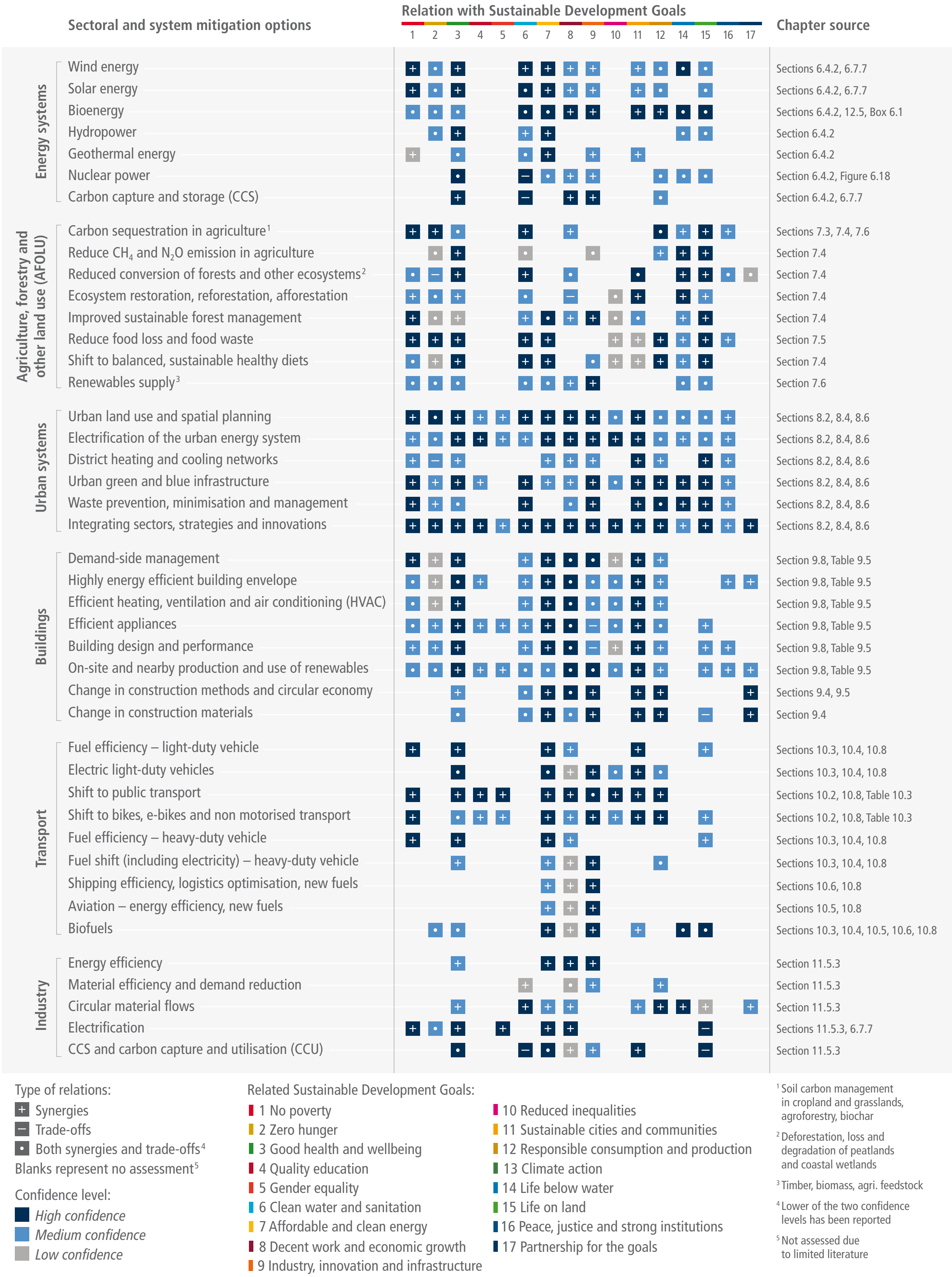


Figure TS.29 | Mitigation options have synergies with many Sustainable Development Goals (SDGs), but there are trade-offs associated with some options especially when implemented at scale.

Figure TS.29 (continued): Mitigation options have synergies with many Sustainable Development Goals (SDGs), but there are trade-offs associated with some options especially when implemented at scale. The synergies and trade-offs vary widely and depend on the context. Figure presents a summary of the chapter-level qualitative assessment of the synergies and trade-offs for selected mitigation options. Overlaps may exist in the mitigation options assessed and presented by sector and system, and interlinkages with the SDGs might differ depending on the application of that option by sector. Interactions of mitigation options with the SDGs are context-specific and dependent on the scale of implementation. For some mitigation options, these scaling and context-specific issues imply that there are both synergies and trade-offs in relation to specific SDGs. The SDGs are displayed as coloured squares. They indicate whether a synergy, trade-off, or both synergies and trade-offs exist between the SDG and the mitigation option. Confidence levels are indicated through the solidity of the squares. A solid square indicates high confidence, a partially filled square indicates medium confidence, and an outlined square indicates low confidence. The final column in the figure provides a line of sight to the chapters that provide details on context-specificity and scale of implementation. {6.3, 6.4, 6.7, 7.3, 7.4, 7.5, 7.6, 8.2, 8.4, 8.6, 9.4, 9.5, 9.8, Table 9.5, 10.3, 10.4, 10.5, 10.6, 10.8, 11.5, Table 10.3, 17.3, Figure 17.1, Supplementary Material Table 17.SM.1, Annex II.IV.12}

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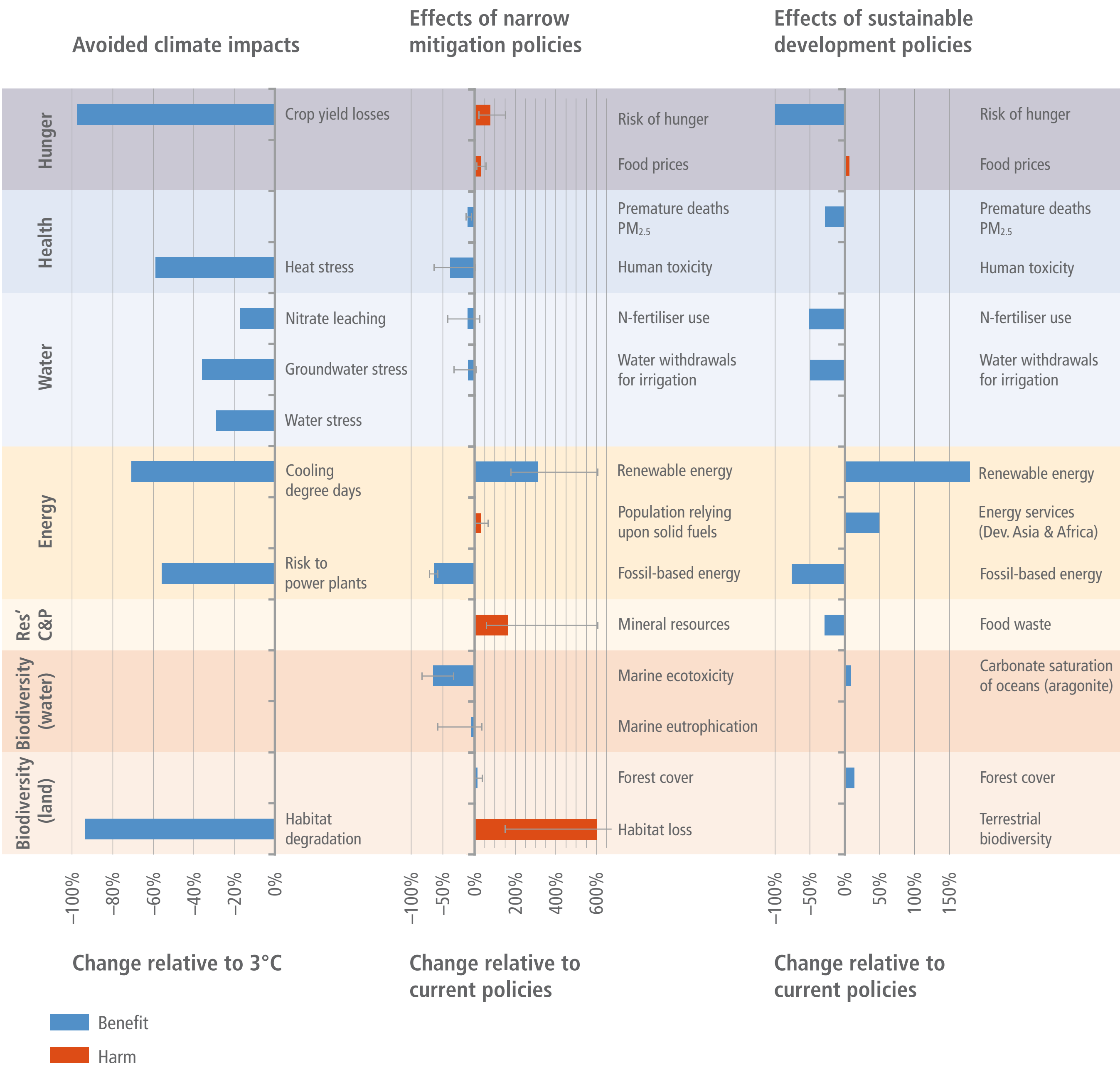

Figure TS.30 | Impacts on SDGs of mitigation limiting warming to 1.5°C (>50%) with narrow mitigation policies vs broader sustainable development policies. Left: benefits of mitigation from avoided impacts. **Middle:** sustainability co-benefits and trade-offs of narrow mitigation policies (averaged over multiple models). **Right:** sustainability co-benefits and trade-offs of mitigation policies integrating Sustainable Development Goals. Scale: 0% means no change compared to 3°C (left) or current policies (middle and right). Green values correspond to proportional improvements, red values to proportional worsening. Note: only the left panel considers climate impacts on sustainable development; the middle and right panels do not. 'Res' C&P' stands for Responsible Consumption and Production (SDG 12). {Figure 3.39}

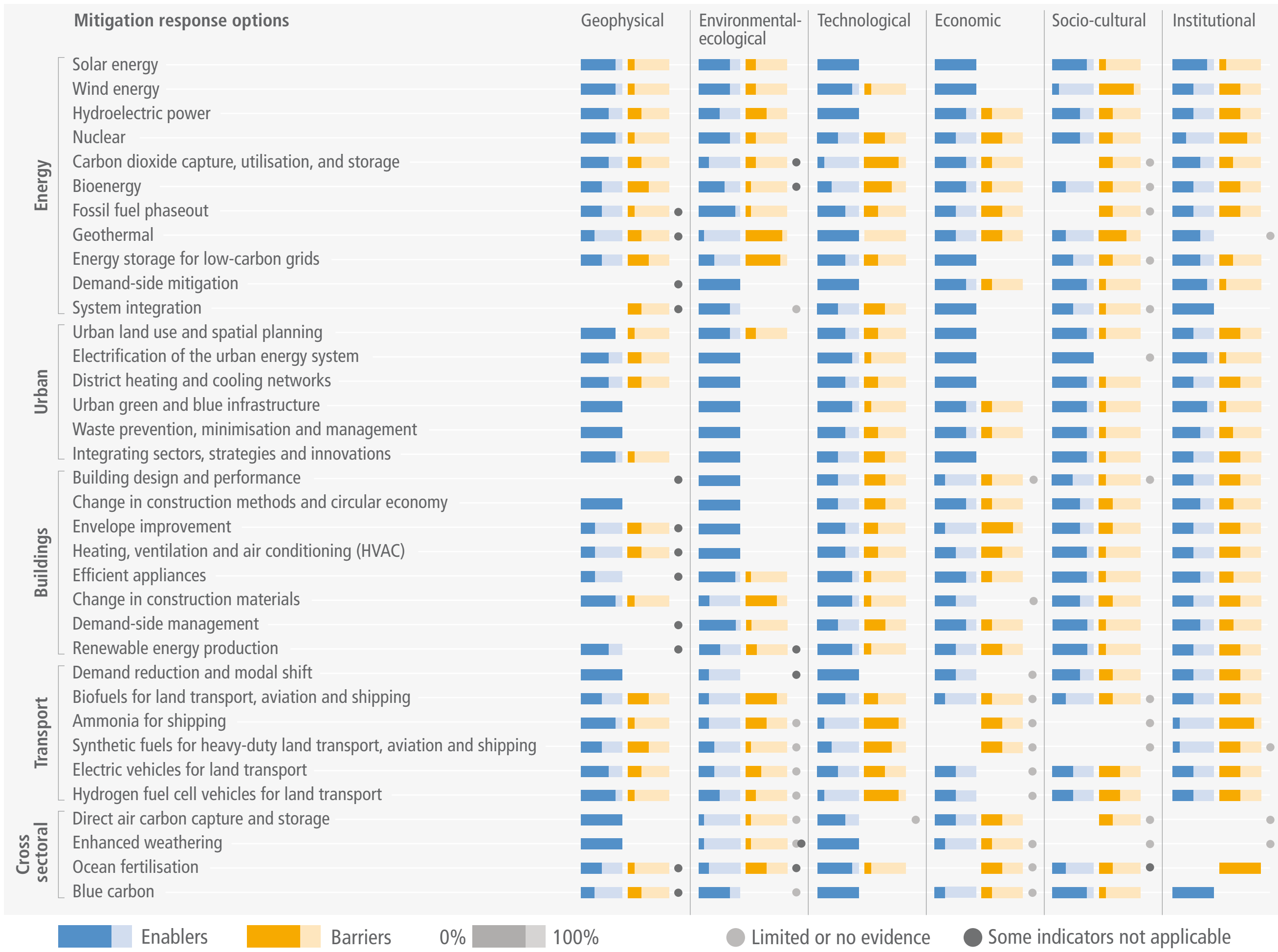

Figure TS.31 | Geophysical, environmental-ecological, technological, economic, socio-cultural and institutional factors can enable or act as barriers to the deployment of response options. Chapter-level assessment for selected mitigation options. Overlaps may exist in the mitigation options assessed and presented by sector and system, and feasibility might differ depending on the demarcation of that option in each sector. Chapters 6, 8, 9, 10, and 12 assess mitigation response options across six feasibility dimensions: *geophysical, environmental-ecological, technological, economic, socio-cultural and institutional*. AFOLU (Chapter 7) and industry (Chapter 11) are not included because of the heterogeneity of options in these sectors. For each dimension, a set of feasibility indicators was identified. Examples of indicators include impacts on land use, air pollution, economic costs, technology scalability, public acceptance and political acceptance (see Box TS.15, and Annex II.IV.11 for a detailed explanation). An indicator could refer to a barrier or an enabler to implementation, or could refer to both a barrier or an enabler, depending on the context, speed, and scale of implementation. Dark blue bars indicate the extent of enablers to deployment within each dimension. This is shown relative to the maximum number of possible enablers, as indicated by the light blue shading. Dark orange bars indicate the extent of barriers to deployment within each dimension. This is shown relative to the maximum number of possible barriers, as indicated by light orange shading. A light grey dot indicates that there is limited or no evidence to assess the option. A dark grey dot indicates that one of the feasibility indicators within that dimension is not relevant for the deployment of the option. The relevant sections in the underlying chapters include references to the literature on which the assessment is based and indicate whether the feasibility of an option varies depending on context (e.g., region), scale (e.g., small, medium or full scale), speed (e.g., implementation in 2030 versus 2050) and warming level (e.g., 1.5°C versus 2°C). {6.4, 8.5, 9.10, 10.8, 12.3, Annex II.IV.11}

The feasibility of deploying response options is shaped by barriers and enabling conditions across geophysical, environmental-ecological, technological, economic, socio-cultural, and institutional dimensions (*high confidence*). Accelerating the deployment of response options depends on reducing or removing barriers across these dimensions, as well on establishing and strengthening enabling conditions. Feasibility is context-dependent, and also depends on the scale and the speed of implementation. For example: the institutional, legal and administrative capacity to support deployment varies across countries; the feasibility of options that involve large-scale land-use changes is highly context-dependent; spatial planning has a higher potential in early stages of urban development; the geophysical potential of geothermal is site-specific; and cultural and local conditions may either inhibit or enable demand-side responses. Figure TS.31 summarises the assessment of barriers and enablers for a broad range of sector-specific, and cross-sectoral response options. (Box TS.15) {6.4, 7.4, 8.5, 9.10, 10.8, 12.3}

Alternative mitigation pathways are also associated with different feasibility challenges (*high confidence*). These challenges are multi-dimensional, context-dependent, malleable to policy and to technological and societal trends. They can also be reduced by putting in place appropriate enabling conditions. Figure TS.32 highlights the dynamic and transient nature of feasibility risks. These risks are transient and concentrated in the decades before mid-century. Figure TS.32 also illustrates how different

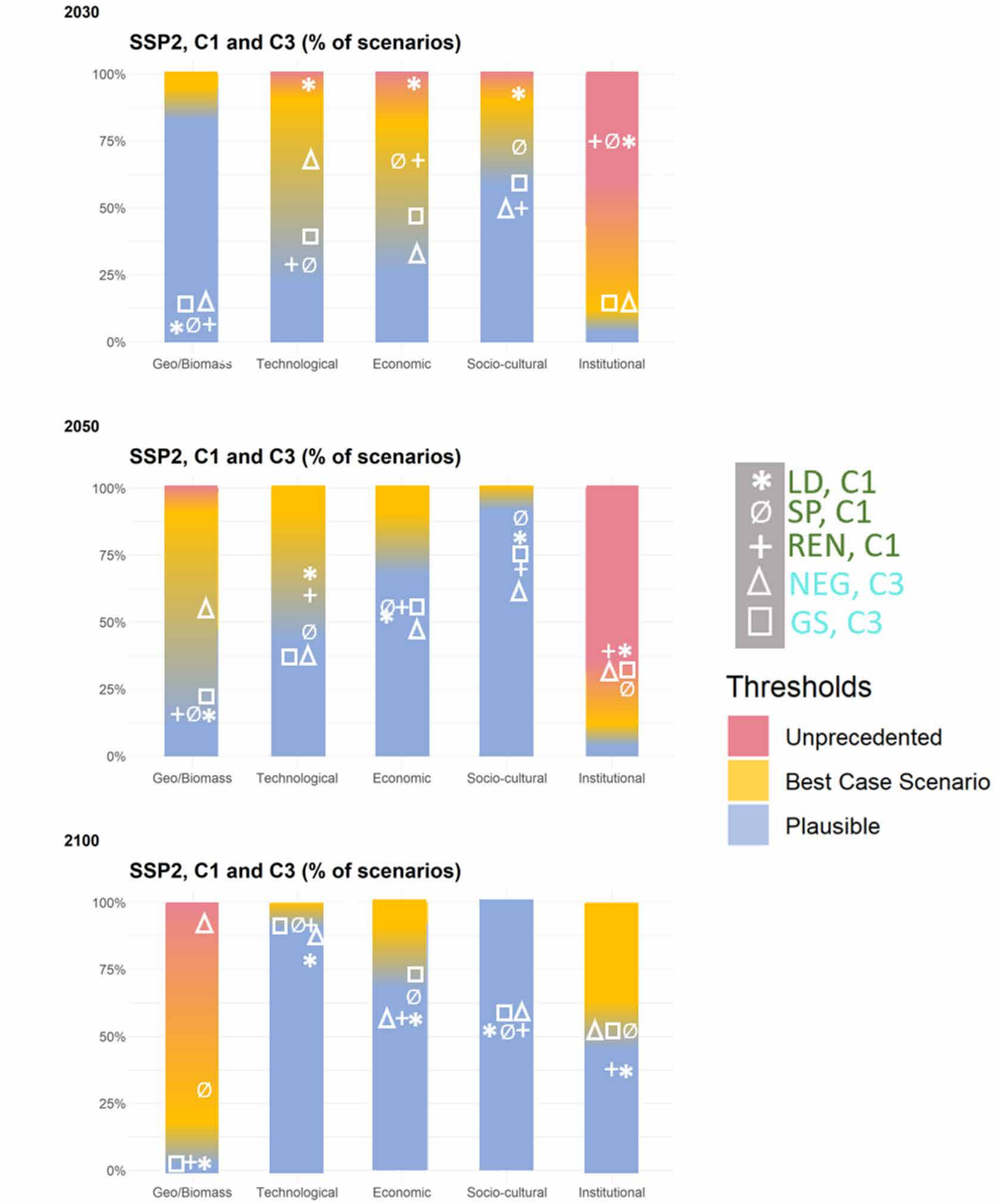

Figure TS.32 | The feasibility of mitigation scenarios. Figure TS.32 shows the proportion of scenarios in the AR6 scenarios database – falling within the warming level classifications C1 and C3 (**C1:** below 1.5°C (>50%), no or limited overshoot; **C3:** below 2°C (>67%)) – that exceed threshold values in 2030, 2050 and 2100 for five dimensions of feasibility (Boxes TS.5 and TS.15). The feasibility dimensions shown are: *geophysical, technological, economic, socio-cultural and institutional*. The thresholds shown are: (i) *plausible* – range of values based on past historical trends or other peer reviewed assessments; (ii) *best-case scenario* – range of values assuming major political support or technological breakthrough; (iii) *unprecedented* – values going beyond those observed or reported in peer-reviewed assessments. Overlayed are the Illustrative Mitigation Pathways consistent with SSP2 (LD, SP, Ren: C1 category; Neg, GS: C3 category). The positioning of the illustrative pathways is simply indicative of the general trade-offs over time and across the feasibility dimensions, it is not determined mathematically. (Box TS.5) {3.8} feasibility dimensions pose differentiated challenges: for example, institutional feasibility challenges are shown as *unprecedented* for a high proportion of scenarios, in line with the qualitative literature, but moving from 2030 to 2050 and 2100 these challenges decrease.

The feasibility challenges associated with mitigation pathways are predominantly *institutional* and *economic* rather than *technological* and *geophysical* (*medium confidence*). The rapid pace of technological development and deployment in mitigation scenarios is not incompatible with historical records, but rather, institutional capacity is a key limiting factor for a successful transition. Emerging economies appear to have highest feasibility challenges in the near to mid-term. This suggests a key role of policy and technology as enabling factors. (Figure TS.32) {3.8}

Pathways relying on a broad portfolio of mitigation strategies are more robust and resilient (*high confidence*). Portfolios of technological solutions reduce the feasibility risks associated with the low-carbon transition. (Figures TS.31 and TS.32, Box TS.15) {3.8}

Box TS.15 | A Harmonised Approach to Assessing Feasibility

The assessment of feasibility in this report aims to identify barriers and enablers to the deployment of mitigation options and pathways. The assessment organises evidence to support policy decisions, and decisions on actions, that would improve the feasibility of mitigation options and pathways by removing relevant barriers and by strengthening enablers of change.

The feasibility of mitigation response options

Mitigation response options are assessed against six dimensions of feasibility. Each dimension comprises a key set of indicators that can be evaluated by combining various strands of literature. {Annex II.IV.11, Table 6.1}

The assessment – undertaken by the sectoral chapters in this report – evaluates to what extent each indicator (listed in Box TS.15, Table.1) would be an enabler or barrier to implementation using a scoring methodology (described in detail in Annex II.IV.11). When appropriate, it is also indicated whether the feasibility of an option varies across context, scale, time and temperature goal. The resulting scores provide insight into the extent to which each feasibility dimension enables or inhibits the deployment of the relevant option. It also provides insight into the nature of the effort needed to reduce or remove barriers, thereby improving the feasibility of individual options. {Annex II.IV.11}

Box TS.15, Table.1 | Feasibility dimensions and indicators to assess the barriers and enablers of implementing mitigation options.

Feasibility dimension	Indicators
Geophysical feasibility	Availability of required geophysical resources: – Physical potential – Geophysical resource availability – Land use
Environmental-ecological feasibility	Impacts on environment: – Air pollution – Toxic waste, ecotoxicity and eutrophication – Water quantity and quality – Biodiversity
Technological feasibility	Extent to which the technology can be implemented at scale soon: – Simplicity – Technology scalability – Maturity and technology readiness
Economic feasibility	Financial costs and economic effects: – Costs now, in 2030 and in the long term – Employment effects and economic growth
Socio-cultural feasibility	Public engagement and support, and social impacts: – Public acceptance – Effects on health and well-being – Distributional effects
Institutional feasibility	Institutional conditions that affect the implementation of the response option: – Political acceptance – Institutional capacity and governance, cross-sectoral coordination – Legal and administrative capacity

Box TS.15 (continued)

The feasibility of mitigation scenarios

Scenarios provide internally consistent projections of emission-reduction drivers and help contextualise the scale of deployment and interactions of mitigation strategies. Recent research has proposed and operationalised frameworks for the feasibility assessment of mitigation scenarios. In this report the feasibility assessment of scenarios uses an approach that involves developing a set of multi-dimensional metrics capturing the *timing*, *disruptiveness* and the *scale* of the transformative change within five dimensions: *geophysical, technological, economic, socio-cultural and institutional,* as illustrated in Box TS.15, Figure 1.

More than 20 indicators were chosen to represent feasibility dimensions that could be related to scenario metrics. Thresholds of feasibility risks of different intensity were obtained through empirical analysis of historical data and assessed literature. Details of indicators, thresholds, and how they were applied is reported in Annex II.IV.11. {3.8}

Step 1 Feasibility dimensions	Step 2 Indicators	Step 3 Thresholds	Step 4 Aggregation (geometric mean)	
Geophysical Technological Economic Institutional Socio-cultural	For each dimension, selection of relevant indicators measuring decadal changes (among indicators available or computable based on scenario set)	Categorisation of level of feasibility concern for each indicator in each decade based on thresholds defined based on the literature and available empirical data – 3 high – 2 medium – 1 low	Aggregation within each dimension →	allows assessing **tradeoffs** among feasibility dimensions
			Aggregation across dimensions at different points in time →	allows assessing the **timing** and **disruptiveness** of the transformation
			Aggregation across dimensions and across time →	allows assessing the **scale** of the transformation

Box TS.15, Figure 1 | Steps involved in evaluating the feasibility of scenarios. {Figure 3.41} Note: in this approach the *environmental-ecological* dimension is captured through different scenarios' categories.

A wide range of factors have been found to enable sustainability transitions, ranging from technological innovations to shifts in markets, and from policies and governance arrangements to shifts in belief systems and market forces (*high confidence*). Many of these factors have come together in a co-evolutionary process that has unfolded globally, internationally and locally over several decades (*low evidence*, *high agreement*). Those same conditions that may serve to impede the transition (i.e., organisational structure, behaviour, technological lock-in) can also 'flip' to enable both the transition and the framing of sustainable development policies to create a stronger basis for policy support (*high confidence*). It is important to note that strong shocks to these systems, including accelerating climate change impacts, economic crises and political changes, may provide crucial openings for accelerated transitions to sustainable systems. For example, rebuilding more sustainably after an extreme event, or renewed public debate about the drivers of social and economic vulnerability to multiple stressors (*medium confidence*). {17.4}

While transition pathways will vary across countries it is anticipated that they will be challenging in many contexts (*high confidence*). Climate change is the result of decades of unsustainable production and consumption patterns, as well as governance arrangements and political economic institutions that lock-in resource-intensive development patterns (*high confidence*). Resource shortages, social divisions, inequitable distributions of wealth, poor infrastructure and limited access to advanced technologies and skilled human resources can constrain the options and capacity of developing countries to achieve sustainable and Just Transitions (*medium evidence*, *high agreement*) {17.1.1}. Reframing development objectives and shifting development pathways towards sustainability can help transform these patterns and practices, allowing space to transform unsustainable systems (*medium evidence*, *high agreement*). {1.6, Cross-Chapter Box 5 in Chapter 4, 17.1, 17.3}

The landscape of transitions to sustainable development is changing rapidly, with multiple transitions already underway. This creates the room to manage these transitions in ways that prioritise the needs of workers in vulnerable sectors (e.g., land, energy) to secure their jobs and maintain secure and healthy lifestyles (*medium evidence*, *high agreement*). {17.3.2}

Actions aligning sustainable development, climate mitigation and partnerships can support transitions. Strengthening different stakeholders' 'response capacities' to mitigate and adapt to a changing climate will be critical for a sustainable transition (*high confidence*). {17.1}

Accelerating the transition to sustainability will be enabled by explicit consideration being given to the principles of justice, equality and fairness (*high confidence*). {5.2, 5.4, 5.6, 13.2, 13.6, 13.8, 13.9,17.4}

Frequently Asked Questions

FAQ

Frequently Asked Questions

These Frequently Asked Questions have been extracted from the chapters and papers of the underlying report and are compiled here. When referencing specific FAQs, please reference the corresponding chapter or paper in the report from where the FAQ originated (e.g., FAQ 3.1 is part of Chapter 3).

Frequently Asked Questions (FAQs)

FAQ 1.1 | What is climate change mitigation?

Climate change mitigation refers to actions or activities that limit emissions of greenhouse gases (GHGs) from entering the atmosphere and/or reduce their levels in the atmosphere. Mitigation includes reducing the GHGs emitted from energy production and use (e.g., that reduces use of fossil fuels), and land use, and methods to mitigate warming, for example, by carbon sinks which remove emissions from the atmosphere through land-use or other (including artificial) mechanisms (Sections 12.3 and 14.4.5; see AR6 WGI for physical science, and WGIII Chapter 7 for AFOLU mitigation).

The ultimate goal of mitigation is to preserve a biosphere which can sustain human civilisation and the complex of ecosystem services which surround and support it. This means reducing anthropogenic GHG emissions towards net zero to limit the warming, with global goals agreed in the Paris Agreement. Effective mitigation strategies require an understanding of mechanisms that underpin release of emissions, and the technical, policy and societal options for influencing these.

FAQ 1.2 | Which greenhouse gases (GHGs) are relevant to which sectors?

Anthropogenic GHGs such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (e.g., hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride) are released from various sources. CO_2 makes the largest contribution to global GHG emissions, but some have extremely long atmospheric lifetimes extending to tens of thousands of years, such as F-gases (Chapter 2).

Different combinations of gases are emitted from different activities. The largest source of CO_2 is combustion of fossil fuels in energy conversion systems like boilers in electric power plants, engines in aircraft and automobiles, and in cooking and heating within homes and businesses (approximately 64% of emissions, Figure SPM.2). Fossil fuels are also a major source of methane (CH_4), the second biggest contributor to global warming. While most GHGs come from fossil fuel combustion, about one quarter comes from land-related activities like agriculture (mainly CH_4 and N_2O) and deforestation (mainly CO_2), with additional emissions from industrial processes (mainly CO_2, N_2O and F-gases), and municipal waste and wastewater (mainly CH_4) (Chapter 2). In addition to these emissions, black carbon – an aerosol that is, for example, emitted during incomplete combustion of fossil fuels – contributes to warming of the Earth's atmosphere, whilst some other short-lived pollutants temporarily cool the surface (IPCC AR6 WGI Section 6.5.4.3).

FAQ 1.3 | What is the difference between 'net zero emissions' and 'carbon neutrality'?

Annex I (Glossary) states that 'carbon neutrality and net zero CO_2 emissions are overlapping concepts' which 'can be applied at the global or sub-global scales (e.g., regional, national and sub-national)'. At the global scale the terms are equivalent. At sub-global scales, net zero CO_2 typically applies to emissions under direct control or territorial responsibility of the entity reporting them (e.g., a country, district or sector); while carbon neutrality is also applied to firms, commodities and activities (e.g., a service or an event) and generally includes emissions and removals beyond the entity's direct control or territorial responsibility, termed 'Scope 3' or 'value chain emissions' (Bhatia et al. 2011).

This means the emissions and removals that should be included are wider for 'neutrality' than for net zero goals, but also that offset mechanisms could be employed to help achieve neutrality through abatement beyond what is possible under the direct control of the entity. Rules and environmental integrity criteria are intended to ensure additionality and avoid double counting of offsets consistent with 'neutrality' claims (see 'carbon neutrality' and 'offset' in Glossary, for detail and a list of criteria).

While the term 'carbon' neutrality in this report is defined as referring specifically to CO_2 neutrality, use of this term in practice can be ambiguous, as some users apply it to neutrality of all GHG emissions. GHG neutrality means an entity's gross emissions of all GHG must be balanced by the removal of an equivalent amount of CO_2 from the atmosphere. This requires the selection of a suitable metric that aggregates emissions from non-CO_2 gases, such as the commonly used GWP100 metric (for a discussion of GHG metrics, see AR6 WGI Box 1.3 and Cross-Chapter Box 2 in Chapter 2 of this report).

Frequently Asked Questions (FAQs)

FAQ 2.1 | Are emissions still increasing or are they falling?

Global greenhouse gas (GHG) emissions continued to rise and reached 59 ± 6.6 $GtCO_2$-eq in 2019, although the rate of growth has fallen compared to the previous decade. However, emissions were higher than at any point in human history before. Emissions were around 12% and 54% higher than in 2010 and 1990, respectively. Average annual GHG emissions for 2009–2019 were higher compared to the periods 2000–2009 and 1990–1999, respectively. GHG emissions growth slowed since 2010: while average annual GHG emissions growth was 2.1% for 2000–2010, it was only 1.3% for 2010–2019. In order to stop the temperature increase, however, net emissions must be zero.

FAQ 2.2 | Are there countries that have reduced emissions and grown economically at the same time?

About 24 countries have reduced territorial CO_2 and GHG emissions for more than 10 years. Uncertainties in emission levels and changes over time prevent a precise assessment in some country cases. In the short observation period of 2010–2015, 43 out of 166 countries have achieved absolute decoupling of consumption-based CO_2 emissions from economic growth, which means that these countries experienced GDP growth while their emissions have stabilised or declined. A group of developed countries, such as some EU countries and the USA, and some developing countries, such as Cuba, have successfully achieved an absolute decoupling of consumption-based CO_2 emissions and GDP growth. Decoupling has been achieved at various levels of per capita income and per capita emissions. Overall, the absolute reduction in annual emissions achieved by some countries has been outweighed by growth in emissions elsewhere in the world.

FAQ 2.3 | How much time do we have to act to keep global warming below 1.5 degrees?

If global CO_2 emissions continue at current rates, the remaining carbon budget for keeping warming to 1.5°C will likely be exhausted before 2030. Between 1850 and 2019, total cumulative CO_2 emissions from the fossil fuel industry (FFI) and agriculture, forestry, and other land use (AFOLU) were 2400 (±240 $GtCO_2$). Of these, about 410 ± 30 $GtCO_2$ were added since 2010. This is about the same size as the remaining carbon budget for keeping global warming to 1.5°C and between one-third and one-half of the 1150 ± 220 (1350, 1700) $GtCO_2$ for limiting global warming below 2°C with a 67% (50%, 33%) probability, respectively (Canadell et al. 2021). At current (2019) rates of emissions, it would only take 8 (2–15) and 25 (18–35) years to emit the equivalent amount of CO_2 for a 67th percentile 1.5°C and 2°C remaining carbon budget, respectively. This highlights the dependence of 1.5°C pathways on the availability of substantial CO_2 removal capacities, as discussed in Chapters 3, 4, and 12, but also Section 2.7 of this chapter.

Frequently Asked Questions (FAQs)

FAQ 3.1 | Is it possible to stabilise warming without net negative CO_2 and GHG emissions?

Yes. Achieving net zero CO_2 emissions and sustaining them into the future is sufficient to stabilise the CO_2-induced warming signal which scales with the cumulative net amount of CO_2 emissions. At the same time, the warming signal of non-CO_2 GHGs can be stabilised or reduced by declining emissions that lead to stable or slightly declining concentrations in the atmosphere. For short-lived GHGs with atmospheric lifetimes of less than 20 years, this is achieved when residual emissions are reduced to levels that are lower than the natural removal of these gases in the atmosphere. Taken together, mitigation pathways that bring CO_2 emissions to net zero and sustain it, while strongly reducing non-CO_2 GHGs to levels that stabilise or decline their aggregate warming contribution, will stabilise warming without using net negative CO_2 emissions and with positive overall GHG emissions when aggregated using GWP-100. A considerable fraction of pathways that limit warming to 1.5°C (>50%) with no or limited overshoot and limit warming to 2°C (>67%), respectively, do not or only marginally (<10 $GtCO_2$ cumulative until 2100) deploy net negative CO_2 emissions (26% and 46%, respectively) and do not reach net zero GHG emissions by the end of the century (48% and 70%, respectively). This is no longer the case in pathways that return warming to 1.5°C (>50%) after a high overshoot (typically >0.1°C). All of these pathways deploy net negative emissions on the order of 360 (60–680) $GtCO_2$ (median and 5–95th percentile) and 87% achieve net negative GHGs emissions in AR6 GWP-100 before the end of the century. Hence, global net negative CO_2 emissions, and net zero or net negative GHG emissions, are only needed to decline, not to stabilise global warming. The deployment of carbon dioxide removal (CDR) is distinct from the deployment of net negative CO_2 emissions, because it is also used to neutralise residual CO_2 emissions to achieve and sustain net zero CO_2 emissions. CDR deployment can be considerable in pathways without net negative emissions and all pathways limiting warming to 1.5°C use it to some extent.

FAQ 3.2 | How can net zero emissions be achieved and what are the implications of net zero emissions for the climate?

Halting global warming in the long term requires, at a minimum, that no additional CO_2 emissions from human activities are added to the atmosphere (i.e., CO_2 emissions must reach 'net' zero). Given that CO_2 emissions constitute the dominant human influence on global climate, global net zero CO_2 emissions are a prerequisite for stabilising warming at any level. However, CO_2 is not the only greenhouse gas that contributes to global warming and reducing emissions of other greenhouse gases (GHGs) alongside CO_2 towards net zero emissions of all GHGs would lower the level at which global temperature would peak. The temperature implications of net zero GHG emissions depend on the bundle of gases that is being considered, and the emissions metric used to calculate aggregated GHG emissions and removals. If reached and sustained, global net zero GHG emissions using the 100-year Global Warming Potential (GWP-100) will lead to gradually declining global temperature.

Not all emissions can be avoided. Achieving net zero CO_2 emissions globally therefore requires deep emissions cuts across all sectors and regions, along with active removal of CO_2 from the atmosphere to balance remaining emissions that may be too difficult, too costly, or impossible to abate at that time. Achieving global net zero GHG emissions would require, in addition, deep reductions of non-CO_2 emissions and additional CO_2 removals to balance remaining non-CO_2 emissions.

Not all regions and sectors must reach net zero CO_2 or GHG emissions individually to achieve global net zero CO_2 or GHG emissions, respectively; instead, positive emissions in one sector or region can be compensated by net negative emissions from another sector or region. The time each sector or region reaches net zero CO_2 or GHG emissions depends on the mitigation options available, the cost of those options, and the policies implemented (including any consideration of equity or fairness). Most modelled pathways that *likely* limit warming to 2°C (>67%) above pre-industrial levels and below use land-based CO_2 removal such as afforestation/reforestation and BECCS to achieve net zero CO_2 and net zero GHG emissions even while some CO_2 and non-CO_2 emissions continue to occur. Pathways with more demand-side interventions that limit the amount of energy we use, or where the diet that we consume is changed, can achieve net zero CO_2, or net zero GHG emissions with less carbon dioxide removal (CDR). All available studies require at least some kind of carbon dioxide removal to reach net zero; that is, there are no studies where absolute zero GHG or even CO_2 emissions are reached by deep emissions reductions alone.

Total GHG emissions are greater than emissions of CO_2 only; reaching net zero CO_2 emissions therefore occurs earlier, by up to several decades, than net zero GHG emissions in all modelled pathways. In most modelled pathways that *likely* limit warming to 2°C (>67%) above pre-industrial levels and below in the most cost-effective way, the agriculture, forestry and other land-use (AFOLU) and energy supply sectors reach net zero CO_2 emissions several decades earlier than other sectors; however, many pathways show much reduced, but still positive, net GHG emissions in the AFOLU sector in 2100.

FAQ 3.3 | How plausible are high emissions scenarios, and how do they inform policy?

IAMs are used to develop a wide range of scenarios describing future trajectories for greenhouse gas emissions based on a wide set of assumptions regarding socio-economic development, technological changes, political development and climate policy. Typically, the IAM-based scenarios can be divided into (i) reference scenarios (describing possible trajectories in the absence of new stringent climate policies) and (ii) mitigation scenarios (describing the impact of various climate policy assumptions). Reference scenarios typically result in high emissions and, subsequently, high levels of climate change (in the order of 2.5°C–4°C during the 21st century). The purpose of such reference scenarios is to explore the consequences of climate change and act as a reference for mitigation scenarios. The possible emission levels for reference scenarios diverge from stabilising and even slowly declining emissions (e.g., for current policy scenarios or SSP1) to very high emission levels (e.g., SSP5 and RCP8.5). The latter leads to nearly 5°C of warming by the end of the century for medium climate sensitivity. Hausfather and Peters (2020) pointed out that since 2011, the rapid development of renewable energy technologies and emerging climate policy have made it considerably less likely that emissions could end up as high as RCP8.5. This means that reaching emissions levels as high as RCP8.5 has become less likely. Still, high emissions cannot be ruled out for many reasons, including political factors and, for instance, higher than anticipated population and economic growth. Climate projections of RCP8.5 can also result from strong feedbacks of climate change on (natural) emission sources and high climate sensitivity (AR6 WGI Chapter 7). Therefore, their median climate impacts might also materialise while following a lower emission path (e.g., Hausfather and Betts 2020). All in all, this means that high-end scenarios have become considerably less likely since AR5 but cannot be ruled out. High-end scenarios (like RCP8.5) can be very useful to explore high-end risks of climate change but are not typical 'business-as-usual' projections and should therefore not be presented as such.

Frequently Asked Questions (FAQs)

FAQ 4.1 | What is to be done over and above countries' existing pledges under the Paris Agreement to keep global warming well below 2°C?

Current pledges and efforts under the PA aimed at keeping global warming below 2°C are not enough, falling short by 14 to 23 $GtCO_2$-eq (Cross-Chapter Box 4 in this Chapter). There is a further shortfall of about 4 to 7 $GtCO_2$-eq in 2030 if the conditions are not fulfilled for those Parties that have made their pledges with conditions for support (Section 4.2.2.3). To cover up for these shortfalls will require taking actions across all sectors that can substantially reduce GHG emissions. Examples of such actions include shifting to low- or zero-emission power generation, such as renewables; changing food systems, such as diet changes away from land-intensive animal products; electrifying transport and developing 'green infrastructure', such as building green roofs, or improving energy efficiency by smart urban planning, which will change the layout of many cities. Because these different actions are connected, it means all relevant companies, industries and stakeholders would need to be involved to increase the support and chance of successful implementation (Section 4.2.5). The deployment of low-emission technology depends upon economic conditions (e.g., employment generation or capacity to mobilise investment), but also on social/cultural conditions (e.g., awareness and acceptability) and institutional conditions (e.g., political support and understanding), and the provision of relevant enabling conditions (Section 4.4.1). Encouraging stronger and more ambitious climate action by non-government and sub-national stakeholders, as well as international cooperative initiatives (ICIs) could make significant contributions to emissions reduction (Section 4.2.3).

FAQ 4.2 | What is to be done in the near term to accelerate mitigation and shift development pathways?

Increasing speed of implementation, breadth of action across all sectors of the economy, and depth of emission reduction faces important obstacles, that are rooted in the underlying structure of societies (Section 4.2.7). Addressing these obstacles amounts to shifting away from existing developmental trends (i.e., shifting development pathways, Cross-Chapter Box 5). This can be done by strengthening governance and institutional capacity, aligning technology and innovation systems with low-carbon development, facilitating behaviour change and providing adequate finance within the context of multi-objective policy packages and sequences (Section 4.4.1). Shifting development pathways towards sustainability broadens the scope for, and is thus a complement to, accelerated mitigation (Section 4.3).

FAQ 4.3 | Is it possible to accelerate mitigation in the near term while there are so many other development priorities? (Education, health, employment, etc.)

It is possible to accelerate mitigation while addressing other developmental priorities by implementing measures that simultaneously address both climate and development goals. Casting mitigation in the broader context of development pathways provides additional opportunities to articulate both (Section 4.3.1.4). Policies such as progressive taxation, investment in public transport, regulatory transparency, commitment to multilateral environmental governance, fiscal incentives for private investments, international technology development and transfer initiatives, and risk disclosure and efforts to improve underlying enabling conditions (improving governance and institutional capacity, fostering behavioural change and technological innovation, and provision of finance) address multiple objectives beyond mitigation, such as job creation, macroeconomic stability, economic growth, public health and welfare, providing energy access, providing formal housing, and providing mobility. How we manage our land and agriculture, growing cities, transport needs, our industries, and the way people are trained and employed all impact on GHG emissions and the options we have to reduce them. In turn, reducing GHG emissions can also contribute to reducing poverty, preventing hunger, improving health and wellbeing, and providing clean water and clean energy. Implementing right policies and investments can help to address the challenges of how to reduce emissions without constraining development. For example, in land use, widespread planting of a single tree species or crops for bioenergy (organic matter turned into renewable energy) could affect food and water supplies. Therefore, if bioenergy is to be relied upon to offset emissions, the right policies and investments are needed (see also Chapter 17).

Frequently Asked Questions (FAQs)

FAQ 5.1 | What can every person do to limit warming to 1.5°C?

People can be educated through knowledge transfer so they can act in different roles, and in each role everyone can contribute to limit global warming to 1.5°C. Citizens with enough knowledge can organise and put political pressure on the system. Role models can set examples to others. Professionals (e.g., engineers, urban planners, teachers, researchers) can change professional standards in consistency with decarbonisation; for example urban planners and architects can design physical infrastructures to facilitate low-carbon mobility and energy use by making walking and cycling safe for children. Rich investors can make strategic plans to divest from fossils and invest in carbon-neutral technologies. Consumers, especially those in the top 10% of the world population in terms of income, can limit consumption, especially in mobility, and explore the good life consistent with sustainable consumption.

Policymakers support individual actions in certain contexts, not only by economic incentives, such as carbon pricing, but also by interventions that understand complex decision-making processes, habits, and routines. Examples of such interventions include, but are not limited to, choice architectures and nudges that set green options as default, shift away from cheap petrol or gasoline, increasing taxes on carbon-intensive products, or substantially tightening regulations and standards to support shifts in social norms, and thus can be effective beyond the direct economic incentive.

FAQ 5.2 | How does society perceive transformative change?

Humaninduced global warming, together with other global trends and events, such as digitalisation and automation, and the COVID-19 pandemic, induce changes in labour markets, and bring large uncertainty and ambiguity. History and psychology reveal that societies can thrive in these circumstances if they openly embrace uncertainty on the future and try out ways to improve life. Tolerating ambiguity can be learned, for example by interacting with history, poetry and the arts. Sometimes religion and philosophy also help.

As a key enabler, novel narratives created in a variety of ways, such as by advertising, images and the entertainment industry, help to break away from the established meanings, values and discourses and the status quo. For example, discourses that frame comfortable public transport services to avoid stress from driving cars on busy, congested roads help avoid car driving as a status symbol and create a new social norm to shift to public transport. Discourses that portray plant-based protein as healthy and natural promote and stabilise particular diets. Novel narratives and inclusive processes help strategies to overcome multiple barriers. Case studies demonstrate that citizens support transformative changes if participatory processes enable a design that meets local interests and culture. Promising narratives specify that even as speed and capabilities differ, humanity embarks on a joint journey towards well-being for all and a healthy planet.

FAQ 5.3 | Is demand reduction compatible with growth of human well-being?

There is a growing realisation that mere monetary value of income growth is insufficient to measure national welfare and individual well-being. Hence, any action towards climate change mitigation is best evaluated against a set of indicators that represent a broader variety of needs to define individual well-being, macroeconomic stability, and planetary health. Many solutions that reduce primary material and fossil energy demand, and thus reduce GHG emissions, provide better services to help achieve well-being for all.

Economic growth measured by total or individual income growth is a main driver of GHG emissions. Only a few countries with low economic growth rates have reduced both territorial and consumption-based GHG emissions, typically by switching from fossil fuels to renewable energy and by reduction in energy use and switching to low/zero carbon fuels, but until now at insufficient rates and levels for stabilising global warming at 1.5°C. High deployment of low/zero carbon fuels and associated rapid reduction in demand for and use of coal, gas, and oil can further reduce the interdependence between economic growth and GHG emissions.

Frequently Asked Questions

FAQ 6.1 | Will energy systems that emit little or no CO_2 be different than those of today?

Low-carbon energy systems will be similar to those of today in that they will provide many of the same services as today – for example, heating and cooling homes, travelling to work or on vacation, transporting goods and services, and powering manufacturing. But future energy systems may be different in that people may also demand new services that aren't foreseen today, just as people now use energy for many information technology uses that were not anticipated 50 years ago. More importantly, low-carbon energy systems will be different in the way that energy is produced, transformed, and used to provide these services. In the future, almost all electricity will be produced from sources that emit little or no CO_2, such as solar power, wind power, nuclear power, bioenergy, hydropower, geothermal power, or fossil energy in which the CO_2 is captured and stored. Electricity, hydrogen, and bioenergy will be used in many situations where fossil fuels are used today, for example, in cars or heating homes. And energy is likely to be used more efficiently than today, for example, through more efficient cars, trucks, and appliances, buildings that use very little energy, and greater use or public transportation. All of these changes may require new policies, institutions, and even new ways for people to live their lives. And fundamental to all of these changes is that low-carbon energy systems will use far less fossil fuel than today.

FAQ 6.2 | Can renewable sources provide all the energy needed for energy systems that emit little or no CO_2?

Renewable energy technologies harness energy from natural sources that are continually replenished, for example, from the sun (solar energy), the wind (wind energy), plants (bioenergy), rainfall (hydropower), or even the ocean. The energy from these sources exceeds the world's current and future energy needs many times. But that does not mean that renewable sources will provide all energy in future low-carbon energy systems. Some countries have a lot of renewable energy, whereas others do not, and other energy sources, such as nuclear power or fossil energy in which CO_2 emissions are captured and stored (carbon dioxide capture and storage, or CCS) can also contribute to low-carbon energy systems. The energy from sources such as solar energy, wind energy, and hydropower can vary throughout the day or over seasons or years. All low-carbon energy sources have other implications for people and countries, some of which are desirable, for example, reducing air pollution or making it easy to provide electricity in remote locations, and some of which are undesirable, for example decreasing biodiversity or mining of minerals to produce low-emissions technologies. For all of these reasons, it is unlikely that all low-carbon energy systems around the world will rely entirely on renewable energy sources.

FAQ 6.3 | What are the most important steps to decarbonise the energy system?

To create a low-carbon energy system, emissions must be reduced across all parts of the system, and not just one or two. This means, for example, reducing the emissions from producing electricity, driving cars, hauling freight, heating and cooling buildings, powering data centres, and manufacturing goods. There are more opportunities to reduce emissions over the next decade in some sectors compared to others. For example, it is possible to substantially reduce electricity emissions over the next decade by investing in low-carbon electricity sources, while at the same time halting the construction of new coal-fired power plants, retiring existing coal-fired power plants or retrofitting them with carbon capture and storage (CCS), and limiting the construction of new gas-fired power plants. There are also opportunities to increase the number of electric cars, trucks, and other vehicles on the road, or to use electricity rather than natural gas or coal to heat homes. And across the whole energy system, emissions can be reduced by using more efficient technologies. While these and other actions will be critical over the coming decade, it is also important to remember that the low-carbon energy transition needs to extend for many decades into the future to limit warming. This means that it is important now to improve and test options that could be useful later on, for example, producing hydrogen from low-carbon sources or producing bioenergy from crops that require less land than today.

Frequently Asked Questions (FAQs)

FAQ 7.1 | Why is the Agriculture, Forestry and Other Land Uses (AFOLU) sector unique when considering GHG mitigation?

There are three principal reasons that make the AFOLU sector unique in terms of mitigation:

In contrast to other sectors, AFOLU can facilitate mitigation in several different ways. Specifically, AFOLU can (i) reduce emissions as a sector in its own right, (ii) remove meaningful quantities of carbon from the atmosphere and relatively cheaply, and (iii) provide raw materials to enable mitigation within other sectors, such as energy, industry or the built environment.

The emissions profile of AFOLU differs from other sectors, with a greater proportion of non-CO_2 gases (N_2O and CH_4). The impacts of mitigation efforts within AFOLU can vary according to which gases are targeted, as a result of the differing atmospheric lifetime of the gases and differing global temperature responses to the accumulation of the specific gases in the atmosphere.

In addition to tackling climate change, AFOLU mitigation measures have capacity, where appropriately implemented, to help address some critical, wider challenges, as well as contributing to climate change adaptation. AFOLU is inextricably linked with some of the most serious challenges that are suggested to have ever faced humanity, such as large-scale biodiversity loss, environmental degradation and the associated consequences. As AFOLU concerns land management and utilises a considerable portion of the Earth's terrestrial area, the sector greatly influences soil, water and air quality, biological and social diversity, the provision of natural habitats, and ecosystem functioning, consequently impacting many SDGs.

FAQ 7.2 | What AFOLU measures have the greatest economic mitigation potential?

Economic mitigation potential refers to the mitigation estimated to be possible at an annual cost of up to USD100 tCO_2^{-1} mitigated. This cost is deemed the price at which society is willing to pay for mitigation and is used as a proxy to estimate the proportion of technical mitigation potential that could realistically be implemented. Between 2020 and 2050, measures concerning forests and other ecosystem are estimated to have an average annual mitigation potential of 7.3 (3.9–13.1) $GtCO_2$-eq yr^{-1} at USD100 tCO_2^{-1}. At the same cost, agricultural measures are estimated to have a potential of 4.1 (1.7–6.7) $GtCO_2$-eq yr^{-1}. Emerging technologies, such as CH_4 vaccines and inhibitors, could sustainably increase agricultural mitigation potential in future. The diverted production effects of changes in demand (reduced food losses, diet changes and improved and enhanced wood products use), is estimated to have an economic potential of 2.2 (1.1–3.6) $GtCO_2$-eq yr^{-1}. However, cost forms only one constraint to mitigation, with realisation of economic potential dependent on multiple context-specific environmental and socio-cultural factors.

FAQ 7.3 | What are potential impacts of large-scale establishment of dedicated bioenergy plantations and crops and why is it so controversial?

The potential of bioenergy with carbon capture and storage (BECCS) remains a focus of debate with several studies evaluating the level at which BECCS could be sustainably implemented, published since AR5. BECCS involves sequestering carbon through plant growth (i.e., in trees or crops) and capturing the carbon generated when this biomass is processed for power or fuel. The captured carbon then requires long-term storage in for example, geological, terrestrial or ocean reservoirs, or in products. While appearing to create a net removal of carbon from the atmosphere, BECCS requires land, water and energy which can create adverse side effects at scale. Controversy has arisen because some of the models calculating the energy mix required to keep the temperature to 1.5°C have included BECCS at very large scales as a means of both providing energy and removing carbon from the atmosphere to offset emissions from industry, power, transport or heat. For example, studies have calculated that for BECCS to achieve 11.5 $GtCO_2$-eq per year of carbon removal in 2100, as envisaged in one scenario, 380–700 Mha or 25–46% of all the world's arable and cropland would be needed. In such a situation, competition for agricultural land seriously threatens food production and food security, while also impacting biodiversity, water and soil quality, and landscape aesthetic value. More recently however, the scenarios for BECCS have become much more realistic, though concerns regarding impacts on food security and the environment remain, while the reliability of models is uncertain due to methodological flaws. Improvements to models are required to better capture wider environmental and social impacts of BECCS in order to ascertain its sustainable contribution in emissions pathways. Additionally, the opportunity for other options that could negate very large-scale deployment of BECCS, such as other carbon dioxide removal measures or more stringent emission reductions in other sectors, could be explored within models.

Frequently Asked Questions (FAQs)

FAQ 8.1 | Why are urban areas important to global climate change mitigation?

Over half of the world's population currently resides in urban areas – a number forecasted to increase to nearly 70% by 2050. Urban areas also account for a growing proportion of national and global emissions, depending on emissions scope and geographic boundary. These trends are projected to grow in the coming decades; in 2100, some scenarios show the urban share of global emissions above 80%, with 63% being the minimum for any scenario (with the shares being in different contexts of emissions reduction or increase) (Sections 8.3.3 and 8.3.4). As such, urban climate change mitigation considers the majority of the world's population, as well as some of the key drivers of global emissions. In general, emissions scenarios with limited outward urban land expansion are also associated with a smaller rise in global temperature (Section 8.3.4).

The urban share of global emissions and its projected growth stem in part from urban carbon lock-in – that is, the path dependency and inertia of committed emissions through the long lifespan of urban layout, infrastructures, and behaviour. As such, urban mitigation efforts that address lock-in can significantly reduce emissions (Section 8.4.1). Electrification of urban energy systems, in tandem with implementing multiple urban-scale mitigation strategies, could reduce urban emissions by 90% by 2050 – thereby significantly reducing global emissions (Section 8.3.4). Urban areas can also act as points of intervention to amplify synergies and co-benefits for accomplishing the Sustainable Development Goals (Section 8.2).

FAQ 8.2 | What are the most impactful options cities can take to mitigate urban emissions, and how can these be best implemented?

The most impactful urban mitigation plans reduce urban GHG emissions by considering the long lifespan of urban layout and urban infrastructures (Sections 8.4.1 and 8.6). Chapter 8 identifies three overarching mitigation strategies with the largest potential to decrease current, and avoid future, urban emissions: (i) reducing or changing urban energy and material use towards more sustainable production and consumption across all sectors including through spatial planning and infrastructure that supports compact, walkable urban form (Section 8.4.2); (ii) decarbonise through electrification of the urban energy system, and switch to net-zero-emissions resources (i.e., low-carbon infrastructure) (Section 8.4.3); and (iii) enhance carbon sequestration through urban green and blue infrastructure (e.g., green roofs, urban forests and street trees), which can also offer multiple co-benefits like reducing ground temperatures and supporting public health and well-being (Section 8.4.4). Integrating these mitigation strategies across sectors, geographic scales, and levels of governance will yield the greatest emissions savings (Sections 8.4 and 8.5).

A city's layout, patterns, and spatial arrangements of land use, transportation systems, and built environment (urban form), as well as its state and form(s) of development (urban growth typology), can inform the most impactful emissions savings 'entry points' and priorities for urban mitigation strategies (Sections 8.4.2 and 8.6). For rapidly growing and emerging urban areas, there is the opportunity to avoid carbon lock-in by focusing on urban form that promotes low-carbon infrastructure and enables low-impact behaviour facilitated by co-located medium to high densities of jobs and housing, walkability, and transit-oriented development (Sections 8.6.2 and 8.6.3). For established cities, strategies include electrification of the grid and transport, and implementing energy efficiency across sectors (Section 8.6.1).

FAQ 8.3 | How do we estimate global emissions from cities, and how reliable are the estimates?

There are two different emissions estimation techniques applied, individually or in combination, to the four frameworks outlined in Section 8.1.6.2 to estimate urban GHG emissions: 'top-down' and 'bottom-up'. The top-down technique uses atmospheric GHG concentrations and atmospheric modelling to estimate direct (scope 1) emissions (see Glossary). The bottom-up technique estimates emissions using local activity data or direct measurements such as in smokestacks, traffic data, energy consumption information, and building use. Bottom-up techniques will often include indirect emissions (see Glossary) from purchased electricity (scope 2) and the urban supply chain (scope 3). Inclusion of supply-chain emissions often requires additional data such as consumer purchasing data and supply chain emission factors. Some researchers also take a hybrid approach combining top-down and bottom-up estimation techniques to quantify territorial emissions. Individual self-reported urban inventories from cities have shown chronic underestimation when compared to estimates using combined top-down/bottom-up atmospherically calibrated estimation techniques.

No approach has been systematically applied to all cities worldwide. Rather, they have been applied individually or in combination to subsets of global cities. Considerable uncertainty remains in estimating urban emissions. However, top-down approaches have somewhat more objective techniques for uncertainty estimation in comparison to bottom-up approaches. Furthermore, supply chain estimation typically has more uncertainty than direct or territorial emission frameworks.

Frequently Asked Questions (FAQs)

FAQ 9.1 | To which GHG emissions do buildings contribute?

There are three categories of GHG emissions from buildings:

i. direct emissions which are defined as all on-site fossil fuel or biomass-based combustion activities (i.e., use of biomass for cooking, or gas for heating and hot water) and F-gas emissions (i.e., use of heating and cooling systems, aerosols, fire extinguishers, soundproof);
ii. indirect emissions which occur off-site and are related to heat and electricity production; and
iii. embodied emissions which are related to extracting, producing, transforming, transporting, and installing the construction material and goods used in buildings.

In 2019, global GHG emissions from buildings were at 12 $GtCO_2$-eq out of which 24% were direct emissions, 57% were indirect emissions, and 18% were embodied emissions. More than 95% of emissions from buildings were CO_2 emissions, CH_4 and N_2O represented 0.08% each and emissions from halocarbon contributed by 3% to global GHG emissions from buildings.

FAQ 9.2 | What are the co-benefits and trade-offs of mitigation actions in buildings?

Mitigation actions in buildings generate multiple co-benefits (e.g., health benefits due to the improved indoor and outdoor conditions, productivity gains in non-residential buildings, creation of new jobs particularly at local level, improvements in social well-being etc.) beyond their direct impact on reducing energy consumption and GHG emissions. Most studies agree that the value of these multiple benefits is greater than the value of energy savings and their inclusion in economic evaluation of mitigation actions may improve substantially their cost-effectiveness. It is also worth mentioning that in several cases the buildings sector is characterised by strong rebound effects, which could be considered as a co-benefit in cases where the mechanisms involved provide faster access to affordable energy but also a trade-off in cases where the external costs of increased energy consumption exceed the welfare benefits of the increased energy service consumption, thus lowering the economic performance of mitigation actions. The magnitude of these co-benefits and trade-offs are characterised by several uncertainties, which may be even higher in the future as mitigation actions will be implemented in a changing climate, with changing building operation style and occupant behaviour. Mitigation measures influence the degree of vulnerability of buildings to future climate change. For instance, temperature rise can increase energy consumption, which may lead to higher GHG emissions. Also, sea level rise, increased storms and rainfall under future climate may impact building structure, materials and components, resulting in increased energy consumption and household expenditure from producing and installing new components and making renovations. Well-planned energy efficiency, sufficiency and on-site renewable energy production can help to increase building resilience to climate change impacts and reduce adaptation needs.

FAQ 9.3 | Which are the most effective policies and measures to decarbonise the building sector?

Several barriers (information, financing, markets, behavioural, etc.) still prevents the decarbonisation of buildings stock, despite the several co-benefits, including large energy savings. Solutions include investments in technological solutions (e.g., insulation, efficient equipment, and low-carbon energies and renewable energies) and lifestyle changes. In addition, the concept of sufficiency is suggested to be promoted and implemented through policies and information, as technological solutions will be not enough to decarbonise the building sector. Due to the different types of buildings, occupants, and development stage there is not a single policy, which alone will reach the building decarbonisation target. A range of policy instruments ranging from regulatory measures such as building energy code for NZEBs and appliance standards, to market-based instruments (carbon tax, personal carbon allowance, renewable portfolio standards, etc.) and information. Financing (grants, loans, performance base incentives, pays as you save, etc.) is another key enabler for energy efficiency technologies and on-site renewables. Finally, effective governance and strong institutional capacity are key to have an effective and successful implementation of policies and financing.

Frequently Asked Questions (FAQs)

FAQ 10.1 | How important is electromobility in decarbonising transport and are there major constraints in battery minerals?

Electromobility is the biggest change in transport since AR5. When powered with low-carbon electricity, electric vehicles (EVs) provide a mechanism for major GHG emissions reductions from the largest sources in the transport sectors, including cars, motorbikes, autorickshaws, buses and trucks. The mitigation potential of EVs depends on the decarbonisation of the power system. EVs can be charged by home or business renewable power before or in parallel to the transition to grid-based low-carbon power.

Electromobility is happening rapidly in micromobility (e-autorickshaws, e-scooters, e-bikes) and in transit systems, especially buses. EV adoption is also accelerating for personal cars. EVs can be used in grid stabilisation through smart charging applications.

The state-of-the-art lithium-Ion batteries (LIBs) available in 2020 are superior to alternative cell technologies in terms of battery life, energy density, specific energy, and cost. The expected further improvements in LIBs suggest these chemistries will remain superior to alternative battery technologies in the medium term, and therefore LIBs will continue to dominate the electric vehicle market.

Dependence on LIB metals will remain, which may be a concern from the perspective of resource availability and costs. However, the demand for such metals is much lower than the reserves available, with many new mines starting up in response to the new market, particularly in a diversity of places.

Recycling batteries will significantly reduce long-term resource requirements. The standardisation of battery modules and packaging within and across vehicle platforms, as well as increased focus on design for recyclability, are important. Many mobility manufacturers and governments are considering battery recycling issues to ensure the process is mainstreamed.

The most significant enabling condition in electromobility is to provide electric recharging opportunities and an integration strategy so that vehicles support the grid.

FAQ 10.2 | How hard is it to decarbonise heavy vehicles in transport like long-haul trucks, ships and planes?

There are few obvious solutions to decarbonising heavy vehicles like international ships and planes. The main focus has been increased efficiency, which so far has not prevented these large vehicles from becoming the fastest-growing source of GHG globally. These vehicles likely need alternative fuels that can be fitted to the present propulsion systems. Emerging demonstrations suggest that ammonia, advanced biofuels, or synthetic fuels could become commercial.

Electric propulsion using hydrogen fuel cells or Li-ion batteries could work with short-haul aviation and shipping, but the large long-lived vessels and aircraft likely need alternative liquid fuels for most major long-distance functions.

Advanced biofuels, if sourced from resources with low GHG footprints, offer decarbonisation opportunities. As shown in Chapters 2, 6, and 12, there are multiple issues constraining traditional biofuels. Sustainable land management and feedstocks, as well as R&D efforts to improve lignocellulosic conversion routes, are key to maximising the mitigation potential from advanced biofuels.

Synthetic jet and marine fuels can be made using CO_2 captured with DAC/BECCS and low-carbon hydrogen. These fuels may also have less contrails-based climate impacts and lower emissions of local air pollutants. However, these fuels still require significant R&D and demonstration.

The deployment of low-carbon aviation and shipping fuels that support decarbonisation of the transport sector will likely require changes to national and international governance structures.

Frequently Asked Questions (FAQs)

FAQ 10.3 | How can governments, communities and individuals reduce demand and be more efficient in consuming transport energy?

Cities can reduce their transport-related fuel consumption by around 25% through combinations of more compact land use and less car-dependent transport infrastructure.

More traditional programmes for reducing unnecessary high-energy travel through behaviour change programmes (e.g., taxes on fuel, parking, and vehicles, or subsidies for alternative low-carbon modes) continue to be evaluated, with mixed results due to the dominance of time savings in an individual's decision-making.

The circular economy, the shared economy, and digitalisation trends can support systemic changes that lead to reductions in demand for transport services or expand the use of more efficient transport modes.

COVID-19 lockdowns have confirmed the transformative value of telecommuting, replacing significant numbers of work and personal journeys, as well as promoting local active transport. These changes may not last and impacts on productivity and health are still to be fully evaluated.

Solutions for individual households and businesses involving pledges and shared communities that set new cultural means of reducing fossil fuel consumption, especially in transport, are setting out new approaches for how climate change mitigation can be achieved.

Frequently Asked Questions (FAQs)

FAQ 11.1 | What are the key options to reduce industrial emissions?

Industry has a diverse set of greenhouse gas (GHG) emission sources across subsectors. To decarbonise industry requires that we pursue several options simultaneously. These include energy efficiency, materials demand management, improving materials efficiency, more circular material flows, electrification, as well as carbon capture and utilisation (CCU) and carbon capture and storage (CCS). Improved materials efficiency and recycling reduces the need for primary resource extraction and the energy-intensive primary processing steps. Future recycling may include chemical recycling of plastics if quality requirements make mechanical recycling difficult. One approach, albeit energy intensive, is to break down waste plastics to produce new monomer building blocks, potentially based on biogenic carbon and hydrogen instead of fossil feedstock. Hydrogen can also be used as a reduction agent instead of coke and coal in ironmaking. Process emissions from cement production can be captured and stored or used as feedstock for chemicals and materials. Electricity and hydrogen needs can be very large but the potential for renewable electricity, possibly in combination with other low carbon options, is not a limiting factor.

FAQ 11.2 | How costly is industrial decarbonisation and will there be synergies or conflicts with sustainable development?

In most cases and in early stages of deployment, decarbonisation through electrification or CCS will make the primary production of basic materials such as cement, steel, or polyethylene more expensive. However, demand management, energy and materials efficiency, and more circular material flows can dampen the effect of such cost increases. In addition, the cost of energy-intensive materials is typically a very small part of the total price of products, such as an appliance, a bottle of soda or a building, so the effect on consumers is very small. Getting actors to pay more for zero-emission materials is a challenge in supply chains with a strong focus on competitiveness and cutting costs, but it is not a significant problem for the broader economy. Reduced demand for services such as square metres of living space or kilometres of car travel is an option where material living standards are already high. If material living standards are very low, increased material use is often needed for more sustainable development. The options of materials and energy efficiency, and more circular material flows, generally have synergies with sustainable development. Increased use of electricity, hydrogen, CCU and CCS may have both positive and negative implications for sustainable development and thus require careful assessment and implementation for different contexts.

FAQ 11.3 | What needs to happen for a low-carbon industry transition?

Broad and sequential policy strategies for industrial development and decarbonisation that pursue several mitigation options at the same time are more likely to result in resource-efficient and cost-effective emission reductions. Industrial decarbonisation is a relatively new field and thus building capacity for industrial transition governance is motivated. For example, policy to support materials efficiency or fundamental technology shifts in primary processes is less developed than energy efficiency policy and carbon pricing. Based on shared visions or pathways for a zero-emission industry, industrial policy needs to support development of new technologies and solutions as well as market creation for low- and zero-emission materials and products. This implies coordination across several policy domains including research and innovation, waste and recycling, product standards, digitalisation, taxes, regional development, infrastructure, public procurement, permit procedures and more to make the transition to a carbon neutral industry. International competition means that trade rules must be evolved to not conflict with industrial decarbonisation. Some local and regional economies may be disadvantaged from the transition which can motivate re-education and other support.

Frequently Asked Questions (FAQs)

FAQ 12.1 | How could new technologies to remove carbon dioxide from the atmosphere contribute to climate change mitigation?

Limiting the increase in warming to well below 2°C, and achieving net zero CO_2 or GHG emissions, will require anthropogenic CO_2 removal from the atmosphere.

The carbon dioxide removal (CDR) methods studied so far have different removal potentials, costs, co-benefits and side effects. Some biological methods for achieving CDR, like afforestation/reforestation or wetland restoration, have long been practised. If implemented well, these practices can provide a range of co-benefits, but they can also have adverse side effects such as biodiversity loss or food price increases. Other chemical and geochemical approaches to CDR include direct air carbon capture and storage (DACCS), enhanced weathering or ocean alkalinity enhancement. They are generally less vulnerable to reversal than biological methods.

DACCS uses chemicals that bind to CO_2 directly from the air; the CO_2 is then removed from the sorbent and stored underground or mineralised. Enhanced weathering involves the mining of rocks containing minerals that naturally absorb CO_2 from the atmosphere over geological timescales, which are crushed to increase the surface area and spread on soils (or elsewhere) where they absorb atmospheric CO_2. Ocean alkalinity enhancement involves the extraction, processing, and dissolution of minerals and addition to the ocean where they enhance sequestration of CO_2 as bicarbonate and carbonate ions in the ocean.

FAQ 12.2 | Why is it important to assess mitigation measures from a systemic perspective, rather than only looking at their potential to reduce greenhouse gas (GHG) emissions?

Mitigation measures do not only reduce GHGs, but have wider impacts. They can result in decreases or increases in GHG emissions in another sector or part of the value chain from where they are applied. They can have wider environmental (e.g., air and water pollution, biodiversity), social (e.g., employment creation, health) and economic (e.g., growth, investment) co-benefits or adverse side effects. Mitigation and adaptation can also be linked. Taking these considerations into account can help to enhance the benefits of mitigation action, and avoid unintended consequences, as well as provide a stronger case for achieving political and societal support and raising the finances required for implementation.

FAQ 12.3 | Why do we need a food systems approach for assessing GHG emissions and mitigation opportunities from food systems?

Activities associated with the food system caused about one-third of total anthropogenic GHG emissions in 2015, distributed across all sectors. Agriculture and fisheries produce crops and animal-source food, which are partly processed in the food industry, packed, distributed, retailed, cooked, and finally eaten. Each step is associated with resource use, waste generation, and GHG emissions.

A food systems approach helps identify critical areas as well as novel and alternative approaches to mitigation on both the supply side and the demand side of the food system. But complex co-impacts need to be considered and mitigation measures tailored to the specific context. International cooperation and governance of global food trade can support both mitigation and adaptation.

There is large scope for emissions reduction in both cropland and grazing production, and also in food processing, storage and distribution. Emerging options such as plant-based alternatives to animal food products and food from cellular agriculture are receiving increasing attention, but their mitigation potential is still uncertain and depends on the GHG intensity of associated energy systems due to relatively high energy needs. Diet changes can reduce GHG emissions and also improve health in groups with excess consumption of calories and animal food products, which is mainly prevalent in developed countries. Reductions in food loss and waste can help reduce GHG emissions further.

Recommendations to buy local food and avoid packaging can contribute to reducing GHG emissions but should not be generalised, as trade-offs exist with food waste, GHG footprint at farm gate, and accessibility to diverse healthy diets.

Frequently Asked Questions (FAQs)

FAQ 13.1 | What roles do national play in climate mitigation, and how can they be effective?

Institutions and governance underpin mitigation. Climate laws provide the legal basis for action, organisations through which policies are developed and implemented, and frameworks through which diverse actors interact. Specific organisations, such as expert committees, can inform emission reduction targets, inform the creation of policies and packages, and strengthen accountability. Institutions enable strategic thinking, building consensus among stakeholders and enhanced coordination.

Climate governance is constrained and enabled by countries' political systems, material endowments and their ideas, values and belief systems, which leads to a variety of country-specific approaches to climate mitigation.

Countries follow diverse approaches. Some countries focus on greenhouse gases emissions by adopting comprehensive climate laws and creating dedicated ministries and institutions focused on climate change. Others consider climate change among broader scope of policy objectives, such as poverty alleviation, energy security, economic development and co-benefits of climate actions, with the involvement of existing agencies and ministries. See also FAQ 13.3 on sub-national climate mitigation.

FAQ 13.2 | What policies and strategies can be applied to combat climate change?

Institutions can enable creation of mitigation and sectoral policy instruments; policy packages for low-carbon system transition, and economy-wide measures for systemic restructuring. Policy instruments to reduce greenhouses gas emissions include economic instruments, regulatory instruments and other approaches.

Economic policy instruments directly influence prices to achieve emission reductions through taxes, permit trading, offset systems, subsidies, and border tax adjustments, and are effective in promoting implementation of low-cost emissions reductions. Regulatory instruments help achieve specific mitigation outcomes particularly in sectoral applications, by establishing technology or performance requirements. Other instruments include information programmes, government provision of goods, services and infrastructure, divestment strategies, and voluntary agreements between governments and private firms.

Climate policy instruments can be sector-specific or economy-wide and could be applied at national, regional, or local levels. Policymakers may directly target GHG emission reduction or seek to achieve multiple objectives, such as urbanisation or energy security, with the effect of reducing emissions. In practice, climate mitigation policy instruments operate in combination with other policy tools, and require attention to the interaction effects between instruments. At all levels of governance, coverage, stringency and design of climate policies define their efficiency in reducing greenhouse gases emissions.

Policy packages, when designed with attention to interactive effects, local governance context, and harnessed to a clear vision for change, are better able to support socio-technical transitions and shifts in development pathways toward low-carbon futures than individual policies. See also Chapter 14 on international climate governance.

FAQ 13.3 | How can actions at the sub-national level contribute to climate mitigation?

Sub-national actors (for example individuals, organisations, jurisdictions and networks at regional, local and city levels) often have a remit over areas salient to climate mitigation, such as land-use planning, waste management, infrastructure, housing, and community development. Despite constraints on legal authority and dependence on national policy priorities in many countries, sub-national climate change policies exist in more than 120 countries. However, they often lack national support, funding, and capacity, and adequate coordination with other scales. Sub-national climate action in support of specific goals is more likely to succeed when linked to local issues such as travel congestion alleviation, air pollution control.

The main drivers of climate actions at sub-national levels include high levels of citizen concern, jurisdictional authority and funding, institutional capacity, national level support and effective linkage to development objectives. Sub-national governments often initiate and implement policy experiments that could be scaled to other levels of governance.

Frequently Asked Questions (FAQs)

FAQ 14.1 | Is international cooperation working?

Yes, to an extent. Countries' emissions were in line with their internationally agreed targets: the collective greenhouse gas (GHG) mitigation target for Annex I countries in the UNFCCC to return to their 1990 emissions levels by 2000, and their individual targets in the Kyoto Protocol for 2008–12. Numerous studies suggest that participation in the Kyoto Protocol led to substantial reductions in national GHG emissions, as well increased levels of innovation and investment in low-carbon technologies. In this latter respect, the Kyoto Protocol set in motion some of the transformational changes that will be required to meet the temperature goal of the Paris Agreement. It is too soon to tell whether the processes and commitments embodied in the Paris Agreement will be effective in achieving its stated goals with respect to limiting temperature rise, adaptation, and financial flows. There is, however, evidence that its entry into force has been a contributing factor to many countries' adopting mid-century targets of net-zero GHG or CO_2 emissions.

FAQ 14.2 | What is the future role of international cooperation in the context of the Paris Agreement?

Continued international cooperation remains critically important both to stimulate countries' enhanced levels of mitigation ambition, and through various means of support to increase the likelihood that they achieve these objectives. The latter is particularly the case in developing countries, where mitigation efforts often rely on bilateral and multilateral cooperation on low-carbon finance, technology support, capacity building, and enhanced South-South cooperation. The Paris Agreement is structured around Nationally Determined Contributions that are subject to an international oversight system, and bolstered through international support. The international oversight system is designed to generate transparency and accountability for individual emissions reduction contributions, and regular moments for stock-taking of these efforts towards global goals. Such enhanced transparency may instil confidence and trust, and foster solidarity among nations, with theory-based arguments that this will lead to greater levels of ambition. Together with other cooperative agreements at the sub-global and sectoral levels, as well as a growing number of transnational networks and initiatives, the implementation of all of these mechanisms is likely to play an important role in making political, economic, and social conditions more favourable to ambitious mitigation efforts in the context of sustainable development and efforts to eradicate poverty.

FAQ 14.3 | Are there any important gaps in international cooperation, which will need to be filled in order for countries to achieve the objectives of the Paris Agreement, such as holding temperature increase to well below 2°C and pursuing efforts towards 1.5°C above pre-industrial levels?

While international cooperation is contributing to global mitigation efforts, its effects are far from uniform. Cooperation has contributed to setting a global direction of travel, and to falling greenhouse gas emissions in many countries and avoided emissions in others. It remains to be seen whether it can achieve the kind of transformational changes needed to achieve the Paris Agreement's long-term global goals. There appears to be a large potential role for international cooperation to better address sector-specific technical and infrastructure challenges that are associated with such transformational changes. Finalising the rules to pursue voluntary cooperation, such as through international carbon market mechanisms and public climate finance in the implementation of NDCs, without compromising environmental integrity, may play an important role in accelerating mitigation efforts in developing countries. Finally, there is room for international cooperation to more explicitly address transboundary issues associated with carbon dioxide removal and solar radiation management.

Frequently Asked Questions (FAQs)

FAQ 15.1 | What's the role of climate finance and the finance sector for a transformation towards a sustainable future?

The Paris Agreement has widened the scope of all financial flows from climate finance only to the full alignment of finance flows with the long-term goals of the Paris Agreement. While climate finance relates historically to the financial support of developed countries to developing countries, the Paris Agreement and its Article 2.1(c) have developed a new narrative that goes much beyond traditional flows and relates to all sectors and actors. Finance flows are consistent when the effects are either neutral with or without positive climate co-benefits to climate objectives; or explicitly targeted to climate benefits in adaptation and/or mitigation result areas. Climate-related financial risk is still massively underestimated by financial institutions, financial decision-makers more generally and also among public sector stakeholders, limiting the sector's potential of being an enabler of the transition. The private sector has started to recognise climate-related risks and consequently redirect investment flows. Dynamics vary across sectors and regions with the financial sector being an enabler of transitions in only some selected (sub-)sectors and regions. Consistent, credible, timely and forward-looking political leadership remains central to strengthen the financial sector as enabler.

FAQ 15.2 | What's the current status of global climate finance and the alignment of global financial flows with the Paris Agreement?

There is no agreed definition of climate finance. The term 'climate finance' is applied to the financial resources devoted to addressing climate change by all public and private actors from global to local scales, including international financial flows to developing countries to assist them in addressing climate change. Total climate finance includes all financial flows whose expected effect aims to reduce net greenhouse gas (GHG) emissions and/or to enhance resilience to the impacts of current and projected climate change. This includes private and public funds, domestic and international flows and expenditures. Tracking of climate finance flows faces limitations, in particular for national climate finance flows.

Progress on the alignment of financial flows with low GHG emissions pathways remains slow. Annual global climate finance flows are on an upward trend since the Fifth Assessment Report, according to the Climate Policy Initiative reaching more than USD630 billion in 2019/2020, however, growth has likely slowed down and flows remain significantly below needs. This is driven by barriers within and outside the financial sector. More than 90% of financing is allocated to mitigation activities despite the strong economic rationale of adaptation action. Adjusting for higher estimates on current flows for energy efficiency based on International Energy Agency data, the dominance of mitigation becomes even stronger. Persistently high levels of both public and private fossil-fuel related financing as well as other misaligned flows continue to be of major concern despite recent commitments. Significant progress has been made in the commercial finance sector with regard to the awareness of climate risks resulting from inadequate financial flows and climate action. However, a more consequent investment and policy decision-making that enables a rapid redirection of financial flows is needed. Regulatory support as a catalyser is an essential driver of such redirections. Dynamics across sectors and regions vary, with some being better positioned to close financing gaps and to benefit from an enabling role of finance in the short-term.

FAQ 15.3 | What defines a financing gap, and where are the critically identified gaps?

A financing gap is defined as the difference between current flows and average needs to meet the long-term goals of the Paris Agreement. Gaps are driven by various barriers inside (short-termism, information gaps, home bias, limited visibility of future pipelines) and outside (e.g., missing pricing of externalities, missing regulatory frameworks) of the financial sector. Current mitigation financing flows come in significantly below average needs across all regions and sectors despite the availability of sufficient capital on a global basis. Globally, yearly climate finance flows have to increase by a factor between three and six to meet average annual needs between 2020 and 2030.

Gaps are in particular concerning for many developing countries, with COVID-19 exacerbating the macroeconomic outlook and fiscal space for governments. Also, limited institutional capacity represents a key barrier for many developing countries, burdening risk perceptions and access to appropriately priced financing as well as limiting their ability to actively manage the transformation. Existing fundamental inequities in access to finance, as well as its terms and conditions, and countries' exposure to physical impacts of climate change, overall result in a worsening outlook for a global just transition.

Frequently Asked Questions (FAQs)

FAQ 16.1 | Will innovation and technological changes be enough to meet the Paris Agreement objectives?

The Paris Agreement stressed the importance of development and transfer of technologies to improve resilience to climate change and to reduce greenhouse gas emissions. However, innovation and even fast technological change will not be enough to achieve Paris Agreement mitigation objectives. Other changes are necessary across the production and consumption system and the society in general, including behavioural changes.

Technological changes never happen in a vacuum; they are always accompanied by, for instance, people changing habits, companies changing value chains, or banks changing risk profiles. Therefore, technological changes driven by holistic approaches can contribute to accelerate and spread those changes towards the achievement of climate and sustainable development goals.

In innovation studies, such systemic approaches are said to strengthen the functions of technological or national innovation systems, so that climate-friendly technologies can flourish. Innovation policies can help respond to local priorities and prevent unintended and undesirable consequences of technological change, such as unequal access to new technologies across countries and between income groups, environmental degradation and negative effects on employment.

FAQ 16.2 | What can be done to promote innovation for climate change and the widespread diffusion of low-emission and climate-resilient technology?

The speed and success of innovation processes could be enhanced with the involvement of a wider range of actors from the industry, research and financial communities working in partnerships at national, regional and international levels. Public policies play a critical role to bring together these different actors and create the necessary enabling conditions, including financial support, through different instruments as well as institutional and human capacities.

The increasing complexity of technologies requires cooperation if their widespread diffusion is to be achieved. Cooperation includes the necessary knowledge flow within and between countries and regions. This knowledge flow can take the form of exchanging experiences, ideas, skills, and practices, among others.

FAQ 16.3 | What is the role of international technology cooperation in addressing climate change?

Technologies that are currently known but not yet widely used need to be spread around the world, and adapted to local preferences and conditions. Innovation capabilities are required not only to adapt new technologies for local use, but also to create new markets and business models. International technology cooperation can serve that purpose.

In fact, evidence shows that international cooperation on technology development and transfer can help developing countries to achieve their climate goals more effectively and, if this is done properly, can also help to addressing other sustainable development goals. Many initiatives exist both regionally and globally to help countries in achieving technology development and transfer through partnerships and research collaboration that include developed and developing countries, with a key role for technological institutions and universities. Enhancing current activities would help an effective, long-term global response to climate change, while promoting sustainable development.

Globalisation of production and supply of goods and services, including innovation and new technologies, may open up opportunities for developing countries to advance technology diffusion; however, so far not all countries have benefitted from the globalisation of innovation due to different barriers, such as access to finance and technical capabilities. These asymmetries between countries in the globalisation process can also lead to dependencies on foreign knowledge and providers.

Not all technology cooperation directly results in mitigation outcomes. Overall, technology transfer broadly has focused on enhancing climate technology absorption and deployment in developing countries as well as research, development and demonstration, and knowledge spillovers.

The Paris Agreement also reflects this view by noting that countries shall strengthen cooperative action on technology development and transfer regarding two main aspects: (i) promoting collaborative approaches to research and development; and (ii) facilitating access to technology to developing country Parties.

Frequently Asked Questions (FAQs)

FAQ 17.1 | Will decarbonisation efforts slow or accelerate sustainable development transitions?

Sustainable development offers a comprehensive pathway to achieving ambitious climate change mitigation goals. Sustainable development requires the pursuit of synergies and the avoidance of trade-offs between the economic, social and environmental dimensions of development. It can thus provide pathways that accelerate progress towards ambitious climate change mitigation goals. Factoring in equality and distributional effects will be particularly important in the pursuit of sustainable policies and partnerships, and in accelerating the transition to sustainable development. Using climate change as a key conduit can only work if synergies across sectors are exploited and if policy implementation is supported by national and international partnerships.

The speed, quality, depth and scale of the transition will depend on the developmental starting point, that is, on explicit goals as well as the enabling environment consisting of individual behaviour, mindsets, beliefs and actions, social cohesion, governance, policies, institutions, social and technological innovations, and so on. The integration of both climate change mitigation and adaptation policies in sustainable development is also essential in the establishment of fair and robust transformation pathways.

FAQ 17.2 | What role do considerations of justice and inclusivity play in the transition towards sustainable development?

Negative economic and social impacts in some regions could emerge as a consequence of ambitious climate change mitigation policies if these are not aligned with key sustainable development aspirations such as those represented by the Sustainable Development Goals (SDGs) on 'no poverty, energy-, water- and food access', and so on, which could in turn slow down the transition process. Nonetheless, many climate change mitigation policies could generate incomes, new jobs and other benefits. Capturing these benefits could require specific policies and investments to be targeted directly towards including all parts of society in the new activities and industries created by the climate change mitigation policies, and that activities that are reduced in the context of transitions to a low-carbon future, including industries and geographical areas, are seeing new opportunities. Poor understanding of how governance at multiple levels can meet these challenges to the transition may fail to make significant progress in relation to national policies and a global climate agreement. It may therefore either support or weaken the climate architecture, thus constituting a limiting factor.

FAQ 17.3 | How critical are the roles of institutions in accelerating the transition and what can governance enable?

Institutions are critical in accelerating the transition towards sustainable development: they can help to shape climate change response strategies in terms of both adaptation and mitigation. Local institutions are the custodians of critical adaptation services, ranging from the mobilisation of resources, skills development and capacity-building to the dissemination of critical strategies. Transitions towards sustainable development are mediated by actors within particular institutions, the governance mechanisms they use as implementing tools and the political coalitions they form to enable action. Patterns of production and consumption have implications for a low-carbon development, and many of these patterns can act as barriers or opportunities towards sustainable development. Trade policies, international economic issues and international financial flows can positively support the speed and scale of the transition; alternatively, they can have negative impacts on policies that may inhibit the process. Nonetheless, contextual factors are a fundamental part of the change process, and institutions and their governance systems provide pathways that can influence contextual realities on the ground. For instance, politically vested interests may lead powerful lobby groups or coalition networks to influence the direction of the transition, or they could put pressure on a given political elite through the imposition of regulatory standards, taxation, incentives and policies that may speed or delay the transition process. Civil-society institutions, such as NGOs or research centres, can act as effective governance 'watchdogs' in the transition process, particularly when they exercise a challenge function and question government actions in respect of transitions related to sustainable development.

Glossary

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Annex I: Glossary

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Note:

This glossary defines some specific terms as the Lead Authors intend them to be interpreted in the context of this report. Italicised words in definitions indicate that the italicised term is defined in the Glossary.

Subterms appear in *italics* beneath main terms.

This chapter should be cited as:

IPCC, 2022: Annex I: Glossary [van Diemen, R., J.B.R. Matthews, V. Möller, J.S. Fuglestvedt, V. Masson-Delmotte, C. Méndez, A. Reisinger, S. Semenov (eds)]. In IPCC, 2022: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.020

1.5°C pathway See *Pathways*.

Acceptability of policy or system change The extent to which a policy or system change is evaluated unfavourably or favourably, or rejected or supported, by members of the general public (public acceptability) or politicians or governments (political acceptability). Acceptability may vary from totally unacceptable/fully rejected to totally acceptable/fully supported; individuals may differ in how acceptable policies or system changes are believed to be.

Access to modern energy services Access to clean, reliable and affordable energy services for cooking, heating, lighting, communications, and productive uses.

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 and its effects. See also *Adaptation options*, *Adaptive capacity*, and *Maladaptive actions (Maladaptation)*.

Adaptation limits
The change in climate where adaptation is unable to prevent damaging impacts and further risk. Soft limits occur when additional adaptation may be possible if constraints are able to be overcome. Hard limits occur when no additional adaptation is possible.

Incremental adaptation
Adaptation that maintains the essence and integrity of a system or process at a given scale (Park et al. 2012). In some cases, incremental adaptation can accrue to result in transformational adaptation (Tàbara et al. 2019; Termeer et al. 2017). 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.

Transformational adaptation
Adaptation that changes the fundamental attributes of a social-ecological system in anticipation of climate change and its impacts.

Adaptation options The array of strategies and measures that are available and appropriate for addressing *adaptation*. They include a wide range of actions that can be categorised as structural, *institutional*, ecological or behavioural.

Adaptation pathways See *Pathways*.

Adaptive capacity The ability of systems, *institutions*, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences (MA 2005).

Adaptive governance See *Governance*.

Additionality The property of being additional. Mitigation is additional if the *greenhouse gas* emission reductions or removals would not have occurred in the absence of the associated policy intervention or activity.

[Note: Additionality is one of several key criteria used to ensure the environmental integrity of *Offsets (in climate change mitigation)*].

See also *Greenhouse gas emission metric*.

Adverse side-effect A negative effect that a policy or measure aimed at one objective has on another objective, thereby potentially reducing the net benefit to society or the environment. See also *Co-benefits*, *Risk*, and *Trade-off*.

Aerosol A suspension of airborne solid or liquid particles, with typical particle size in the range of a few nanometres to several tens of micrometres and atmospheric lifetimes of up to several days in the troposphere and up to years in the stratosphere. The term aerosol, which includes both the particles and the suspending gas, is often used in this report in its plural form to mean 'aerosol particles'. Aerosols may be of either natural or anthropogenic origin in the troposphere; stratospheric aerosols mostly stem from volcanic eruptions. Aerosols can cause an effective radiative forcing directly through scattering and absorbing radiation (aerosol–radiation interaction), and indirectly by acting as cloud condensation nuclei or ice nucleating particles that affect the properties of clouds (aerosol–cloud interaction), and upon deposition on snow- or ice-covered surfaces. Atmospheric aerosols may be either emitted as primary particulate matter or formed within the atmosphere from gaseous precursors (secondary production). Aerosols may be composed of sea salt, organic carbon, black carbon (BC), mineral species (mainly desert dust), sulphate, nitrate and ammonium or their mixtures. See also *Short-lived climate forcers (SLCFs)*.

Afforestation Conversion to *forest* of land that historically has not contained forests.

[Note: For a discussion of the term *forest* and related terms such as *afforestation*, *reforestation* and *deforestation*, see the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and their 2019 Refinement, and information provided by the *United Nations Framework Convention on Climate Change* (IPCC 2006, 2019; UNFCCC 2021a,b).]

See also *Deforestation*, *Reducing Emissions from Deforestation and Forest Degradation (REDD+)*, *Reforestation*, *Anthropogenic Removals*, and *Carbon dioxide removal (CDR)*.

Agreement In this report, the degree of agreement within the scientific body of knowledge on a particular finding is assessed based on multiple lines of *evidence* (e.g., mechanistic understanding, theory, data, models, expert judgement) and expressed qualitatively (Mastrandrea et al. 2010). See also *Confidence*, *Likelihood*, and *Uncertainty*.

Agriculture, Forestry and Other Land Use (AFOLU) In the context of national *greenhouse gas (GHG)* inventories under the *United Nations Framework Convention on Climate Change (UNFCCC)*, AFOLU is the sum of the GHG inventory sectors Agriculture and Land Use, Land-Use Change and Forestry (LULUCF); see the 2006 IPCC Guidelines for National GHG Inventories for details. Given the difference in estimating the 'anthropogenic' *carbon dioxide* *(CO_2)* removals between countries and the global modelling community, the land-related net GHG emissions from global models included in this report are not necessarily directly comparable with LULUCF estimates in national GHG Inventories. See also *Land use*, *Land-use change and forestry (LULUCF)* and *Land-use change (LUC)*.

Agroecology The science and practice of applying ecological concepts, principles and knowledge (i.e., the interactions of, and explanations for, the diversity, abundance and activities of organisms) to the study, design and management of sustainable agroecosystems.

It includes the roles of human beings as a central organism in agroecology by way of social and economic processes in farming systems. Agroecology examines the roles and interactions among all relevant biophysical, technical and socio-economic components of farming systems and their surrounding landscapes (IPBES 2019).

Air pollution Degradation of air quality with negative effects on human health or the natural or built environment due to the introduction, by natural processes or human activity, into the *atmosphere* of substances (gases, *aerosols*) which have a direct (primary pollutants) or indirect (secondary pollutants) harmful effect. See also *Short-lived climate forcers (SLCFs)*.

Albedo The proportion of sunlight (solar radiation) reflected by a surface or object, often expressed as a percentage. Clouds, snow and ice usually have high albedo; soil surfaces cover the albedo range from high to low; vegetation in the dry season and/or in arid zones can have high albedo, whereas photosynthetically active vegetation and the ocean have low albedo. The Earth's planetary albedo changes mainly through changes in cloudiness and of snow, ice, leaf area and *land cover*.

Anomaly The deviation of a variable from its value averaged over a *reference period*.

Anthropogenic Resulting from or produced by human activities.

Anthropogenic emissions Emissions of *greenhouse gases (GHGs)*, *precursors* of GHGs and *aerosols* caused by human activities. These activities include the burning of *fossil fuels*, *deforestation*, *land use and land-use changes (LULUC)*, livestock production, fertilisation, waste management, and industrial processes. See also *Anthropogenic* and *Anthropogenic removals*.

Anthropogenic removals The withdrawal of *greenhouse gases* (GHGs) from the *atmosphere* as a result of deliberate human activities. These include enhancing biological sinks of CO_2 and using chemical engineering to achieve long-term removal and storage. *Carbon capture and storage (CCS)*, which alone does not remove CO_2 from the atmosphere, can help reduce atmospheric CO_2 from industrial and energy-related sources if it is combined with bioenergy production (*BECCS*), or if CO_2 is captured from the air directly and stored (*DACCS*).

[Note: In the 2006 IPCC Guidelines for National GHG Inventories (IPCC 2006), which are used in reporting of emissions to the UNFCCC, 'anthropogenic' land-related GHG fluxes are defined as all those occurring on 'managed land', i.e., 'where human interventions and practices have been applied to perform production, ecological or social functions'. However, some removals (e.g., removals associated with CO_2 fertilisation and N deposition) are not considered as 'anthropogenic', or are referred to as 'indirect' anthropogenic effects, in some of the scientific literature assessed in this report. As a consequence, the land-related net GHG emission estimates from global models included in this report are not necessarily directly comparable with LULUCF estimates in national GHG Inventories.]

See also *Carbon dioxide removal (CDR)*, *Afforestation*, *Biochar*, *Enhanced weathering*, *Ocean alkalinisation/Ocean alkalinity enhancement*, *Reforestation*, and *Soil carbon sequestration (SCS)*.

Atmosphere The gaseous envelope surrounding the Earth, divided into five layers – the troposphere which contains half of the Earth's atmosphere, the stratosphere, the mesosphere, the thermosphere, and the exosphere, which is the outer limit of the atmosphere. The dry atmosphere consists almost entirely of nitrogen (78.1% volume mixing ratio) and oxygen (20.9% volume mixing ratio), together with a number of trace gases, such as argon (0.93 % volume mixing ratio), helium and radiatively active *greenhouse gases (GHGs)* such as *carbon dioxide* (CO_2) (0.04% volume mixing ratio), *methane* (CH_4), *nitrous oxide* (N_2O) and *ozone* (O_3). In addition, the atmosphere contains the GHG water vapour (H_2O), whose concentrations are highly variable (0–5% volume mixing ratio) as the sources (*evapotranspiration*) and sinks (precipitation) of water vapour show large spatio-temporal variations, and atmospheric temperature exerts a strong constraint on the amount of water vapour an air parcel can hold. The atmosphere also contains clouds and *aerosols*.

Avoid, Shift, Improve (ASI) Reducing *greenhouse gas* emissions by avoiding the use of an emissions-producing service entirely, shifting to the lowest-emission mode of providing the service, and/or improving the technologies and systems for providing the service in ways that reduce emissions.

Baseline/reference See *Reference period* and *Reference scenario*.

Baseline period See *Reference period*.

Biochar Relatively stable, carbon-rich material produced by heating *biomass* in an oxygen-limited environment. Biochar is distinguished from charcoal by its application: biochar is used as a soil amendment with the intention to improve soil functions and to reduce *greenhouse gas* emissions from *biomass* that would otherwise decompose rapidly (IBI 2018). See also *Anthropogenic removals* and *Carbon dioxide removal (CDR)*.

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 (UN 1992). See also *Bioenergy* and *Biomass*.

Bioenergy Energy derived from any form of *biomass* or its metabolic by-products. See also *Biofuel*.

Bioenergy with carbon dioxide capture and storage (BECCS) *Carbon dioxide capture and storage (CCS)* technology applied to a *bioenergy* facility. Note that, depending on the total emissions of the BECCS supply chain, *carbon dioxide* (CO_2) can be removed from the *atmosphere*. See also *Anthropogenic removals* and *Carbon dioxide removal*.

Biofuel A fuel, generally in liquid form, produced from *biomass*. Biofuels include bioethanol from sugarcane, sugar beet or maize, and biodiesel from canola or soybeans. See also *Bioenergy*.

Biogenic carbon emissions Carbon released as *carbon dioxide* or *methane* from combustion or decomposition of *biomass* or biobased products.

Biomass Organic material excluding the material that is fossilised or embedded in geological formations. Biomass may refer to the mass of organic matter in a specific area (ISO 2014). See also *Bioenergy* and *Biofuel*.

Traditional biomass
The combustion of wood, charcoal, agricultural residues and/or animal dung for cooking or heating in open fires or in inefficient stoves as is common in low-income countries.

Black carbon (BC) A relatively pure form of carbon, also known as soot, arising from the incomplete combustion of *fossil fuels*, *biofuel*, and *biomass*. It only stays in the *atmosphere* for days or weeks. BC is a climate forcing agent with strong warming effect, both in the atmosphere and when deposited on snow or ice. See also *Aerosol*.

Blue carbon Biologically-driven carbon fluxes and storage in marine systems that are amenable to management. Coastal blue carbon focuses on rooted vegetation in the coastal zone, such as tidal marshes, mangroves and seagrasses. These *ecosystems* have high carbon burial rates on a per unit area basis and accumulate carbon in their soils and sediments. They provide many non-climatic benefits and can contribute to *ecosystem-based adaptation*. If degraded or lost, coastal blue carbon ecosystems are likely to release most of their carbon back to the *atmosphere*. There is current debate regarding the application of the blue carbon concept to other coastal and non-coastal processes and ecosystems, including the open ocean. See also *Sequestration*.

Blue infrastructure See *Infrastructure*.

Business as usual (BAU) The term *business as usual* scenario has been used to describe a scenario that assumes no additional policies beyond those currently in place and that patterns of socio-economic development are consistent with recent trends. The term is now used less frequently than in the past. See also *Reference scenario* (under *Scenario*).

Carbon budget Refers to two concepts in the literature: (i) an assessment of carbon cycle *sources* and *sinks* on a global level, through the synthesis of evidence for *fossil fuel* and cement emissions, emissions and removals associated with *land use* and *land-use change*, ocean and natural land sources and sinks of *carbon dioxide* *(CO_2)*, and the resulting change in atmospheric CO_2 concentration. This is referred to as the global carbon budget; (ii) 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.

[Note 1: Net anthropogenic CO_2 emissions are anthropogenic CO_2 emissions minus anthropogenic CO_2 removals. See also *Carbon Dioxide Removal (CDR)*.

Note 2: The maximum amount of cumulative net global anthropogenic CO_2 emissions is reached at the time that annual net anthropogenic CO_2 emissions reach zero.

Note 3: The degree to which anthropogenic climate forcers other than CO_2 affect the Total Carbon Budget and Remaining Carbon Budget depends on human choices about the extent to which these forcers are mitigated and their resulting *climate* effects.

Note 4: The notions of a Total Carbon Budget and Remaining Carbon Budget are also being applied in parts of the scientific literature and by some entities at regional, national, or sub-national level. The distribution of global budgets across individual different entities and emitters depends strongly on considerations of equity and other value judgements.]

Carbon cycle The flow of carbon (in various forms, e.g., as *carbon dioxide (CO_2)*, carbon in *biomass*, and carbon dissolved in the ocean as carbonate and bicarbonate) through the atmosphere, hydrosphere, terrestrial and marine biosphere and lithosphere. In this report, the reference unit for the global carbon cycle is $GtCO_2$ or GtC (one Gigatonne = 1 Gt = 10^{15} grams; 1GtC corresponds to 3.664 $GtCO_2$).

Carbon dioxide (CO_2) A naturally occurring gas, CO_2 is also a by-product of burning *fossil fuels* (such as oil, gas and coal), of burning *biomass*, of *land-use changes* (LUCs) and of industrial processes (e.g., cement production). It is the principal *anthropogenic* greenhouse gas (GHG) that affects the Earth's radiative balance. It is the reference gas against which other GHGs are measured and therefore has a *global warming potential* (GWP) of 1.

Carbon dioxide capture and storage (CCS) A process in which a relatively pure stream of *carbon dioxide (CO_2)* from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the *atmosphere*. Sometimes referred to as Carbon Capture and Storage. See also *Anthropogenic removals*, *Bioenergy with carbon dioxide capture and storage (BECCS)*, *Carbon dioxide capture and utilisation (CCU)*, *Carbon dioxide removal (CDR)*, and *Sequestration*.

Carbon dioxide capture and utilisation (CCU) A process in which *carbon dioxide (CO_2)* is captured and the carbon then used in a product. The *climate* effect of CCU depends on the product lifetime, the product it displaces, and the CO_2 source (fossil, *biomass* or *atmosphere*). CCU is sometimes referred to as Carbon Dioxide Capture and Use, or Carbon Capture and Utilisation. See also *Anthropogenic removals*, *Carbon dioxide capture and storage (CCS)*, and *Carbon dioxide removal (CDR)*.

Carbon dioxide removal (CDR) *Anthropogenic* activities removing *carbon dioxide (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 CO_2 *sinks* and *direct air carbon dioxide capture and storage (DACCS)*, but excludes natural CO_2 *uptake* not directly caused by human activities. See also *Anthropogenic removals*, *Afforestation*, *Biochar*, *Bioenergy with carbon dioxide capture and storage (BECCS)*, *Carbon dioxide capture and storage (CCS)*, *Enhanced weathering*, *Ocean alkalinisation/Ocean alkalinity enhancement*, *Reforestation*, and *Soil carbon sequestration (SCS)*.

Carbon footprint Measure of the exclusive total amount of emissions of *carbon dioxide (CO_2)* that is directly and indirectly caused by an activity or is accumulated over the lifecycle stages of a product (Wiedmann and Minx 2008).

Household carbon footprint
The carbon footprint of an individual household, inclusive of the direct and indirect *carbon dioxide (CO_2)* emissions associated with home energy use, transportation, food provision, and consumption of other goods and services associated with household expenditures.

Carbon intensity The amount of emissions of *carbon dioxide (CO_2)* released per unit of another variable such as *gross domestic product (GDP)*, output energy use or transport.

Carbon leakage See *Leakage*.

Carbon neutrality Condition in which *anthropogenic carbon dioxide (CO_2)* emissions associated with a subject are balanced by anthropogenic CO_2 removals. The subject can be an entity such as a country, an organisation, a district or a commodity, or an activity such as a service and an event. Carbon neutrality is often assessed over the lifecycle including indirect ('scope 3') emissions, but can also be limited to the emissions and removals, over a specified period, for which the subject has direct control, as determined by the relevant scheme.

[Note 1: Carbon neutrality and *net-zero CO_2 emissions* are overlapping concepts. The concepts can be applied at global or sub-global scales (e.g., regional, national and sub-national). At a global scale, the terms carbon neutrality and *net-zero CO_2 emissions* are equivalent. At sub-global scales, *net-zero CO_2 emissions* is generally applied to emissions and removals under direct control or territorial responsibility of the reporting entity, while carbon neutrality generally includes emissions and removals within and beyond the direct control or territorial responsibility of the reporting entity. Accounting rules specified by *greenhouse gas (GHG)* programmes or schemes can have a significant influence on the quantification of relevant CO_2 emissions and removals.

Note 2: In some cases, achieving carbon neutrality may rely on the supplementary use of *offsets* to balance emissions that remain after actions by the reporting entity are taken into account.]

See also *Greenhouse gas neutrality*, *Land use, land-use change and forestry (LULUCF)* and *Net-zero CO_2 emissions*.

Carbon price The price for avoided or released *carbon dioxide (CO_2)* or CO_2-equivalent emissions. This may refer to the rate of a carbon tax, or the price of emission permits. In many models that are used to assess the economic costs of *mitigation*, carbon prices are used as a proxy to represent the level of effort in mitigation policies.

Carbon sink See *Sink*.

Carbon stock The quantity of carbon in a carbon *pool*.

Choice architecture The presentation of choices to consumers, and the impact that presentation has on consumer decision-making.

Circular economy A system with minimal input and operational losses of materials and energy through extensive reduce, reuse, recycling, and recovery activities. Ten strategies for circularity include: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover.

Cities Cities are open systems, continually exchanging resources, products and services, waste, people, ideas, and finances with the hinterlands and broader world. Cities are complex, self-organising, adaptive, and constantly evolving. Cities also encompass multiple actors with varying responsibilities, capabilities and priorities, as well as processes that transcend the institutional sector-based approach to city administration. Cities are embedded in broader ecological, economic, technical, institutional, legal, and governance structures that enable or often constrain their systemic function, which cannot be separated from wider power relations. Urban processes of physical, social, and economic nature are causally interlinked, with interactions and feedbacks that result in both intended and unintended impacts on emissions. See also *City region*, *Peri-urban areas* and *Urban*.

Citizen science A voluntary participation of the public in the collection and/or processing of data as part of a scientific study (Silvertown 2009).

City region The areal extent of an individual city's material associations and economic or political influence. The city region concept accepts that rural livelihoods and land uses can be incorporated within the functional activities of a city. This will include dormitory settlements, sources for critical inputs of water, some food, and waste disposal. See also *Cities*, *Region* and *Urban systems*.

Climate Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization (WMO). The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the *climate system*.

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 such as modulations of the solar cycles, volcanic eruptions and persistent *anthropogenic* changes in the composition of the *atmosphere* or in *land use*. Note that the *United Nations Framework Convention on Climate Change (UNFCCC)*, in its Article 1, 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 the atmospheric composition and *climate variability* attributable to natural causes.

Climate change commitment The unavoidable future *climate change* resulting from inertia in the geophysical and socio-economic systems. Different types of climate change commitment are discussed in the literature. Climate change commitment is usually quantified in terms of the further change in temperature, but it includes other future changes, for example in the hydrological cycle, in *extreme weather events*, in extreme climate events, and in sea level.

Zero emissions commitment
The zero emissions commitment is an estimate of the subsequent *global warming* that would result after *anthropogenic emissions* are set to zero. It is determined by both inertia in physical *climate system* components (ocean, cryosphere, land surface) and *carbon cycle* inertia. In its widest sense it refers to emissions of each climate *forcer* including *greenhouses gases*, *aerosols* and their precursors. The climate response to this can be complex due to the different climate response time scale of each climate forcer. A specific sub-category of zero emissions commitment is the Zero CO_2 Emissions Commitment which refers to the climate system response to CO_2 emissions after setting these to net zero. The CO_2-only definition is of specific use in estimating *remaining carbon budgets*.

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. By definition, the characteristics of what is called *extreme weather* may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classified as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., high temperature, *drought*, or heavy rainfall over a season). For simplicity, both extreme weather events and extreme climate events are referred to collectively as 'climate extremes'.

Climate finance There is no agreed definition of climate finance. The term 'climate finance' is applied to the financial resources devoted to addressing climate change by all public and private actors from global to local scales, including international financial flows to developing countries to assist them in addressing climate change. Climate finance aims to reduce net *greenhouse gas* emissions and/or to enhance adaptation and increase resilience to the impacts of current and projected climate change. Finance can come from private and public sources, channelled by various intermediaries, and is delivered by a range of instruments, including grants, concessional and non-concessional debt, and internal budget reallocations.

Climate governance See *Governance*.

Climate justice See *Justice*.

Climate model A qualitative or quantitative representation of the *climate* system based on the physical, chemical and biological properties of its components, their interactions and feedback processes and accounting for some of its known properties. The *climate system* can be represented by models of varying complexity; that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parametrisations are involved. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate and for operational purposes, including monthly, seasonal and interannual climate predictions. See also *Simple climate model (SCM)* and *Emulators*.

Climate projection Simulated response of the *climate system* to a *scenario* of future emissions or concentrations of *greenhouse gases (GHGs)* and *aerosols* and changes in *land use*, generally derived using *climate models*. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/radiative forcing *scenario* used, which is in turn based on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realised.

Climate sensitivity The change in the surface temperature in response to a change in the *atmospheric carbon dioxide (CO_2)* concentration or other *radiative forcing*.

Transient climate response (TCR)
The surface temperature response for the hypothetical scenario in which atmospheric *carbon dioxide (CO_2)* increases at 1% yr^{-1} from *pre-industrial* to the time of a doubling of atmospheric CO_2 concentration (year 70).

Transient climate response to cumulative CO2 emissions (TCRE)
The transient surface temperature change per unit cumulative *carbon dioxide (CO_2)* emissions, usually 1000 GtC. TCRE combines both information on the airborne fraction of cumulative CO_2 emissions (the fraction of the total CO_2 emitted that remains in the *atmosphere*, which is determined by *carbon cycle* processes) and on the *transient climate response (TCR)*.

Climate services Climate services involve the provision of climate information in such a way as to assist decision-making. The service includes appropriate engagement from users and providers, is based on scientifically credible information and expertise, has an effective access mechanism, and responds to user needs (Hewitt et al. 2012).

Climate system The global system consisting of five major components: the *atmosphere*, the hydrosphere, the cryosphere, the lithosphere and the biosphere and the interactions between them. The climate system changes in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations, orbital forcing, and *anthropogenic* forcings such as the changing composition of the atmosphere and *land-use change*.

Climate variability Deviations of climate variables from a given mean state (including the occurrence of extremes, etc.) at all spatial and temporal scales beyond that of individual weather events. Variability may be intrinsic, due to fluctuations of processes internal to the *climate system* (*internal variability*), or extrinsic, due to variations in natural or anthropogenic external forcing (forced variability). See also *Climate change*.

Co-benefits A positive effect that a policy or measure aimed at one objective has on another objective, thereby increasing the total benefit to society or the environment. Co-benefits are also referred to as ancillary benefits. See also *Adverse side-effect* and *Trade-off*.

CO_2 equivalent (CO_2-eq) emission The amount of *carbon dioxide (CO_2)* emission that would have an equivalent effect on a specified key measure of *climate change*, over a specified time horizon, as an emitted amount of another *greenhouse gas (GHG)* or a mixture of other GHGs. For a mix of GHGs, it is obtained by summing the CO_2-equivalent emissions of each gas. There are various ways and time horizons to compute such equivalent emissions (see *greenhouse gas emission metric*). CO_2-equivalent emissions are commonly used to compare emissions of different GHGs, but should not be taken to imply that these emissions have an equivalent effect across all key measures of climate change.

[Note: Under the Paris Rulebook [Decision 18/CMA.1, annex, paragraph 37], parties have agreed to use GWP100 values from the IPCC AR5 or GWP100 values from a subsequent IPCC Assessment Report to report aggregate emissions and removals of GHGs. In addition, parties may use other metrics to report supplemental information on aggregate emissions and removals of GHGs.]

Concentrations scenario See *Scenario*.

Conference of the Parties (COP) The supreme body of UN conventions, such as the *United Nations Framework Convention on*

Climate Change (UNFCCC), comprising parties with a right to vote that have ratified or acceded to the convention.

Confidence The robustness of a finding based on the type, amount, quality and consistency of *evidence* (e.g., mechanistic understanding, theory, data, models, expert judgement) and on the degree of *agreement* across multiple lines of evidence. In this report, confidence is expressed qualitatively (Mastrandrea et al. 2010).

Conservation agriculture A farming system that promotes minimum soil disturbance (e.g., by using no till practices), maintenance of a permanent soil cover, and diversification of plant species. It aims to prevent *land degradation* and regenerate degraded lands by enhancing *biodiversity* and natural biological processes above and below the ground surface, that contribute to increased water and nutrient use efficiency and improved and sustained crop production (FAO 2016).

Consumption-based emissions Emissions released to the atmosphere in order to generate the goods and services consumed by a certain entity (e.g., a person, firm, country, or region). See also *Production-based emissions*.

Coping capacity The ability of people, *institutions*, organisations, and systems, using available skills, values, beliefs, resources, and opportunities, to address, manage, and overcome adverse conditions in the short to medium term (UNISDR 2009; IPCC 2012). See also *Resilience*.

Cost-benefit analysis A type of economic evaluation that compares all monetised negative and positive impacts associated with a given action. Cost-benefit analysis enables comparison of different interventions, investments or strategies, and reveals how a given investment or policy effort pays off for a particular person, company or country, or at a global scale. Cost-benefit analyses representing society's point of view are important for *climate change* decision-making, but there are difficulties in aggregating costs and benefits across different actors and across time scales. See also *Discounting*.

Cost-effectiveness analysis (CEA) A type of economic evaluation that compares the costs of different courses of action reaching the same outcome. In this report, CEA focuses on comparing the costs of *mitigation* strategies designed to meet a prespecified *climate change* mitigation goal (e.g., an emission-reduction target or a temperature stabilisation target).

Cumulative emissions The total amount of emissions released over a specified period of time. See also *Carbon budget* and *Transient climate response to cumulative* CO_2 *emissions (TCRE)*.

Decarbonisation Human actions to reduce *carbon dioxide* emissions from human activities.

Decent Living Standard A set of minimal material requirements essential for achieving basic human *well-being* including nutrition, shelter, basic living conditions, clothing, healthcare, education, and mobility (Rao and Baer 2012; Rao and Min 2018; O'Neill et al. 2018).

Decoupling Decoupling (in relation to climate change) is where economic growth is no longer strongly associated with another relevant indicator such as *greenhouse gas* emissions. Relative decoupling is where both these indicators grow but the other indicators grow more slowly than the economy. Absolute decoupling is where there is economic growth but there is a decline in the other indicator.

Deforestation Conversion of *forest* to non-forest.

[Note: For a discussion of the term *forest* and related terms such as *afforestation*, *reforestation* and *deforestation*, see the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and their 2019 Refinement, and information provided by the United Nations Framework Convention on Climate Change (IPCC 2006, 2019; UNFCCC 2021a,b).]

See also *Reducing Emissions from Deforestation and Forest Degradation (REDD+)*.

Deliberative governance See *Governance*.

Demand Disciplinary approaches use the term in different ways. In economics, demand by a consumer is willingness and ability to purchase in a marketplace. However, the motivation for purchase may vary and can include economic utility, welfare, *Decent standard of living (DSL)*, or for the good/services.

Demand- and supply-side measures

Demand-side measures
Policies and programmes for influencing the *demand* for goods and/or services. In the energy sector, demand-side mitigation measures aim at reducing the amount of *greenhouse gas* emissions emitted per unit of energy service used.

Supply-side measures
Policies and programmes for influencing how a certain *demand* for goods and/or services is met. In the energy sector, supply-side mitigation measures aim at reducing the amount of *greenhouse gas* emissions emitted per unit of energy service produced.

Demand-side management See *Demand-side measures*.

Desertification *Land degradation* in arid, semi-arid, and dry sub-humid areas resulting from many factors, including climatic variations and human activities (UNCCD 1994).

Developed/developing countries (Industrialised/developed/developing countries) There is a diversity of approaches for categorising countries on the basis of their level of development, and for defining terms such as 'industrialised', 'developed', or 'developing'. Several categorisations are used in this report: (i) In the United Nations (UN) system, there is no established convention for the designation of developed and developing countries or areas. (ii) The UN Statistics Division specifies developed and developing regions based on common practice. In addition, specific countries are designated as least developed countries, landlocked developing countries, *Small Island Developing States (SIDS)*, and transition economies. Many countries appear in more than one of these categories. (iii) The World Bank uses income as the main criterion for classifying countries as low, lower middle, upper middle, and high income. (iv) The UN Development Programme (UNDP) aggregates indicators for life expectancy, educational attainment, and income into a single composite Human Development Index (HDI) to classify countries as low, medium, high, or very high human development.

Development pathway See *Pathways*.

Diet The kinds of food that follow a particular pattern that a person or community eats (FAO and Alliance of Bioversity International and CIAT, 2021).

Direct air capture (DAC) Chemical process by which a pure *carbon dioxide (CO_2)* stream is produced by capturing CO_2 from the ambient air. See also *Anthropogenic removals*, *Carbon dioxide removal (CDR)* and *Direct air carbon dioxide capture and storage (DACCS)*.

Direct air carbon dioxide capture and storage (DACCS) Chemical process by which *carbon dioxide* (*CO_2*) is captured directly from the ambient air, with subsequent storage. Also known as direct air capture and storage (DACS). See also *Anthropogenic removals*, *Carbon dioxide removal (CDR)* and *Direct air capture (DAC)*.

Direct and indirect services Direct Services: Services (e.g., passenger mobility) required by end-users (consumers). Indirect services: Services required (e.g., goods transport, manufacturing) for provisioning systems of direct services.

Direct emissions Emissions that physically arise from activities within well-defined boundaries of, for instance, a *region*, an economic sector, a company, or a process. See also *Indirect emissions*.

Disaster A 'serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts' (UNGA 2016). See also *Exposure*, *Hazard*, *Risk* and *Vulnerability*.

Disaster risk management (DRM) Processes for designing, implementing, and evaluating strategies, policies, and measures to improve the understanding of current and future disaster *risk*, foster *disaster* risk reduction and transfer, and promote continuous improvement in disaster preparedness, prevention and protection, response, and recovery practices, with the explicit purpose of increasing human security, *well-being*, quality of life, and *sustainable development (SD)*.

Discount rate See *Discounting*.

Discounting A mathematical operation that aims to make monetary (or other) amounts received or expended at different times (years) comparable across time. If the discount rate is positive, future values are given less weight than those today. The choice of discount rate(s) is debated as it is a judgement based on hidden and/or explicit values.

Disruptive innovation Demand-led technological change that leads to significant system change and is characterised by strong exponential growth.

Distributive equity See *Equity*.

Drought An exceptional period of water shortage for existing *ecosystems* and the human population (due to low rainfall, high temperature, and/or wind).

Ecosystem A functional unit consisting of living organisms, their non-living environment and the interactions within and between them. The components included in a given ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined: in some cases they are relatively sharp, while in others they are diffuse. Ecosystem boundaries can change over time. Ecosystems are nested within other ecosystems and their scale can range from very small to the entire biosphere. In the current era, most ecosystems either contain people as key organisms, or are influenced by the effects of human activities in their environment. See also *Ecosystem services*.

Ecosystem services Ecological processes or functions having monetary or non-monetary value to individuals or society at large. These are frequently classified as: (i) supporting services such as productivity or biodiversity maintenance; (ii) provisioning services such as food or fibre; (iii) regulating services such as climate regulation or carbon *sequestration*; and (iv) cultural services such as tourism or spiritual and aesthetic appreciation. See also *Ecosystem* and *Nature's Contribution to People*.

Ecosystem-based adaptation (EBA) The use of *ecosystem* management activities to increase the *resilience* and reduce the *vulnerability* of people and *ecosystems* to *climate change* (Campbell et al. 2009).

Embodied (embedded) [emissions, water, land] The total emissions [water use, *land use*] generated [used] in the production of goods and services regardless of the location and timing of those emissions [water use, land use] in the production process. This includes emissions [water use, land use] within the country used to produce goods or services for the country's own use, but also includes the emissions [water use, land use] related to the production of such goods or services in other countries that are then consumed in another country through imports. Such emissions [water, land] are termed 'embodied' or 'embedded' emissions, or, in some cases, (particularly with water) as 'virtual water use' (Davis and Caldeira 2010; Allan 2005; MacDonald et al. 2015).

Emission and Socioe-conomic Scenario Ensemble A set of modelled emission and socio-economic *scenarios* collected in a database. The scenarios can come from a single multi-model study with systematic variation of harmonised scenario designs (structured ensemble) or from multiple studies in the literature (unstructured ensemble). Depending on the scope of the ensemble, variation of the results across the scenarios in the ensemble give an indication of the spread of results in the literature (unstructured ensemble), or an estimate of uncertainties due to different modelling structures and methodologies (structured ensemble).

Emission factor/Emissions intensity A coefficient that quantifies the emissions or removals of a gas per unit activity. Emission factors are often based on a sample of measurement data, averaged to develop a representative rate of emission for a given activity level under a given set of operating conditions.

Emission pathways See *Pathways*.

Emission trajectories A projected development in time of the emission of a *greenhouse gas (GHG)* or group of GHGs, *aerosols*, and GHG *precursors*. See also *Pathways*.

Emissions See *Anthropogenic emissions*, *Direct emissions*, *Cumulative emissions*, *Indirect emissions*, *Consumption-based emissions*, *Production-based emissions* and *Embodied (embedded) [emissions, water, land]*.

Emissions scenario See *Scenario*.

Emulation Reproducing the behaviour of complex, process-based models – namely, Earth System Models (ESMs) – via simpler approaches, using either *emulators* or *simple climate models (SCMs)*. The computational efficiency of emulating approaches opens new analytical possibilities, given that ESMs take a lot of computational resources for each simulation.

Emulators A broad class of heavily parametrised models ('simple climate models'), statistical methods like neural networks, genetic algorithms or other artificial intelligence approaches, designed to reproduce the responses of more complex, process-based Earth System Models (ESMs). The main application of emulators is to extrapolate insights from ESMs and observational constraints to a larger set of emission scenarios. See also *Emulation* and *Simple climate models (SCMs)*.

Enabling conditions (for adaptation and mitigation options) 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.

Energy access Access to clean, reliable and affordable energy services for cooking and heating, lighting, communications, and productive uses (with special reference to *Sustainable Development Goal* 7) (AGECC 2010). See also *Traditional biomass*.

Energy efficiency The ratio of output or useful energy or energy services or other useful physical outputs obtained from a system, conversion process, transmission or storage activity to the input of energy (measured as kWh kWh^{-1}, tonnes kWh^{-1} or any other physical measure of useful output like tonne-km transported). Energy efficiency is often described by energy intensity.

Energy poverty The absence of sufficient choice in accessing adequate, affordable, reliable, high quality, safe and environmentally benign energy services to support economic and human development (Reddy 2000). See also *Fuel poverty*.

Energy security The goal of a given country, or the global community as a whole, to maintain an adequate, stable and predictable energy supply. Measures encompass safeguarding the sufficiency of energy resources to meet national energy demand at competitive and stable prices and the resilience of the energy supply; enabling development and deployment of technologies; building sufficient infrastructure to generate, store and transmit energy supplies and ensuring enforceable contracts of delivery.

Energy services A benefit or amenity (e.g., mobility, communication, thermal comfort) received as a result of energy or other resources use.

Enhanced weathering A proposed method to increase the natural rate of removal of *carbon dioxide* (CO_2) from the *atmosphere* using silicate and carbonate rocks. The active surface area of these minerals is increased by grinding, before they are actively added to soil, beaches or the open ocean. See also *Anthropogenic removals* and *Carbon dioxide removal (CDR)*.

Ensemble A collection of comparable datasets that reflect variations within the bounds of one or more sources of *uncertainty*, and that when averaged can provide a more robust estimate of underlying behaviour. Ensemble techniques are used by the observational, reanalysis and modelling communities. See also *Emission and Socio-economic Scenario Ensemble* and *Integrated Assessment Scenario Ensemble*.

Enteric fermentation A natural part of the digestion process in ruminant animal species (domesticated and wild), such as cattle, buffalo, sheep, goats, antelope, etc. Microorganisms (bacteria, archaea, fungi, protozoa and viruses) present in the fore-stomach (reticulorumen or rumen) breakdown plant *biomass* to produce substrates that can be used by the animal for energy and growth with methane produced as a by-product. Fermentation end-products such as hydrogen, *carbon dioxide*, formate and methyl-containing compounds are important substrates for the production of methane by the rumen's methane-forming archaea (known as methanogens).

Equality A principle that ascribes equal worth to all human beings, including equal opportunities, rights, and obligations, irrespective of origins.

Inequality
Uneven opportunities and social positions, and processes of discrimination within a group or society, based on gender, class, ethnicity, age, and (dis)ability, often produced by uneven development. Income inequality refers to gaps between highest and lowest income earners within a country and between countries.

See also *Equity* and *Fairness*.

Equity The principle of being fair and impartial, and a basis for understanding how the *impacts* and responses to *climate change*, including costs and benefits, are distributed in and by society in more or less equal ways. Often aligned with ideas of *equality*, *fairness* and *justice* and applied with respect to equity in the responsibility for, and distribution of, *climate* impacts and policies across society, generations, and gender, and in the sense of who participates and controls the processes of decision-making.

Distributive equity
Equity in the consequences, outcomes, costs and benefits of actions or policies. In the case of *climate change* or climate policies for different people, places and countries, including equity aspects of sharing burdens and benefits for mitigation and adaptation.

Gender equity
Equity between women and men with regard to their rights, resources and opportunities. In the case of climate change, gender equity recognises that women are often more vulnerable to the impacts of climate change and may be disadvantaged in the process and outcomes of climate policy.

Inter-generational equity
Equity between generations. In the context of climate change, inter-generational equity acknowledges that the effects of past and present emissions, vulnerabilities and policies impose costs and benefits for people in the future and of different age groups.

Evidence Data and information used in the scientific process to establish findings. In this report, the degree of evidence reflects the amount, quality and consistency of scientific/technical information on which the Lead Authors are basing their findings. See also *Agreement*, *Confidence*, *Likelihood*, and *Uncertainty*.

Exergy Capacity of energy flows to perform useful work. Exergy is a quality (versatility) indicator of energy flows which ranges from low (e.g., low-temperature heat, biomass) to high (e.g., electricity). Exergy efficiency describes how much useful work can be performed by a particular energy flow in relation to the thermodynamic maximum possible. It can be determined for all energy flows and energy conversion steps, also including alternative service delivery systems (Grubler et al. 2012).

Exposure 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.

Extreme weather event An event that is rare at a particular place and time of year. Definitions of 'rare' vary, but an extreme weather event would normally be as rare as, or rarer than, the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. See also *Climate extreme (extreme weather or climate event)*.

Fairness Impartial and just treatment without favouritism or discrimination in which each person is considered of equal worth with equal opportunity. See also *Equality* and *Equity*.

Feasibility 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. See also *Enabling conditions (for adaptation and mitigation options)*.

Final energy The energy delivered to final users (firms, individuals, *institutions*), where it becomes usable energy in supplying energy services (e.g., light, heat, mobility). See also *Primary energy*.

Flexibility (demand and supply) Adjustment of energy load characteristics by technical and/or non-technical change to balance energy demand and supply.

Flexible governance See *Governance*.

Flood The overflowing of the normal confines of a stream or other water body, or the accumulation of water over areas that are not normally submerged. Floods can be caused by unusually heavy rain, for example, during storms and cyclones. Floods include river (fluvial) floods, flash floods, *urban* floods, rain (pluvial) floods, sewer floods, coastal floods, and glacial lake outburst floods (GLOFs).

Food loss and waste 'The decrease in quantity or quality of food'. Food waste is part of food loss and refers to discarding or alternative (non-food) use of food that is safe and nutritious for human consumption along the entire food supply chain, from primary production to end household consumer level. Food waste is recognised as a distinct part of food loss because the drivers that generate it and the solutions to it are different from those of food losses (FAO 2015).

Food security 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. The four pillars of food security are: availability; access; utilisation; and stability. The nutritional dimension is integral to the concept of food security (FAO 2009, 2018).

Access
Economic and/or physical access to food. Economic access is determined by disposable income, food prices and the provision of and access to social support. Physical access is determined by the availability and quality of land and other infrastructure, property rights or the functioning of markets.

Availability
Physical availability of food. Food availability addresses the supply side of food security and is determined by the levels of food production, stocks and net trade.

Stability
The stability of the other three dimensions over time. Even if individuals' food intake is adequate today, they are still considered food-insecure if periodically they have inadequate access to food, risking deterioration of their nutrition status. Adverse weather conditions, political instability or economic factors (unemployment, rising food prices) may have an impact on individuals' food security status.

Utilisation
The way in which the body uses the various nutrients in food. Individuals achieve sufficient energy and nutrient intake through good care and feeding practices, food preparation, diet diversity and intra-household distribution of food. Combined with biological utilisation of the food consumed, energy and nutrient intake determine the nutrition status of individuals.

Food system 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 socio-economic and environmental outcomes (HLPE 2017).

[Note: Whilst there is a global food system (encompassing the totality of global production and consumption), each location's food system is unique, being defined by that place's mix of food produced locally, nationally, regionally or globally.]

Forest A vegetation type dominated by trees. Many definitions of the term forest are in use throughout the world, reflecting wide differences in biogeophysical conditions, social structure and economics.

[Note: For a discussion of the term forest in the context of National GHG inventories, see the 2006 IPCC Guidelines for National GHG Inventories and their 2019 Refinement, and information provided by the United Nations Framework Convention on Climate Change (IPCC 2006, 2019; UNFCCC 2021a,b).]

Fossil fuels Carbon-based fuels from fossil hydrocarbon deposits, including coal, oil, and natural gas.

Fuel poverty A condition in which a household is unable to guarantee a certain level of consumption of domestic energy services (especially heating) or suffers disproportionate expenditure burdens to meet these needs. See also *Energy poverty*.

Fugitive emissions (oil and natural gas systems) The release of *greenhouse gases* that occur during the exploration, processing and delivery of *fossil fuels* to the point of final use. This excludes *greenhouse gas emissions* from fuel combustion for the production of useful heat or power. It encompasses venting, flaring, and leaks.

Gender equity See *Equity*.

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. See also *Renewable energy*.

Gini coefficient A statistical measure of dispersion in a distribution and degree of mathematical measure of *inequality*. For example, it can be used for measuring inequality in income, wealth, carbon emissions, and access to well-being defining services. The dimensionless GINI coefficient ranges between 0 (absolute *equality*) and 1 (absolute inequality).

Global carbon budget See *Carbon budget*.

Global mean surface air temperature (GSAT) Global average of near-surface air temperatures over land, oceans and sea ice. Changes in GSAT are often used as a measure of global temperature change in *climate models*. See also *Global mean surface temperature (GMST)*.

Global mean surface temperature (GMST) Estimated global average of near-surface air temperatures over land and sea ice, and *sea surface temperature (SST)* over ice-free ocean regions, with changes normally expressed as departures from a value over a specified *reference period*. See also *Global mean surface air temperature (GSAT)*.

Global warming Global warming refers to the increase in *global surface temperature* relative to a baseline *reference period*, averaging over a period sufficient to remove interannual variations (e.g., 20 or 30 years). A common choice for the baseline is 1850–1900 (the earliest period of reliable observations with sufficient geographic coverage), with more modern baselines used depending upon the application. See also *Climate change* and *Climate variability*.

Global warming potential (GWP) An index measuring the *radiative forcing* following an emission of a unit mass of a given substance, accumulated over a chosen time horizon, relative to that of the reference substance, *carbon dioxide* (CO_2). The GWP thus represents the combined effect of the differing times these substances remain in the atmosphere, and their effectiveness in causing radiative forcing. See also *Greenhouse gas emission metric*.

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.

Adaptive governance
Adjusting to changing conditions, such as climate change, through governance interactions that seek to maintain a desired state in a social-ecological system.

Climate governance
The structures, processes, and actions through which private and public actors seek to mitigate and adapt to climate change.

Deliberative governance
Deliberative governance involves decision-making through inclusive public conversation which allows opportunity for developing policy options through public discussion rather than collating individual preferences through voting or referenda (although the latter governance mechanisms can also be preceded and legitimated by public deliberation processes).

Flexible governance
Strategies of governance at various levels, which prioritise the use of social learning and rapid feedback mechanisms in planning and policymaking, often through incremental, experimental and iterative management processes.

Multi-level governance
The dispersion of governance across multiple levels of jurisdiction and decision-making, including, global, regional, national and local, as well as trans-regional and trans-national levels.

Participatory governance
A governance system that enables direct public engagement in decision-making using a variety of techniques, for example, referenda, community deliberation, citizen juries or participatory budgeting. The approach can be applied in formal and informal institutional contexts from national to local, but is usually associated with devolved decision-making (Fung and Wright 2003; Sarmiento and Tilly 2018).

Governance capacity The ability of governance *institutions*, leaders, and non-state and civil society to plan, coordinate, fund, implement, evaluate and adjust policies and measures over the short, medium and long term, adjusting for uncertainty, rapid change and wide-ranging impacts and multiple actors and demands. See also *Governance*.

Grazing land The sum of rangelands and pastures not considered as cropland, and subject to livestock grazing or hay production. It includes a wide range of *ecosystems*, for example, systems with vegetation that fall below the threshold used in the *forest* land category, silvo-pastoral systems, as well as natural, managed grasslands and semi-deserts.

Green Climate Fund (GCF) The GCF was established by the 16th Session of the *Conference of the Parties (COP)* in 2010 as an operating entity of the financial mechanism of the *United Nations Framework Convention on Climate Change (UNFCCC)*, in accordance with Article 11 of the Convention, to support projects, programmes and policies and other activities in developing country Parties. The Fund is governed by a Board and will receive guidance of the COP. See also *Climate finance*.

Green infrastructure See *Infrastructure*.

Greenhouse gas emission metric A simplified relationship used to quantify the effect of emitting a unit mass of a given *greenhouse gas (GHG)* on a specified key measure of *climate change*. A relative GHG emission metric expresses the effect from one gas relative to the effect of emitting a unit mass of a reference GHG on the same measure of climate change. There are multiple emission metrics, and the most appropriate metric depends on the application. GHG emission metrics may differ with respect to: (i) the key measure of climate change they consider; (ii) whether they consider climate outcomes for a specified point in time or integrated over a specified time horizon; (iii) the time horizon over which the metric is applied; (iv) whether they apply to a single emission pulse, emissions sustained over a period of time, or a combination of both; and (v) whether they consider the climate effect from an emission compared to the absence of that emission or compared to a reference emissions level or climate state.

[Note: Most relative GHG emission metrics (such as the *global warming potential (GWP)*, global temperature change potential (GTP), global damage potential, and GWP*), use carbon dioxide *(CO_2)* as the reference gas. Emissions of non-CO_2 gases, when expressed using such metrics, are often referred to as 'carbon dioxide equivalent' emissions. A metric that establishes equivalence regarding one key measure of the *climate system* response to emissions does not imply equivalence regarding other key measures. The choice of a metric, including its time horizon, should reflect the policy objectives for which the metric is applied.]

Greenhouse gas neutrality Condition in which metric-weighted anthropogenic *greenhouse gas (GHG)* emissions associated with a subject are balanced by metric-weighted *anthropogenic* GHG removals. The subject can be an entity such as a country, an organisation, a district or a commodity, or an activity such as a service and an event. GHG neutrality is often assessed over the lifecycle, including indirect ('scope 3') emissions, but can also be limited to the emissions and removals, over a specified period, for which the subject has direct control, as determined by the relevant scheme. The quantification of GHG emissions and removals depends on the GHG emission metric chosen to compare emissions and removals of different gases, as well as the time horizon chosen for that metric.

[Note 1: Greenhouse gas neutrality and net-zero greenhouse gas emissions are overlapping concepts. The concepts can be applied at global or sub-global scales (e.g., regional, national and sub-national). At a global scale, the terms greenhouse gas neutrality and net-zero greenhouse gas emissions are equivalent. At sub-global scales, net-zero GHG emissions is generally applied to emissions and removals under direct control or territorial responsibility of the reporting entity, while GHG neutrality generally includes emissions and removals within and beyond the direct control or territorial responsibility of the reporting entity. Accounting rules specified by GHG programmes or schemes can have a significant influence on the quantification of relevant emissions and removals.

Note 2: Under the Paris Rulebook (Decision 18/CMA.1, annex, paragraph 37), parties have agreed to use GWP100 values from the IPCC AR5 or GWP100 values from a subsequent IPCC Assessment Report to report aggregate emissions and removals of GHGs. In addition, parties may use other metrics to report supplemental information on aggregate emissions and removals of GHGs.

Note 3: In some cases, achieving greenhouse gas neutrality may rely on the supplementary use of *offsets* to balance emissions that remain after actions by the reporting entity are taken into account.]

See also *Carbon neutrality*, *Greenhouse gas emission metric*, *Land use*, *Land-use change and forestry (LULUCF)* and *Net-zero greenhouse gas emissions*.

Greenhouse gases (GHGs) Gaseous constituents of the *atmosphere*, both natural and *anthropogenic*, that absorb and emit radiation at specific wavelengths within the spectrum of radiation emitted by the Earth's surface, by the atmosphere itself, and by 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 GHGs in the Earth's atmosphere. Human-made GHGs include sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs), chlorofluorocarbons (CFCs) and perfluorocarbons (PFCs); several of these are also O_3-depleting (and are regulated under the Montreal Protocol).

Grey infrastructure See *Infrastructure*.

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. GDP is calculated without deducting for depreciation of fabricated assets or depletion and degradation of natural resources.

Halocarbons A collective term for the group of partially halogenated organic species, which includes the chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), halons, methyl chloride and methyl bromide. Many of the halocarbons have large *global warming potentials*. The chlorine and bromine-containing halocarbons are also involved in the depletion of the ozone layer.

Human behaviour The responses of persons or groups to a particular situation, here likely to relate to *climate change*. Human behaviour covers the range of actions by individuals, communities, *organisations*, governments and at the international level.

Human rights Rights that are inherent to all human beings, universal, inalienable, and indivisible, typically expressed and guaranteed by law. They include the right to life, economic, social, and cultural rights, and the right to development and self-determination (OHCHR 2018).

Human security A condition that is met when the vital core of human lives is protected, and when people have the freedom and capacity to live with dignity. In the context of *climate change*, the vital core of human lives includes the universal and culturally specific, material and non-material elements necessary for people to act on behalf of their interests and to live with dignity.

Human system Any system in which human organisations and *institutions* play a major role. Often, but not always, the term is synonymous with society or social system. Systems such as agricultural systems, urban systems, political systems, technological systems and economic systems are all human systems in the sense applied in this report.

Hydropower Power harnessed from the flow of water. See also *Renewable energy*.

Impacts The consequences of realised *risks* on natural and *human systems*, where risks result from the interactions of climate-related *hazards* (including *extreme weather/climate events*), *exposure*, and *vulnerability*. Impacts generally refer to effects on lives, *livelihoods*, health and *well-being*, *ecosystems* and species, economic, social and cultural assets, services (including *ecosystem services*), and *infrastructure*. Impacts may be referred to as consequences or outcomes, and can be adverse or beneficial. See also *Adaptation*, *Loss and Damage*, *and losses and damages*.

Indigenous knowledge The understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings. For many indigenous peoples, indigenous knowledge informs decision-making about fundamental aspects of life, from day-to-day activities to longer-term actions. This knowledge is integral to cultural complexes, which also encompass language, systems of classification, resource use practices, social interactions, values, ritual and spirituality. These distinctive ways of knowing are important facets of the world's cultural diversity (UNESCO 2018). See also *Local knowledge*.

Indirect emissions Emissions that are a consequence of the activities within well-defined boundaries of, for instance, a *region*, an economic sector, a company or process, but which occur outside the specified boundaries. For example, emissions are described as indirect if they relate to the use of heat but physically arise outside the boundaries of the heat user, or to electricity production but physically arise outside of the boundaries of the power supply sector. See also *Direct emissions*.

Indirect land-use change (iLUC) See *Land-use change (LUC)*.

Industrial revolution A period of rapid industrial growth with far-reaching social and economic consequences, beginning in Britain during the second half of the 18th century and spreading to Europe and later to other countries including the United States. The invention of the steam engine was an important trigger of this development. The industrial revolution marks the beginning of a strong increase in the use of *fossil fuels*, initially coal, and hence emission of *carbon dioxide* (CO_2).

Inequality See *Equality*.

Infrastructure The designed and built set of physical systems and corresponding *institutional* arrangements that mediate between people, their communities, and the broader environment to provide services that support economic growth, health, quality of life, and safety (Chester 2019; Dawson et al. 2018).

Blue infrastructure
Blue infrastructure includes bodies of water, watercourses, ponds, lakes and storm drainage, that provide ecological and hydrological functions including evaporation, transpiration, drainage, infiltration, and temporary storage of runoff and discharge.

Green infrastructure
The strategically planned interconnected set of natural and constructed ecological systems, green spaces and other landscape features that can provide functions and services including air and water purification, temperature management, floodwater management and coastal defence often with co-benefits for people and biodiversity. Green infrastructure includes planted and remnant native vegetation, soils, wetlands, parks and green open spaces, as well as building and street-level design interventions that incorporate vegetation (Bobbins and Culwick 2016).

Grey infrastructure
Engineered physical components and networks of pipes, wires, roads, tracks that underpin energy, transport, communications (including digital), built form, water and sanitation and solid waste management systems.

Social infrastructure
The social, cultural, and financial activities and institutions as well as associated property, buildings and artefacts and policy domains such as social protection, health and education that support well-being and public life (Latham and Layton 2019; Frolova et al. 2016).

Institutional capacity Building and strengthening individual organisations and providing technical and management training to support integrated planning and decision-making processes between organisations and people, as well as empowerment, social capital, and an enabling environment, including the culture, values and power relations (Willems and Baumert 2003). See also *Governance* and *Institutions*.

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.

[Note: Institutions can also refer to a large organisation.]

See also *Institutional capacity*.

Integrated assessment A method of analysis that combines results and models from the physical, biological, economic and social sciences and the interactions among these components in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it. See also *Integrated assessment model (IAM)*.

Integrated assessment model (IAM) Models that integrate knowledge from two or more domains into a single framework. They are one of the main tools for undertaking integrated assessments. One class of IAM used with respect to climate change *mitigation* may include representations of: multiple sectors of the economy, such as energy, *land use* and *land-use change*; interactions between sectors; the economy as a whole; associated *greenhouse gas (GHG)* emissions and *sinks*; and reduced representations of the *climate system*. This class of model is used to assess linkages between economic, social and technological development and the evolution of the climate system. Another class of IAM additionally includes representations of the costs associated with climate change *impacts*, but includes less detailed representations of economic systems. These can be used to assess impacts and mitigation in a cost–benefit framework and have been used to estimate the *social cost of carbon*. See also *Integrated Assessment Scenario Ensemble*.

Integrated Assessment Scenario Ensemble A set of modelled scenarios from an intercomparison of *integrated assessment models (IAMs)* based on a systematic variation of harmonised scenario designs.

Inter-generational equity See *Equity*.

Internet of Things (IoT) The network of computing devices embedded in everyday objects such as cars, phones and computers, connected via the internet, enabling them to send and receive data.

Irreversibility A perturbed state of a dynamical system is defined as irreversible on a given time scale if the recovery from this state due to natural processes takes substantially longer than the time scale of interest. See also *Tipping point*.

Just transitions A set of principles, processes and practices that aim to ensure that no people, workers, places, sectors, countries or regions are left behind in the transition from a high-carbon to a low-carbon economy. It stresses the need for targeted and proactive measures from governments, agencies, and authorities to ensure that any negative social, environmental or economic impacts of economy-wide transitions are minimised, whilst benefits are maximised for those disproportionally affected. Key principles of just transitions include: respect and dignity for vulnerable groups; fairness in energy access and use, social dialogue and democratic consultation with relevant stakeholders; the creation of decent jobs; social protection; and rights at work. Just transitions could include fairness in energy, land use and climate planning and decision-making processes; economic diversification based on low-carbon investments; realistic training/retraining programmes that lead to decent work; gender-specific policies that promote equitable outcomes; the fostering of international cooperation and coordinated multilateral actions; and the eradication of poverty. Lastly, just transitions may embody the redressing of past harms and perceived injustices (ILO 2015; UNFCCC 2016).

Justice Justice is concerned with ensuring that people get what is due to them, 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.

Climate justice
Justice that links development and human rights to achieve a human-centred approach to addressing *climate change*, safeguarding the rights of the most vulnerable people and sharing the burdens and benefits of climate change and its impacts equitably and fairly (MRFCJ 2018).

Kaya identity In this identity, global emissions are equal to the population size, multiplied by per capita output (gross world product), multiplied by the energy intensity of production, multiplied by the carbon intensity of energy.

Land 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 (FAO 2007; UNCCD 1994).

Land cover The biophysical coverage of *land* (e.g., bare soil, rocks, forests, buildings and roads or lakes). Land cover is often categorised in broad land-cover classes (e.g., deciduous forest, coniferous forest, mixed forest, grassland, bare ground).

[Note: In some literature, land cover and land use are used interchangeably, but the two represent distinct classification systems. For example, the land cover class woodland can be under various land uses such as livestock grazing, recreation, conservation, or wood harvest.]

Land cover change Change from one *land cover* class to another, due to change in *land use* or change in natural conditions (Pongratz et al. 2018).

Land degradation A negative trend in land condition, caused by direct or indirect human-induced processes including *anthropogenic* climate change, expressed as long-term reduction or loss of at least one of the following: biological productivity, ecological integrity or value to humans.

[Note: This definition applies to *forest* and non-forest land. Changes in land condition resulting solely from natural processes (such as volcanic eruptions) are not considered to be land degradation. Reduction of biological productivity or ecological integrity or value to humans can constitute degradation, but any one of these changes need not necessarily be considered degradation.]

See also *Desertification*.

Land degradation neutrality A state whereby the amount and quality of land resources necessary to support *ecosystem* functions and services and enhance *food security* remain stable or increase within specified temporal and spatial scales and ecosystems (UNCCD 2020).

Land management Sum of land-use practices (e.g., sowing, fertilising, weeding, harvesting, thinning, clear-cutting) that take place within broader *land-use* categories (Pongratz et al. 2018).

Land management change
A change in land management that occurs within a *land-use* category.

Land potential The inherent, long-term potential of the *land* to sustainably generate *ecosystem services*, which reflects the capacity and *resilience* of the land-based natural capital, in the face of ongoing environmental change (UNEP 2016).

Land rehabilitation Direct or indirect actions undertaken with the aim of reinstating a level of *ecosystem* functionality, where the goal is provision of goods and services rather than ecological restoration (McDonald et al. 2016).

Land restoration The process of assisting the recovery of *land* from a degraded state (IPBES 2018; McDonald et al. 2016).

Land use The total of arrangements, activities and inputs applied to a parcel of *land*. The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction, conservation and city dwelling). In national *greenhouse gas (GHG)* inventories, land use is classified according to the IPCC land-use categories of forest land, cropland, grassland, wetlands, settlements, other lands (see the 2006 IPCC Guidelines for National GHG Inventories and their 2019 Refinement for details (IPCC 2006, 2019)).

Land use, land-use change and forestry (LULUCF) In the context of national greenhouse gas (GHG) inventories under the *United Nations Framework Convention on Climate Change* (UNFCCC 2019), LULUCF is a GHG inventory sector that covers *anthropogenic* emissions and removals of GHG in managed lands, excluding non-CO_2 agricultural emissions. Following the 2006 IPCC Guidelines for National GHG Inventories and their 2019 Refinement, 'anthropogenic' land-related GHG fluxes are defined as all those occurring on 'managed land', that is, 'where human interventions and practices have been applied to perform production, ecological or social functions'. Since managed land may include *carbon dioxide (CO_2)*, removals not considered as 'anthropogenic' in some of the scientific literature assessed in this report (e.g., removals associated with CO_2 fertilisation and N deposition), the land-related net GHG emission estimates from global models included in this report are not necessarily directly comparable with LULUCF estimates in National GHG Inventories (IPCC 2006, 2019).

Land-use change (LUC) The change from one *land use* category to another. Note that, in some scientific literature, land-use change encompasses changes in land-use categories as well as changes in land management. See also *Afforestation*, *Agriculture*, *Forestry and Other Land Use (AFOLU)*, *Deforestation*, *Land use*, *land-use change and forestry (LULUCF)*, and *Reforestation*.

Indirect land-use change (iLUC)
Land-use change outside the area of focus that occurs as a consequence of change in use or management of land within the area of focus, such as through market or policy drivers. For example, if agricultural land is diverted to *biofuel* production, forest clearance may occur elsewhere to replace the former agricultural production.

Latent heat flux The turbulent *flux* of heat from the Earth's surface to the *atmosphere* that is associated with evaporation or condensation of water vapour at the surface; a component of the surface energy budget.

Leakage The effects of policies that result in a displacement of the environmental impact, thereby counteracting the intended effects of the initial policies.

Leapfrogging The ability of developing countries to bypass intermediate technologies and jump straight to advanced clean technologies.

Lifecycle assessment (LCA) Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product or service throughout its lifecycle (ISO 2018).

Likelihood The chance of a specific outcome occurring, where this might be estimated probabilistically. Likelihood is expressed in this report using a standard terminology (Mastrandrea et al. 2010). See also *Agreement*, *Confidence*, *Evidence*, and *Uncertainty*.

Livelihood The resources used and the activities undertaken in order for people to live. Livelihoods are usually determined by the entitlements and assets to which people have access. Such assets can be categorised as human, social, natural, physical or financial.

Local knowledge (LK) The understandings and skills developed by individuals and populations, specific to the places where they live. Local knowledge informs decision-making about fundamental aspects of life, from day-to-day activities to longer-term actions. This knowledge is a key element of the social and cultural systems which influence observations of and responses to climate change; it also informs *governance* decisions (UNESCO 2018). See also *Indigenous knowledge*.

Lock-in A situation in which the future development of a system, including *infrastructure*, technologies, investments, *institutions*, and behavioural norms, is determined or constrained ('locked in') by historic developments. See also *Path dependence*.

Long-lived greenhouse gases (LLGHGs) A set of well-mixed *greenhouse gases* with long atmospheric lifetimes. This set of compounds includes *carbon dioxide (CO_2)* and *nitrous oxide (N_2O)*, together with some fluorinated gases. They have a warming effect on *climate*. These compounds accumulate in the *atmosphere* at decadal to centennial time scales, and their effect on *climate* hence persists for decades to centuries after their emission. On time scales of decades to a century already emitted emissions of long-lived climate forcers can only be abated by greenhouse gas removal (GGR).

Loss and Damage, and losses and damages Research has taken Loss and Damage (capitalised letters) to refer to political debate under the *United Nations Framework Convention on Climate Change (UNFCCC)* following the establishment of the Warsaw International Mechanism for Loss and Damage in 2013, which is to 'address loss and damage associated with impacts of climate change, including extreme events and slow onset events, in developing countries that are particularly vulnerable to the adverse effects of climate change.' Lowercase letters (losses and damages) have been taken to refer broadly to harm from (observed) impacts and (projected) risks, and can be economic or non-economic (Mechler et al. 2018).

Maladaptive actions (Maladaptation) Actions that may lead to increased risk of adverse climate-related outcomes, including via increased *greenhouse gas (GHG)* emissions, increased *vulnerability* to climate change, or diminished welfare, now or in the future. Maladaptation is usually an unintended consequence.

Malnutrition Deficiencies, excesses, or imbalances in a person's intake of energy and/or nutrients. The term malnutrition addresses three broad groups of conditions: undernutrition, which includes wasting (low weight-for-height), stunting (low height-for-age) and underweight (low weight-for-age); micronutrient-related malnutrition, which includes micronutrient deficiencies (a lack of important vitamins and minerals) or micronutrient excess; and overweight, obesity and diet-related noncommunicable diseases (such as heart disease, stroke, diabetes and some cancers) (WHO 2018). Micronutrient deficiencies are sometimes termed 'hidden hunger' to emphasise that people can be malnourished in the sense of deficient without being deficient in calories. Hidden hunger can apply even where people are obese.

Managed forest *Forests* subject to human interventions (notably silvicultural management such as planting, pruning, thinning), timber and fuelwood harvest, protection (fire suppression, insect suppression) and management for amenity values or conservation, with defined geographical boundaries (Ogle et al. 2018). See also *Managed land*.

[Note: For a discussion of the term 'forest' in the context of National GHG inventories, see the 2006 IPCC Guidelines for National GHG Inventories (IPCC 2006).]

Managed grassland Grasslands on which human interventions are carried out, such as grazing domestic livestock or hay removal.

Managed land In the context of national *greenhouse gas (GHG)* inventories under the *United Nations Framework Convention on Climate Change (UNFCCC)*, the 2006 IPCC Guidelines for National GHG Inventories (IPCC 2006) defines managed land 'where human interventions and practices have been applied to perform production, ecological or social functions'. IPCC (2006) defines *anthropogenic* GHG emissions and removals in the *LULUCF* sector as all those occurring on 'managed land'. The key rationale for this approach is that the preponderance of anthropogenic effects occurs on managed lands.

[Note: More details can be found in IPCC 2006 Guidelines for National GHG Inventories, Volume 4, Chapter 1.]

Market failure When private decisions are based on market prices that do not reflect the real scarcity of goods and services but rather reflect market distortions, they do not generate an efficient allocation of resources but cause welfare losses. A market distortion is any event in which a market reaches a market clearing price that is substantially different from the price that a market would achieve while operating under conditions of perfect competition and state enforcement of legal contracts and the ownership of private property. Examples of factors causing market prices to deviate from real economic scarcity are environmental externalities, public goods, monopoly power, information asymmetry, transaction costs, and non-rational behaviour.

Material substitution Replacement of one material (including an energy carrier used as a feedstock) by another, due to scarcity, price, technological change, or because of lower environmental impacts or *greenhouse gas emissions*.

Measurement, Reporting and Verification (MRV)

Measurement
'Processes of data collection over time, providing basic datasets, including associated accuracy and precision, for the range of relevant variables. Possible data sources are field measurements, field observations, detection through remote sensing and interviews' (UN-REDD 2009).

Reporting
'The process of formal reporting of assessment results to the UNFCCC, according to predetermined formats and established standards, especially the Intergovernmental Panel on Climate Change (IPCC) Guidelines and GPG (Good Practice Guidance)' (UN-REDD 2009).

Verification
'The process of formal verification of reports, for example, the established approach to verify national communications and national inventory reports to the UNFCCC' (UN-REDD 2009).

Megacity Urban agglomerations with 10 million inhabitants or more. See also *City*.

Methane (CH_4) The *greenhouse gas (GHG)* methane is the major component of natural gas and associated with all hydrocarbon fuels. Significant *anthropogenic* emissions also occur as a result of animal husbandry and paddy rice production. Methane is also produced naturally where organic matter decays under anaerobic conditions, such as in wetlands. Under future *global warming*, there is potential for increased methane emissions from thawing permafrost, wetlands and sub-sea gas hydrates. See also *Short-lived climate forcers (SLCFs)*.

Migrant Any person who is moving or has moved across an international border or within a State away from his/her habitual place of residence, regardless of: (1) the person's legal status; (2) whether the movement is voluntary or involuntary; (3) what the causes for the movement are; or (4) what the length of the stay is (IOM 2018).

Migration (of humans) Movement of a person or a group of persons, either across an international border, or within a State. It is a population movement, encompassing any kind of movement of people, whatever its length, composition and causes; it includes migration of refugees, displaced persons, economic migrants, and persons moving for other purposes, including family reunification (IOM 2018).

Mitigation (of climate change) A human intervention to reduce emissions or enhance the *sinks* of *greenhouse gases*.

Mitigation measures In climate policy, mitigation measures are technologies, processes or practices that contribute to *mitigation*, for example, *renewable energy* technologies, waste minimisation processes, and public transport commuting practices.

Mitigation option A technology or practice that reduces *greenhouse gas* emissions or enhances *sinks*.

Mitigation pathways See *Pathways*.

Mitigation potential The quantity of net *greenhouse gas* emission reductions that can be achieved by a given *mitigation option* relative to specified emission baselines.

[Note: Net greenhouse gas emissions reduction is the sum of reduced emissions and/or enhanced *sinks*.]

See also *Sequestration potential*.

Biogeophysical potential
The mitigation potential constrained by biological, geophysical and geochemical limits and thermodynamics, without taking into account technical, social, economic and/or environmental considerations.

Economic potential
The portion of the technical potential for which the social benefits exceed the social costs, taking into account a social discount rate and the value of externalities.

Technical potential
The mitigation potential constrained by biogeophysical limits as well as availability of technologies and practices. Quantification of technical potentials takes into account primarily technical considerations, but social, economic and/or environmental considerations are occasionally also included, if these represent strong barriers for the deployment of an option.

Mitigation scenario See *Scenario*.

Multi-level governance See *Governance*.

Narrative See *Storyline*.

Nature's contributions to people (NCP) All the contributions, both positive and negative, of living nature (i.e., diversity of organisms, *ecosystems*, and their associated ecological and evolutionary processes) to the quality of life for people. Beneficial contributions from nature include such things as food provision, water purification, flood control, and artistic inspiration, whereas detrimental contributions include disease transmission and predation that damages people or their assets. Many NCP may be perceived as benefits or detriments depending on the cultural, temporal or spatial context (Díaz et al. 2018). See also *Ecosystem services*.

Nature-based solutions Actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (IUCN 2016). See also *Biodiversity* and *Ecosystem*.

Net negative greenhouse gas emissions A situation of net negative greenhouse gas emissions is achieved when metric-weighted *anthropogenic greenhouse gas (GHG)* removals exceed metric-weighted anthropogenic GHG emissions. Where multiple GHG are involved, the quantification of net emissions depends on the metric chosen to compare emissions of different gases (such as *global warming potential*, global temperature change potential, and others, as well as the chosen time horizon). See also *Carbon dioxide removal (CDR)*, *Greenhouse gas emission metric*, *Net-zero CO_2 emissions; Net-zero greenhouse gas emissions*, and *Negative greenhouse gas emissions*.

Net-zero CO_2 emissions Condition in which *anthropogenic carbon dioxide (CO_2)* emissions are balanced by anthropogenic CO_2 removals over a specified period.

[Note: *Carbon neutrality* and net-zero CO_2 emissions are overlapping concepts. The concepts can be applied at global or sub-global scales (e.g., regional, national and sub-national). At a global scale, the terms *carbon neutrality* and net-zero CO_2 emissions are equivalent. At sub-global scales, net-zero CO_2 emissions is generally applied to emissions and removals under direct control or territorial responsibility of the reporting entity, while *carbon neutrality* generally includes emissions and removals within and beyond the direct control or territorial responsibility of the reporting entity. Accounting rules specified by GHG programmes or schemes can have a significant influence on the quantification of relevant CO_2 emissions and removals.]

See also *Carbon neutrality*, *Land use*, *land-use change and forestry (LULUCF)* and *Net-zero greenhouse gas emissions*.

Net-zero greenhouse gas emissions Condition in which metric-weighted *anthropogenic greenhouse gas (GHG)* emissions are balanced by metric-weighted anthropogenic GHG removals over a specified period. The quantification of net-zero GHG emissions depends on the *GHG emission metric* chosen to compare emissions and removals of different gases, as well as the time horizon chosen for that metric.

[Note 1: Greenhouse gas neutrality and net-zero GHG emissions are overlapping concepts. The concept of net-zero GHG emissions can be applied at global or sub-global scales (e.g., regional, national and sub-national). At a global scale, the terms GHG neutrality and net-zero GHG emissions are equivalent. At sub-global scales, net-zero GHG emissions is generally applied to emissions and removals under direct control or territorial responsibility of the reporting entity, while GHG neutrality generally includes anthropogenic emissions and anthropogenic removals within and beyond the direct control or territorial responsibility of the reporting entity. Accounting rules specified by GHG programmes or schemes can have a significant influence on the quantification of relevant emissions and removals.

Note 2: Under the Paris Rulebook (Decision 18/CMA.1, annex, paragraph 37), parties have agreed to use GWP100 values from the IPCC AR5 or GWP100 values from a subsequent IPCC Assessment Report to report aggregate emissions and removals of GHGs. In addition, parties may use other metrics to report supplemental information on aggregate emissions and removals of GHGs.]

See also *Greenhouse gas neutrality*, *Net-zero CO_2 emissions*, and *Land use*, *land-use change and forestry (LULUCF)*.

Nitrous oxide (N_2O) The main *anthropogenic* source of N_2O, a *greenhouse gas (GHG)*, is agriculture (soil and animal manure management), but important contributions also come from sewage treatment, *fossil fuel* combustion, and chemical industrial processes. N_2O is also produced naturally from a wide variety of biological sources in soil and water, particularly microbial action in wet tropical *forests*.

Non-overshoot pathways See *Pathways*.

Ocean alkalinisation/Ocean alkalinity enhancement A proposed *carbon dioxide removal (CDR)* method that involves deposition of alkaline minerals or their dissociation products at the ocean surface. This increases surface total alkalinity, and may thus increase ocean *carbon dioxide (CO_2)* uptake and ameliorate surface ocean acidification. See also *Anthropogenic removals*.

Ocean fertilisation A proposed *carbon dioxide removal (CDR)* method that relies on the deliberate increase of nutrient supply to the near-surface *ocean* with the aim of *sequestering* additional CO_2 from the *atmosphere* through biological production. Methods include direct addition of micro-nutrients or macro-nutrients. To be successful, the additional carbon needs to reach the deep ocean where it has the potential to be sequestered on climatically relevant time scales. See also *Anthropogenic removals*.

Offset (in climate policy) The reduction, avoidance or removal of a unit of *greenhouse gas (GHG)* emissions by one entity, purchased by another entity to counterbalance a unit of GHG emissions by that other entity. Offsets are commonly subject to rules and environmental integrity criteria intended to ensure that offsets achieve their stated mitigation outcome. Relevant criteria include, but are not limited to, the avoidance of double counting and *leakage*, use of appropriate baselines, *additionality*, and permanence or measures to address impermanence. See also *Greenhouse gas emission metric* and *Carbon neutrality*.

Organic farming An agricultural production system that aims to utilise natural processes and cycles to limit off-farm and notably synthetic inputs, while also aiming to enhance agroecosystems and society. Organic farming is often legally defined and governed by standards, typically guided by principles outlined by the International Federation of Organic Agriculture Movements (IFOAM – Organics International) (IFOAM – Organics International 2014).

Overshoot pathways See *Pathways*.

Ozone (O_3) The triatomic form of oxygen, and a gaseous *atmospheric* constituent. In the troposphere, O_3 is created both naturally and by photochemical reactions involving gases resulting from human activities (e.g., smog). Tropospheric O_3 acts as a *greenhouse gas (GHG)*. In the stratosphere, O_3 is created by the interaction between solar ultraviolet radiation and molecular oxygen

(O_2). Stratospheric O_3 plays a dominant role in the stratospheric radiative balance. Its concentration is highest in the ozone layer.

Pareto optimum A state in which no one's welfare can be increased without reducing someone else's welfare.

Participatory governance See *Governance*.

Particulate matter (PM) Atmospheric aerosols involved in air pollution issues. Of greatest concern for health are particles of aerodynamic diameter less than or equal to 10 micrometers, usually designated as PM10 and particles of diameter less than or equal to 2.5 micrometers, usually designated as PM2.5.

Path dependence The generic situation where decisions, events, or outcomes at one point in time constrain *adaptation*, *mitigation*, or other actions or options at a later point in time. See also *Lock-in*.

Pathways The temporal evolution of natural and/or human systems towards a future state. Pathway concepts range from sets of quantitative and qualitative *scenarios* or narratives of potential futures to solution-oriented decision-making processes to achieve desirable societal goals. Pathway approaches typically focus on biophysical, techno-economic, and/or socio-behavioural trajectories and involve various dynamics, goals, and actors across different scales. See also *Scenario* and *Storyline*.

1.5°C pathway
A pathway of emissions of *greenhouse gases* and other climate *forcers* that provides an approximately one-in-two to two-in-three chance, given current knowledge of the climate response, of global warming either remaining below 1.5°C or returning to 1.5°C by around 2100 following an overshoot.

Adaptation pathways
A series of *adaptation* choices involving trade-offs between short-term and long-term goals and values. These are processes of deliberation to identify solutions that are meaningful to people in the context of their daily lives and to avoid potential *maladaptation*.

Climate-resilient pathways
Iterative processes for managing change within complex systems in order to reduce disruptions and enhance opportunities associated with climate change.

Development pathways
Development pathways evolve as the result of the countless decisions being made and actions being taken at all levels of societal structure, as well due to the emergent dynamics within and between institutions, cultural norms, technological systems and other drivers of behavioural change.

See also *Shifting development pathways (SDPs)* and *Shifting development pathways to sustainability (SDPS)*.

Emission pathways
Modelled trajectories of global *anthropogenic emissions* over the 21st century.

Mitigation pathways
A temporal evolution of a set of *mitigation scenario* features, such as *greenhouse gas* emissions and socio-economic development.

Non-overshoot pathways
Pathways that stay below a specified concentration, *forcing*, or global warming level during a specified period of time (e.g., until 2100).

Overshoot pathways
Pathways that first exceed a specified concentration, *forcing*, or global warming level, 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 characterised. The overshoot duration can vary from one pathway to the next, but in most overshoot pathways in the literature and referred to as overshoot pathways in the AR6, the overshoot occurs over a period of at least one decade and up to several decades.

Representative Concentration Pathways (RCPs)
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* (Moss et al. 2010). The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific *radiative forcing* characteristics. The term pathway emphasises that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome (Moss et al. 2010).

RCPs usually refer to the portion of the concentration pathway extending up to 2100, for which *integrated assessment models* produced corresponding emission scenarios. Extended concentration pathways describe extensions of the RCPs from 2100 to 2300 that were calculated using simple rules generated by stakeholder consultations, and do not represent fully consistent scenarios. Four RCPs produced from integrated assessment models were selected from the published literature and used in the Fifth IPCC Assessment, and are also used in this Assessment for comparison, spanning the range from approximately below 2°C warming to high (>4°C) warming best-estimates by the end of the 21st century: RCP2.6, RCP4.5 and RCP6.0 and RCP8.5.

- RCP2.6: One pathway where radiative forcing peaks at approximately 3 W m^{-2} and then declines to be limited at 2.6 W m^{-2} in 2100 (the corresponding Extended Concentration Pathway, or ECP, has constant emissions after 2100).
- RCP4.5 and RCP6.0: Two intermediate stabilisation pathways in which radiative forcing is limited at approximately 4.5 W m^{-2} and 6.0 W m^{-2} in 2100 (the corresponding ECPs have constant concentrations after 2150).
- RCP8.5: One high pathway which leads to >8.5 W m^{-2} in 2100 (the corresponding ECP has constant emissions after 2100 until 2150 and constant concentrations after 2250).

See also *Shared socio-economic pathways (SSPs)* (under *Pathways*).

Shared Socio-economic Pathways (SSPs)
SSPs have been developed to complement the *Representative Concentration Pathways (RCPs)*. By design, the RCP emission and concentration pathways were stripped of their association with a certain socio-economic development. Different levels of *emissions* and *climate change* along the dimension of the RCPs can hence be explored against the backdrop of different socio-economic development pathways (SSPs) on the other dimension in a matrix. This integrative SSP-RCP framework is now widely used in the climate *impact* and policy analysis literature, where *climate projections*

obtained under the RCP scenarios are analysed against the backdrop of various SSPs. As several emission updates were due, a new set of emission scenarios was developed in conjunction with the SSPs. Hence, the abbreviation SSP is now used for two things: On the one hand SSP1, SSP2, …, SSP5 are used to denote the five socio-economic scenario families. On the other hand, the abbreviations SSP1-1.9, SSP1-2.6, …, SSP5-8.5 are used to denote the newly developed emission scenarios that are the result of an SSP implementation within an integrated assessment model. Those SSP scenarios are bare of climate policy assumption, but in combination with so-called shared policy assumptions (SPAs), various approximate *radiative forcing* levels of 1.9, 2.6, …, or 8.5 W m^{-2} are reached by the end of the century, respectively.

Transformation pathways
Trajectories describing consistent sets of possible futures of *greenhouse gas (GHG)* emissions, atmospheric concentrations, or *global mean surface temperatures* implied from mitigation and adaptation actions associated with a set of broad and irreversible economic, technological, societal, and behavioural changes. This can encompass changes in the way energy and infrastructure are used and produced, natural resources are managed and institutions are set up, and in the pace and direction of technological change.

Peri-urban areas Dynamic transition zones that have intense interaction between rural and *urban* economies, activities, households, and lifestyles. Neither fully rural or urban (Seto et al. 2010).

Policies (for climate change mitigation and adaptation) Strategies that enable actions to be undertaken to accelerate *adaptation* and *mitigation*. Policies include those developed by national and subnational public agencies, and with the private sector. Policies for adaptation and mitigation often take the form of economic incentives, regulatory instruments, and decision-making and engagement processes.

Political economy The set of interlinked relationships between people, the state, society and markets as defined by law, politics, economics, customs and power that determine the outcome of trade and transactions and the distribution of wealth in a country or economy.

Pool, carbon and nitrogen A reservoir in the Earth System where elements, such as carbon and nitrogen, reside in various chemical forms for a period of time. See also *Sequestration*, *Sink*, *Source* and *Uptake*.

Poverty A complex concept with several definitions stemming from different schools of thought. It can refer to material circumstances (such as need, pattern of deprivation or limited resources), economic conditions (such as standard of living, *inequality* or economic position) and/or social relationships (such as social class, dependency, exclusion, lack of basic security or lack of entitlement).

Poverty eradication A set of measures to end poverty in all its forms everywhere. See also *Sustainable Development Goals (SDGs)*.

Precursors Atmospheric compounds that are not *greenhouse gases (GHGs)* or *aerosols*, but that have an effect on GHG or aerosol concentrations by taking part in physical or chemical processes regulating their production or destruction rates.

Pre-industrial (period) 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 *global mean surface temperature (GMST)*. See also *Industrial revolution*.

Primary energy The energy that is embodied in resources as they exist in nature (e.g., coal, biomass uranium, solar radiation, wind, ocean currents) (Grubler et al. 2012).

[Note: Primary energy is defined in several alternative ways. The method used in this report is the direct equivalent method, which counts one unit of secondary energy provided from non-combustible sources as one unit of primary energy. For more details on the methodology, see Section 7 in Working Group III Annex II.]

See also *Final energy*.

Primary production The synthesis of organic compounds by plants and microbes, on land or in the ocean, primarily by photosynthesis using light and *carbon dioxide (CO_2)* as sources of energy and carbon respectively. It can also occur through chemosynthesis, using chemical energy, for example, in deep sea vents.

Private costs Costs carried by individuals, companies or other private entities that undertake an action, whereas *social costs* include additionally the external costs on the environment and on society as a whole. Quantitative estimates of both private and social costs may be incomplete, because of difficulties in measuring all relevant effects.

Production-based emissions Emissions released to the *atmosphere* for the production of goods and services by a certain entity (e.g., a person, firm, country, or region). See also *Consumption-based emissions*.

Projection A potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Unlike predictions, projections are conditional on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realised. See also *Climate projection*, *Pathways* and *Scenario*.

Prosumers A consumer that also produces energy and inputs energy to the system, for which it is an active agent in the energy system and market.

Radiative forcing The change in the net, downward minus upward, radiative flux (expressed in W m^{-2}) due to a change in an external driver of *climate change*, such as a change in the concentration of *carbon dioxide (CO_2)*, the concentration of volcanic *aerosols* or in the output of the Sun. The stratospherically adjusted radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is called instantaneous if no change in stratospheric temperature is accounted for. The radiative forcing once both stratospheric and tropospheric adjustments are accounted for is termed the 'effective radiative forcing'.

Rebound effect Phenomena whereby the reduction in energy consumption or emissions (relative to a baseline) associated with the implementation of *mitigation measures* in a jurisdiction is offset to some degree through induced changes in consumption, production, and prices within the same jurisdiction. The rebound effect is most typically ascribed to technological energy efficiency improvements.

Reducing Emissions from Deforestation and Forest Degradation (REDD+) REDD+ refers to reducing emissions from *deforestation*; reducing emissions from *forest* degradation; conservation of forest carbon stocks; sustainable management of forests; and enhancement of forest carbon stocks (see UNFCCC decision 1/CP.16, para. 70).

Reference period A time period of interest, or a period over which some relevant statistics are calculated. A reference period can be used as a *baseline period* or as a comparison to a baseline period.

Baseline period
A time period against which differences are calculated (e.g., expressed as anomalies relative to a baseline).

Reference scenario See *Scenario*.

Reforestation Conversion to *forest* of land that has previously contained forests but that has been converted to some other use.

[Note: For a discussion of the term forest and related terms such as *afforestation*, reforestation and *deforestation*, see the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and their 2019 Refinement, and information provided by the United Nations Framework Convention on Climate Change (IPCC 2006, 2019; UNFCCC 2021a,b).]

See also *Anthropogenic removals*, *Carbon dioxide removal (CDR)* and *Reducing Emissions from Deforestation and Forest Degradation (REDD+)*.

Regenerative agriculture A universally agreed definition of this relatively new farming approach has yet to be established, but regenerative agriculture broadly refers to the implementation of varying combinations of agricultural management practices, to ensure the continued restoration and enhancement of soil health, *biodiversity* and *ecosystem* functioning, in conjunction with profitable agricultural production.

Region *Land* and/or *ocean* area characterised by specific geographical and/or climatological features. The *climate* of a region emerges from a multi-scale combination of its own features, remote influences from other regions, and global climate conditions.

Remaining carbon budget See *Carbon budget*.

Renewable energy (RE) Any form of energy that is replenished by natural processes at a rate that equals or exceeds its rate of use.

Variable renewable energy (VRE)
Renewable energy sources such as *wind* and *solar energy* whose output is determined by weather, in contrast to 'dispatchable' generators that adjust their output as a reaction to economic incentives. Variable renewables have also been termed intermittent, fluctuating, or non-dispatchable (Hirth 2013).

Representative Concentration Pathways (RCPs) See *Pathways*.

Resilience The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for *adaptation*, learning and/or transformation (Arctic Council 2016). See also *Hazard*, *Risk* and *Vulnerability*.

Resource cascade Tracking resource use (materials, energy, water, etc.), efficiency and losses through all conversion steps from primary resource extraction to various conversion steps, all the way to final service delivery.

Risk The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of *climate change*, risks can arise from potential *impacts* of climate change as well as human responses to climate change. Relevant adverse consequences include those on lives, *livelihoods*, health and *well-being*, economic, social and cultural assets and investments, *infrastructure*, services (including *ecosystem services*), *ecosystems* and species.

In the context of climate change impacts, risks result from dynamic interactions between climate-related *hazards* with the *exposure* and *vulnerability* of the affected human or ecological system to the hazards. Hazards, exposure and vulnerability may each be subject to uncertainty in terms of magnitude and *likelihood* of occurrence, and each may change over time and space due to socio-economic changes and human decision-making (see also *risk management*, *adaptation* and *mitigation*).

In the context of climate change responses, risks result from the potential for such responses not achieving the intended objective(s), or from potential trade-offs with, or negative side-effects on, other societal objectives, such as the *Sustainable Development Goals (SDGs)* (see also *risk trade-off*). Risks can arise, for example, from uncertainty in implementation, effectiveness or outcomes of *climate policy*, climate-related investments, technology development or adoption, and system transitions.

See also *Hazard* and *Impacts*.

Risk assessment The qualitative and/or quantitative scientific estimation of *risks*. See also *Risk management* and *Risk perception*.

Risk management Plans, actions, strategies or policies to reduce the *likelihood* and/or magnitude of adverse potential consequences, based on assessed or perceived *risks*. See also *Risk assessment*, and *Risk perception*.

Risk perception The subjective judgement that people make about the characteristics and severity of a *risk*. See also *Risk assessment*, and *Risk management*.

Risk trade-off The change in the portfolio of *risks* that occurs when a countervailing risk is generated (knowingly or inadvertently) by an intervention to reduce the target risk (Wiener and Graham 2009).

Sea surface temperature (SST) The subsurface bulk temperature in the top few metres of the ocean, measured by ships, buoys and drifters. From ships, measurements of water samples in buckets were mostly switched in the 1940s to samples from engine intake water. Satellite measurements of skin temperature (uppermost layer; a fraction of a millimetre thick) in the infrared or the top centimetre or so in the microwave are also used, but must be adjusted to be compatible with the bulk temperature.

Scenario A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions.

Baseline scenario
See *Reference Scenario* (under *Scenario*).

Concentrations scenario
A plausible representation of the future development of atmospheric concentrations of substances that are radiatively active (e.g., *greenhouse gases*, *aerosols*, tropospheric *ozone*), plus human-induced *land cover changes* that can be radiatively active via *albedo* changes, and often used as input to a *climate model* to compute *climate projections*.

Emissions scenario
A plausible representation of the future development of emissions of substances that are radiatively active (e.g., *greenhouse gases* or *aerosols*), plus human-induced land-cover changes that can be radiatively active via *albedo* changes, based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change, energy and *land use*) and their key relationships. *Concentration scenarios*, derived from emission scenarios, are often used as input to a *climate model* to compute *climate projections*.

Mitigation scenario
A plausible description of the future that describes how the (studied) system responds to the implementation of *mitigation* policies and measures.

Reference scenario
Scenario used as starting or reference point for a comparison between two or more scenarios.

[Note 1: In many types of *climate change* research, reference scenarios reflect specific assumptions about patterns of socio-economic development and may represent futures that assume no climate policies or specified climate policies, for example, those in place or planned at the time a study is carried out. Reference scenarios may also represent futures with limited or no climate impacts or adaptation, to serve as a point of comparison for futures with impacts and adaptation. These are also referred to as 'baseline scenarios' in the literature.

Note 2: Reference scenarios can also be climate policy or impact scenarios, which in that case are taken as a point of comparison to explore the implications of other features, for example, of delay, technological options, policy design and strategy or to explore the effects of additional impacts and adaptation beyond those represented in the reference scenario.

Note 3: The term *business as usual* scenario has been used to describe a scenario that assumes no additional policies beyond those currently in place, and where patterns of socio-economic development are consistent with recent trends. The term is now used less frequently than in the past.

Note 4: In climate change attribution or impact attribution research reference scenarios may refer to counterfactual historical scenarios assuming no anthropogenic *greenhouse gas (GHG)* emissions (climate change attribution) or no climate change (impact attribution).]

Socio-economic scenario
A scenario that describes a plausible future in terms of population, *gross domestic product (GDP)*, and other socio-economic factors relevant to understanding the implications of *climate change*.

Scenario storyline See *Storyline*.

Sequestration The process of storing carbon in a carbon pool. See also *Pool, carbon and nitrogen*, *Sequestration potential*, *Sink*, *Soil carbon sequestration (SCS)*, *Source*, and *Uptake*.

Sequestration potential The quantity of *greenhouse gases* that can be removed from the *atmosphere* by anthropogenic enhancement of *sinks* and stored in a pool. See *Mitigation potential* for different subcategories of sequestration potential. See also *Pool, carbon and nitrogen*, *Sequestration*, *Sink*, *Source*, and *Uptake*.

Service provisioning Various services (such as illumination and mobility) can be provided by 'systems' through the use of energy, materials, and other resources comprising: (i) Resource flows (e.g., energy); (ii) Technologies for resource use and energy conversion (e.g., vehicles and their engines); and (iii) Social/organisational forms of service delivery (e.g., publicly owned companies, or privately owned companies, e-commerce).

Services Activities that help satisfy human wants or needs. While they usually involve relationships between producers and consumers, services are less tangible and less storable than goods since they represent flows not stocks, and when their regeneration conditions are protected they may be reused over time.

Settlements Places of concentrated human habitation. Settlements can range from isolated rural villages to *urban regions* with significant global influence. They can include formally planned and informal or illegal habitation and related infrastructure. See also *Cities* and *Urban*.

Shared policy assumptions (SPAs) See *Shared Socio-economic Pathways (SSPs)*.

Shared Socio-economic Pathways (SSPs) See *Pathways*.

Sharing economy A system which allows people to share goods and services by enabling collaborative use, access or ownership.

Shifting development pathways (SDPs) In this report, shifting development pathways describes transitions aimed at re-directing existing developmental trends. Societies may put in place *enabling conditions* to influence their future development pathways, when they endeavour to achieve certain outcomes. Some outcomes may be common, while others may be context-specific, given different starting points. See also *Development pathways* (under *Pathways*), and *Shifting development pathways to sustainability*.

Shifting development pathways to sustainability Shifting development pathways to sustainability involves transitions aligned with a shared aspiration in the *Sustainable Development Goals (SDGs)* agreed globally, though sustainability may be interpreted differently in various contexts as societies pursue a variety of sustainable development objectives. See also *Development pathways* (under *Pathways*), and *Shifting development pathways (SDPs)*.

Short-lived climate forcers (SLCFs) A set of chemically reactive compounds with short (relative to *carbon dioxide*) atmospheric lifetimes (from hours to about two decades) but characterised by different physiochemical properties and environmental effects. Their emission or formation has a significant effect on radiative forcing over a period determined by their respective atmospheric lifetimes. Changes in their *emissions* can also induce long-term *climate* effects via, in particular, their interactions with some biogeochemical cycles. SLCFs are classified as direct or indirect, with direct SLCFs exerting climate effects through their *radiative forcing* and indirect SLCFs being the *precursors* of other direct climate forcers. Direct SLCFs include *methane (CH_4)*, *ozone (O_3)*, primary *aerosols* and some halogenated species. Indirect SLCFs are *precursors* of ozone or secondary aerosols. SLCFs can be cooling or warming through interactions with radiation and clouds. They are also referred to as near-term climate forcers. Many SLCFs are also air pollutants. A subset of exclusively warming SLCFs is also referred to as short-lived climate pollutants (SLCPs), including methane, ozone, and *black carbon (BC)*.

Short-lived climate pollutants (SLCP) See *Short-lived climate forcers (SLCFs)*.

Simple climate model (SCM) A broad class of lower-dimensional models of the energy balance, radiative transfer, *carbon cycle*, or a combination of such physical components. SCMs are also suitable for performing emulations of climate-mean variables of Earth System Models (ESMs), given that their structural flexibility can capture both the parametric and structural uncertainties across process-oriented ESM responses. They can also be used to test consistency across multiple lines of evidence with regard to *climate sensitivity* ranges, *transient climate responses (TCRs)*, *transient climate response to cumulative CO_2 emissions (TCREs)* and *carbon cycle* feedbacks. See also *Emulators*.

Sink Any process, activity or mechanism which removes a *greenhouse gas*, an *aerosol* or a *precursor* of a *greenhouse gas* from the *atmosphere* (UNFCCC Article 1.8 (UNFCCC 1992)). See also *Pool, carbon and nitrogen*, *Sequestration*, *Source* and *Uptake*.

Small Island Developing States (SIDS) SIDS, as recognised by the United Nations OHRLLS (UN Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States), are a distinct group of developing countries facing specific social, economic and environmental vulnerabilities (UN-OHRLLS 2011). They were recognised as a special case, both for their environment and development, at the Rio Earth Summit in Brazil in 1992. Fifty-eight countries and territories are presently classified as SIDS by the UN OHRLLS, with 38 being UN member states and 20 being non-UN members or associate members of the Regional Commissions (UN-OHRLLS 2018).

Smart grids A smart grid uses information and communications technology to gather data on the behaviours of suppliers and consumers in the production, distribution, and use of electricity. Through automated responses or the provision of price signals, this information can then be used to improve the efficiency, reliability, economics, and sustainability of the electricity network.

Social cost of carbon (SCC) The net present value of aggregate climate damages (with overall harmful damages expressed as a number with positive sign) from one more tonne of carbon in the form of *carbon dioxide (CO_2)*, conditional on a global emissions trajectory over time.

Social costs The full costs of an action in terms of social welfare losses, including external costs associated with the impacts of this action on the environment, the economy (*GDP*, employment) and on the society as a whole.

Social group A collective of people who share similar characteristics and collectively may have a sense of unity (Forsyth 2010).

Social identity The portion of an individual's self-concept derived from perceived membership in a relevant *social group* (Tajfel and Turner 1986).

Social inclusion A process of improving the terms of participation in society, particularly for people who are disadvantaged, through enhancing opportunities, access to resources, and respect for rights (UNDESA 2018).

Social infrastructure See *Infrastructure*.

Social learning A process of social interaction through which people learn new behaviours, capacities, values, and attitudes.

Social-ecological system An integrated system that includes human societies and *ecosystems*, in which humans are part of nature. The functions of such a system arise from the interactions and interdependence of the social and ecological subsystems. The system's structure is characterised by reciprocal feedbacks, emphasising that humans must be seen as a part of, not apart from, nature (Berkes and Folke 1998; Arctic Council 2016).

Socio-economic scenario See *Scenario*.

Socio-technical transitions Where technological change is associated with social systems and the two are inextricably linked.

Soil carbon sequestration (SCS) *Land management* changes which increase the *soil organic carbon* content, resulting in a net removal of *carbon dioxide (CO_2)* from the *atmosphere*. See also *Anthropogenic removals* and *Carbon dioxide removal (CDR)*.

Soil organic carbon Carbon contained in *soil organic matter*.

Soil organic matter The organic component of soil, comprising plant and animal residue at various stages of decomposition, and soil organisms.

Solar energy Energy from the Sun. Often the phrase is used to mean energy that is captured from solar radiation 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. See also *Renewable energy*.

Solar radiation modification (SRM) Refers to a range of radiation modification measures not related to *greenhouse gas (GHG)* mitigation that seek to limit *global warming*. Most methods involve reducing the amount of incoming solar radiation reaching the surface, but others also act on the longwave radiation budget by reducing optical thickness and cloud lifetime.

Source Any process or activity which releases a *greenhouse gas (GHG)*, an *aerosol* or a *precursor* of a GHG into the *atmosphere*

(UNFCCC Article 1.9 (UNFCCC 1992)). See also *Sink*, *Pool, carbon and nitrogen*, *Sequestration*, *Sequestration Potential* and *Uptake*.

Spill-over effect The effects of domestic or sector mitigation measures on other countries or sectors. Spill-over effects can be positive or negative and include effects on trade, (carbon) *leakage*, transfer of innovations, and diffusion of environmentally sound technology and other issues.

Storyline A way of making sense of a situation or a series of events through the construction of a set of explanatory elements. Usually, it is built on logical or causal reasoning. In *climate* research, the term storyline is used both in connection to *scenarios* as related to a future trajectory of the climate and human systems or to a weather or climate event. In this context, storylines can be used to describe plural, conditional possible futures or explanations of a current situation, in contrast to single, definitive futures or explanations.

Scenario storyline
A narrative description of a *scenario* (or family of scenarios), highlighting the main scenario characteristics, relationships between key driving forces and the dynamics of their evolution.

Stranded assets Assets exposed to devaluations or conversion to 'liabilities' because of unanticipated changes in their initially expected revenues due to innovations and/or evolutions of the business context, including changes in public regulations at the domestic and international levels.

Subnational actors State/provincial, regional, metropolitan and local/municipal governments as well as non-party stakeholders, such as civil society, the private sector, *cities* and other subnational authorities, local communities and indigenous peoples.

Sufficiency 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.

Sustainability A dynamic process that guarantees the persistence of natural and human systems in an equitable manner.

Sustainable development (SD) Development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED 1987) and balances social, economic and environmental concerns. See also *Development pathways* and *Sustainable Development Goals (SDGs)*.

Sustainable Development Goals (SDGs) The 17 global goals for development for all countries established by the United Nations through a participatory process and elaborated in the 2030 Agenda for Sustainable Development, including ending poverty and hunger; ensuring health and well-being, education, gender equality, clean water and energy, and decent work; building and ensuring resilient and sustainable infrastructure, cities and consumption; reducing inequalities; protecting land and water ecosystems; promoting peace, justice and partnerships; and taking urgent action on climate change. See also *Sustainable development*.

Sustainable forest management 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* (Forest Europe 1993).

Sustainable intensification (of agriculture) Increasing yields from the same area of land while decreasing negative environmental impacts of agricultural production and increasing the provision of environmental services (CGIAR 2019).

[Note: This definition is based on the concept of meeting demand from a finite land area, but it is scale-dependent. Sustainable intensification at a given scale (e.g., global or national) may require a decrease in production intensity at smaller scales and, in particular, places (often associated with previous, unsustainable, intensification) to achieve *sustainability* (Garnett et al. 2013).]

Sustainable land management 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 (WOCAT, no date).

Systems of Innovation (SI) The set of public and private sector organisations (i.e., formally organised entities such as firms and universities; 'actors') and *institutions*, whose activities and interactions generate, modify and deploy new technologies. The SI approach has been used to understand and analyse innovation at the national, regional, and technological levels, and in transnational contexts (Lundvall 1992, 1988).

Technology deployment The act of bringing technology into effective application, involving a set of actors and activities to initiate, facilitate and/or support its implementation. See also *Technology diffusion*.

Technology diffusion The spread of a technology across different groups users/markets over time. See also *Technology deployment* and *Technology transfer*.

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. See also *Technology diffusion*.

Teleconnection Association between *climate* variables at widely separated, geographically fixed locations related to each other through physical processes and oceanic and/or atmospheric dynamical pathways. Teleconnections can be caused by several climate phenomena, such as Rossby wave-trains, mid-latitude jet and storm track displacements, fluctuations of the Atlantic Meridional Overturning Circulation (AMOC), fluctuations of the Walker circulation, etc. They can be initiated by modes of climate variability, thus providing the development of remote climate anomalies at various temporal lags.

Temperature overshoot Exceedance of a specified global warming level, followed by a decline to or below that level during a specified period of time (e.g., before 2100). Sometimes the magnitude and likelihood of the overshoot is also characterised. The overshoot duration can vary from one *pathway* to the next, but in most *overshoot pathways* in the literature and as referred to as overshoot pathways in the AR6, the overshoot occurs over a period of at least one decade and up to several decades.

Tipping point A critical threshold beyond which a system reorganises, often abruptly and/or irreversibly. See also *Irreversibility*.

Total carbon budget See *Carbon budget*.

Trade-off A competition between different objectives within a decision situation, where pursuing one objective will diminish achievement of other objective(s). A trade-off exists when a policy or measure aimed at one objective (e.g., reducing *greenhouse gas* emissions) reduces outcomes for other objective(s) (e.g., *biodiversity* conservation, *energy security*) due to *adverse side effects*, thereby potentially reducing the net benefit to society or the environment. See also *Co-benefit*.

Transformation A change in the fundamental attributes of natural and human systems.

Transformation pathways See *Pathways*.

Transient climate response (TCR) See *Climate sensitivity*.

Transient climate response to cumulative CO_2 emissions (TCRE) See *Climate sensitivity*.

Transition The process of changing from one state or condition to another in a given period of time. Transition can occur in individuals, firms, cities, regions and nations, and can be based on incremental or transformative change.

Uncertainty A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, incomplete understanding of critical processes, or uncertain projections of *human behaviour*. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgement of a team of experts) (Moss and Schneider 2000; Mastrandrea et al. 2010). See also *Confidence* and *Likelihood*.

United Nations Convention to Combat Desertification (UNCCD) A legally binding international agreement linking environment and development to sustainable land management, established in 1994. The Convention's objective is 'to combat desertification and mitigate the effects of drought in countries experiencing drought and/or desertification'. The Convention specifically addresses the arid, semi-arid and dry sub-humid areas, known as the drylands, and has a particular focus on Africa. As of September 2020, the UNCCD had 197 Parties. See also *Desertification*, *Drought* and *Land degradation*.

United Nations Framework Convention on Climate Change (UNFCCC) The UNFCCC was adopted in May 1992 and opened for signature at the 1992 Earth Summit in Rio de Janeiro. It entered into force in March 1994 and, as of September 2020, had 197 Parties (196 States and the European Union). The Convention's ultimate objective is the 'stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system' (UNFCCC 1992). The provisions of the Convention are pursued and implemented by two further treaties: the Kyoto Protocol and the Paris Agreement.

Uptake The transfer of substances (such as carbon) or energy (e.g., heat) from one compartment of a system to another; for example, in the Earth System from the atmosphere to the ocean or to the land. See also *Pool, carbon and nitrogen*, *Sequestration*, *Sequestration potential*, *Sink* and *Source*.

Urban The categorisation of areas as 'urban' by government statistical departments is generally based either on population size, population density, economic base, provision of services, or some combination of the above. *Urban systems* are networks and nodes of intensive interaction and exchange including capital, culture, and material objects. Urban areas exist on a continuum with rural areas and tend to exhibit higher levels of complexity, higher populations and population density, intensity of capital investment, and a preponderance of secondary (processing) and tertiary (service) sector industries. The extent and intensity of these features varies significantly within and between urban areas. Urban places and systems are open with much movement and exchange between more rural areas as well as other urban regions. Urban areas can be globally interconnected facilitating rapid flows between them – of capital investment, of ideas and culture, human migration, and disease. See also *Cities*, *Peri-urban areas*, and *Urbanisation*.

Urban heat island The relative warmth of a *city* compared with surrounding rural areas, associated with heat trapping due to land use, the configuration and design of the built environment, including street layout and building size, the heat-absorbing properties of urban building materials, reduced ventilation, reduced greenery and water features, and domestic and industrial heat emissions generated directly from human activities. See also *City region*, *Urban*, and *Urban System*.

Urban Systems Urban systems refer to two interconnected systems: first, the comprehensive collections of city elements with multiple dimensions and characteristics: a) encompass physical, built, socio-economic-technical, political, and ecological subsystems; b) integrate social agent/constituency/processes with physical structure and processes; and c) exist within broader spatial and temporal scales and governance and institutional contexts; and second, the global system of cities and towns. See also *City region*, and *Urban*.

Urbanisation Urbanisation is a multi-dimensional process that involves at least three simultaneous changes: (i) land-use change: transformation of formerly rural settlements or natural land into urban settlements; (ii) demographic change: a shift in the spatial distribution of a population from rural to urban areas; and (iii) infrastructure change: an increase in provision of infrastructure services including electricity, sanitation, etc. Urbanisation often includes changes in lifestyle, culture, and behaviour, and thus alters the demographic, economic, and social structure of both urban and rural areas (Stokes and Seto 2019; Seto et al. 2014; UNDESA 2018). See also *Urban*, and *Urban Systems*.

Variable renewable energy (VRE) See *Renewable energy*.

Vulnerability The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. See also *Exposure*, *Hazard* and *Risk*.

Well-being A state of existence that fulfils various human needs, including material living conditions, meaningful social and community relationships and quality of life, as well as the ability to pursue one's goals, to thrive, and feel satisfied with one's life. Ecosystem well-being refers to the ability of *ecosystems* to maintain their diversity and quality.

Eudaimonic
Relational well-being concept based on the premise that experiencing life purpose, challenges and growth leads to flourishing, self-realisation, personal expression, and full functioning (Niemiec 2014; Lamb and Steinberger 2017).

Hedonic
Subjective well-being concept based on the idea that attaining pleasure and avoiding pain leads to happiness (Ryan and Deci 2001).

Wind energy Kinetic energy from airflow arising from the uneven heating of the Earth's surface. The wind's kinetic energy is converted to mechanical shaft energy and electricity by a wind turbine, a rotating machine. A wind farm, wind project, wind park, 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. See also *Renewable energy*.

Zero emissions commitment See *Climate change commitment*.

References

AGECC, 2010: *Energy for a Sustainable Future. The secretary-general's Advisory group on Energy and climate Change*, New York, NY, USA.

Allan, J.A., 2005: Virtual water: A strategic resource global solutions to regional deficits. *Groundwater*, **36(4)**, 545–546, doi:10.1111/j.1745- 6584. 1998.tb02825.x.

Arctic Council, 2016: *Arctic Resilience Report 2016*. [Carson, M. and G. Peterson (eds.)]. Stockholm Environment Institute and Stockholm Resilience Centre, Stockholm, Sweden, 218 pp. https://oaarchive.arctic-council.org/handle/11374/1838 (Accessed October 2021).

Berkes, F. and C. Folke, 1998: *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience*. [Berkes, F. and C. Folke (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 459 pp.

Bobbins, K. and C. Culwick, 2016: *A Framework for a Green Infrastructure Planning Approach in the Gauteng City-Region*. Gauteng City-Region Observatory (GRCO), Johannesburg, South Africa, 127 pp. http://hdl.handle.net/10539/23595.

Campbell, A. et al., 2009: *Review of the Literature on the Links between Biodiversity and Climate Change: Impacts, Adaptation and Mitigation*. Secretariat of the Convention on Biological Diversity, Montreal, QC, Canada, 124 pp. https://www.cbd.int/doc/publications/cbd-ts-42-en.pdf (Accessed October 11, 2021).

CGIAR, 2019: Sustainable intensification of agriculture: oxymoron or real deal? https://wle.cgiar.org/thrive/big-questions/sustainable-intensification-agriculture-oxymoron-or-real-deal/sustainable-1 (Accessed October 11, 2021).

Chester, M.V, 2019: Sustainability and infrastructure challenges. *Nat. Sustain.*, **2**(4), 265–266, doi:10.1038/s41893-019-0272-8.

Davis, S.J. and K. Caldeira, 2010: Consumption-based accounting of CO_2 emissions. *Proc. Natl. Acad. Sci.*, **107(12)**, 5687–5692, doi:10.1073/pnas.0906974107.

Dawson, R.J. et al., 2018: A systems framework for national assessment of climate risks to infrastructure. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, **376(2121)**, 20170298, doi:10.1098/rsta.2017.0298.

Díaz, S. et al., 2018: Assessing nature's contributions to people. *Science*, **359(6373)**, 270–272, doi:10.1126/science.aap8826.

FAO, 2007: *Land evaluation: Towards a revised framework. Land and water discussion paper*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

FAO, 2009: *Declaration of the World Summit on Food Security. WSFS 2009/2*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

FAO, 2015: Food waste. Food and Agriculture Organization of the United Nations (FAO). http://www.fao.org/platform-food-loss-waste/food-waste/definition.

FAO, 2016: Conservation agriculture. https://www.fao.org/conservation-agriculture/overview/what-is-conservation-agriculture/en/ (Accessed October 11, 2021).

FAO, 2018: *The State of Food Security and Nutrition in the World: Building Climate Resilience for Food Security and Nutrition*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 181 pp.

FAO and Alliance of Bioversity International and CIAT, 2021: *Indigenous Peoples' food systems: Insights on sustainability and resilience from the front line of climate change*, Rome, doi: 10.4060/cb5131en.

Forest Europe, 1993: *Resolution H1 General Guidelines for the Sustainable Management of Forests in Europe*. Second Ministerial Conference on the Protection of Forests in Europe, 16–17 June 1993, Helsinki, https://www.foresteurope.org/docs/MC/MC_helsinki_resolutionH1.pdf.

Forsyth, D.R., 2010: *Group Dynamics*. Fifth Edition. Wadswoth Cengage Learning, Inc., Belmont, CA, USA.

Frolova, E.V, M.K. Vinichenko, A.V Kirillov, O.V Rogach, and E.E. Kabanova, 2016: Development of social infrastructure in the management practices of local authorities: trends and factors. *Int. J. Environ. Sci. Educ.*, **11(15)**, 7421–7430.

Fung, A. and E.O. Wright, 2003: *Deepening Democracy: Institutional Innovations in Empowered Participatory Governance*. [Fung, A. and E.O. Wright (eds.)]. Verso, London, UK, 312 pp.

Garnett, T. et al., 2013: Sustainable intensification in agriculture: Premises and policies. *Science.*, **341(6161)**, 33, doi:10.1126/science.1234485.

Grubler, A. et al., 2012: Energy Primer. In: *Global Energy Assessment*, pp. 99–150. Cambridge University Press, Cambridge, UK, doi:10.1017/CBO9780511793677.007.

Hewitt, C., S. Mason, and D. Walland, 2012: The Global Framework for Climate Services. *Nat. Clim. Change*, **2(12)**, 831–832, doi:10.1038/nclimate1745.

Hirth, L., 2013: The market value of variable renewables: The effect of solar wind power variability on their relative price. *Energy Econ.*, **38**, 218–236, doi:10.1016/j.eneco.2013.02.004.

HLPE, 2017: *Nutrition and food systems*. High Level Panel of Experts on Food Security and Nutrition (HLPE), Rome, Italy, 152 pp.

IBI, 2018: Frequently Asked Questions About Biochar: What is biochar? International Biochar Initiative (IBI). https://biochar-international.org/faqs/ (Accessed October 11, 2021).

IFOAM-Organics International, 2014: *The IFOAM Norms for Organic Production and Processing*. IFOAM-Organics International, Germany. https://www.ifoam.bio/sites/default/files/2020-09/IFOAM Norms July 2014 Edits 2019.pdf (Accessed October 11, 2021).

ILO, 2015: *Guidelines for a just transition towards environmentally sustainable economies and societies for all*. International Labour Organization (ILO), Switzerland.

IOM, 2018: Key Migration Terms. Retrieved from: https://www.iom.int/key-migration-terms (Accessed May 15, 2018).

IPBES, 2018: *The IPBES assessment report on land degradation and restoration*. [Montanarella, L., R. Scholes, and A. Brainich (eds.)]. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Bonn, Germany, 744 pp.

IPBES, 2019: Glossary. *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.* Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Bonn, Germany.

IPCC, 2006: *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*. [Eggleston, H.S., L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.)]. Institute for Global Environmental Strategies (IGES), Hayama, Japan, https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*. [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

IPCC, 2019: *Refinement to the 2006 IPCC Guidelines for National Greenhouse gas Inventories*. [Buendia, E.C., S. Guendehou, B. Limmeechokchai, R. Pipatti, Y. Rojas, R. Sturgiss, K. Tanabe, T. Wirth, D. Romano, J. Witi, A. Garg, M.M. Weitz, B. Cai, D.A. Ottinger, H. Dong, J.D. MacDonald, S.M. Ogle, M.T. Rocha, M. José Sanz Sanchez, D.M. Bartram, S. Towprayoon (eds.)]. Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland. https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html (Accessed October 11, 2021).

ISO, 2014: ISO 16559:2014(en). Solid biofuels – Terminology, definitions and descriptions. http://www.iso.org/obp/ui/#iso:std:iso:16559:ed-1:v1:en (Accessed October 11, 2021).

ISO, 2018: ISO 14044:2006. Environmental management – Life cycle assessment – Requirements and guidelines. https://www.iso.org/standard/38498.html (Accessed May 31, 2018).

IUCN, 2016: Defining Nature-based Solutions. WCC-2016-Res-069-EN, World Conservation Congress.

Lamb, W.F. and J.K. Steinberger, 2017: Human well-being and climate change mitigation. *Wiley Interdiscip. Rev. Clim. Change.*, **8(6)**, doi:10.1002/wcc.485.

Latham, A. and J. Layton, 2019: Social infrastruture and the public life of cities: Studying urban sociality and public spaces. *Geogr. Compass*, **13(7)**, 12444.

Lundvall, B.-Å., 1988: Innovation as an interactive process: from user-producer interaction to the national system of innovation. In: *Technical Change and Economic Theory* [Dosi, G., C. Freeman, R. Nelson, G. Silverberg, and L. Soete (eds.)]. Pinter Publishers, London, UK and New York, NY, USA.

Lundvall, B.-Å., 1992: *National Systems of Innovation: Toward a Theory of Innovation and Interactive Learning*. [Lundvall, B.-A., (ed.)]. Pinter Publishers, London, UK, 342 pp.

MA, 2005: Appendix D: Glossary. In: *Ecosystems and Human Well-being: Current States and Trends. Findings of the Condition and Trends Working Group* [Hassan, R., R. Scholes, and N. Ash (eds.)], Millennium Ecosystem Assessment (MA). Island Press, Washington, DC, USA, pp. 893–900.

MacDonald, G.K. et al., 2015: Rethinking agricultural trade relationships in an era of globalization. *Bioscience*, **65(3)**, 275–289, doi:10.1093/biosci/biu225.

Mastrandrea, M.D. et al., 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, 6 pp.

McDonald, T., J. Jonson, and K.W. Dixon, 2016: National standards for the practice of ecological restoration in Australia. *Restor. Ecol.*, **24**(S1), S4–S32, doi:10.1111/rec.12359.

Mechler, R., L. Bouwer, T. Schinko, S. Surminski, and J. Linnerooth-Bayer, 2018: *Loss and Damage from Climate Change: Concepts, Methods and Policy Options*. [Mechler, R., L.M. Bouwer, T. Schinko, S. Surminski, and J. Linnerooth-Bayer (eds.)]. Springer International Publishing, Cham, Switzerland, 561 pp.

Moss, R.H. and S.H. Schneider, 2000: Uncertainties in the IPCC TAR: Recommendations to Lead Authors for More Consistent Assessment and Reporting. In: *Guidance Papers on the Cross Cutting Issues of the Third Assessment Report of the IPCC* [Pachauri, R., T. Taniguchi, and K. Tanaka (eds.)], Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, pp. 33–51.

Moss, R.H. et al., 2010: The next generation of scenarios for climate change research and assessment. *Nature*, **463(7282)**, 747–756, doi:10.1038/nature08823.

MRFCJ, 2018: Principles of Climate Justice. Mary Robinson Foundation – Climate Justice (MRFCJ). http://www.mrfcj.org/principles-of-climate-justice (Accessed May 15, 2018).

Niemiec, C.P., 2014: Eudaimonic Well-Being. In: *Encyclopedia of Quality of Life and Well-Being Research* [Michalos, A.C. (ed.)]. Springer, Dordrecht, The Netherlands, pp. 2004–2005, doi:10.1007/978-94-007-0753-5_929.

O'Neill, D.W., A.L. Fanning, W.F. Lamb, and J.K. Steinberger, 2018: A good life for all within planetary boundaries. *Nat. Sustain.*, **1(2)**, 88–95, doi:10.1038/s41893-018-0021-4.

Ogle, S.M. et al., 2018: Delineating managed land for reporting national greenhouse gas emissions and removals to the United Nations framework convention on climate change. *Carbon Balance Manag.*, **13(1)**, 9, doi:10.1186/s13021-018-0095-3.

OHCHR, 2018: What are Human rights? Office of the High Commissioner for Human Rights (OHCHR). https://www.ohchr.org/en/what-are-human-rights (Accessed October 11, 2021).

Park, S.E. et al., 2012: Informing adaptation responses to climate change through theories of transformation. *Glob. Environ. Change.*, **22(1)**, 115–126, doi:10.1016/j.gloenvcha.2011.10.003.

Pongratz, J. et al., 2018: Models meet data: Challenges and opportunities in implementing land management in Earth system models. *Glob. Change. Biol.*, **24(4)**, 1470–1487, doi:10.1111/gcb.13988.

Rao, N.D. and P. Baer, 2012: "Decent Living" emissions: A conceptual framework. *Sustainability*, **4(4)**, 656–681, doi:10.3390/su4040656.

Rao, N.D. and J. Min, 2018: Decent Living Standards: Material Prerequisites for Human Wellbeing. *Soc. Indic. Res.*, **138(1)**, 225–244, doi:10.1007/s11205-017-1650-0.

Reddy, A.K.N., 2000: *Energy and social issues*. World Energy Council, New York, NY, USA.

Ryan, R.M. and E.L. Deci, 2001: On happiness and human potentials: a review of research on hedonic and eudaimonic well-being. *Annu. Rev. Psychol.*, **52**, 141–166, doi:10.1146/annurev.psych.52.1.141.

Sarmiento, H. and C. Tilly, 2018: Governance Lessons from Urban Informality. *Polit. Gov.*, **6(1)**, 199–202, doi:10.17645/pag.v6i1.1169.

Seto, K.C., R. Sánchez-Rodríguez, and M. Fragkias, 2010: The New Geography of Contemporary Urbanization and the Environment. *Annu. Rev. Environ. Resour.*, **35(1)**, 167–194, doi:10.1146/annurev-environ-100809-125336.

Seto, K.C., S. Dhakal, A. Bigio, H. Blanco, G.C. Delgado, D. Dewar, L. Huang, A. Inaba, A. Kansal, S. Lwasa, J.E. McMahon, D.B. Müller, J. Murakami, H. Nagendra, and A. Ramaswami, 2014: Human Settlements, Infrastructure and Social Planning. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 923–1000.

Silvertown, J., 2009: A new dawn for citizen science. In: *Trophic Cascades: Predators, Prey, and the Changing Dynamics of Nature* [Terborgh, J. and J.A. Estes (eds.)]. Island Press, Washington DC, USA, pp. 337–352.

Stokes, E.C. and K.C. Seto, 2019: Characterizing and measuring urban landscapes for sustainability. *Environ. Res. Lett.*, **14(4)**, 045002, doi:10.1088/1748-9326/aafab8.

Tàbara, D.J., J. Jäger, D. Mangalagiu, and M. Grasso, 2019: Defining transformative climate science to address high-end climate change. *Reg. Environ. Change.*, **19(3)**, 807–818, doi:10.1007/s10113-018-1288-8.

Tajfel, H. and J.C. Turner, 1986: The social identity theory of intergroup behaviour. In: *Psychology of Intergroup Relations* [Worschel, S. and W.G. Austin (eds.)], IL: Nelson-Hall, Chicago, USA, pp. 7–24.

Termeer, C.J.A.M., A. Dewulf, and G.R. Biesbroek, 2017: Transformational change: governance interventions for climate change adaptation from a continuous change perspective. *J. Environ. Plan. Manag.*, **60(4)**, 558–576, doi:10.1080/09640568.2016.1168288.

UN, 1992: Article 2: Use of Terms. In: *Convention on Biological Diversity*, United Nations (UN), pp. 3–4.

UN-OHRLLS, 2011: *Small Island Developing States: Small Islands Big(ger) Stakes*. Office for the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States (UN-OHRLLS), New York, NY, USA, 32 pp.

UN-OHRLLS, 2018: Small Island Developing States: Country profiles. https://www.un.org/ohrlls/content/list-sids.

UN-REDD, 2009: *Measurement, Assessment, Reporting and Verification (MARV): Issues and Options for REDD*. United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (UN-REDD), Geneva, Switzerland, 12 pp. https://unredd.net/index.php?option=com_docman&task=doc_download&gid=148&Itemid=53 (Accessed October 11, 2021).

UNCCD, 1994: *Elaboration of an international convention to combat desertification in countries experiencing serious drought and/or desertification, particularly in Africa*. United Nations Convention to Combat Desertification (UNCCD), Paris, France, 1–58 pp.

UNCCD, 2020: Achieving Land Degradation Neutrality. United Nations Convention to Combat Desertification (UNCCD). https://www.unccd.int/.

UNDESA, 2018: *World Urbanization Prospects, the 2018 Revision, Technical Report*. United Nations Department of Economic and Social Affairs (UNDESA), New York, NY, USA.

UNEP, 2016: *Unlocking the sustainable potential of land resources: evaluating systems, strategies and tools*. United Nations Environment Programme (UNEP). https://www.unep.org/resources/report/unlocking-sustainable-potential-land-resources-evaluating-systems-strategies-and.

UNESCO, 2018: Local and Indigenous Knowledge Systems. United Nations Educational, Scientific and Cultural Organization (UNESCO). https://en.unesco.org/links.

UNFCCC, 1992: *United Nations Framework Convention on Climate Change*. United Nations Framework Convention on Climate Change (UNFCCC), 24 pp. https://unfccc.int/resource/docs/convkp/conveng.pdf.

UNFCCC, 2016: *Just transition of the workforce, and the creation of decent work and quality jobs*. United Nations Framework Convention on Climate Change (UNFCCC).

UNFCCC, 2019: Land Use, Land-Use Change and Forestry (LULUCF). United Nations Framework Convention on Climate Change (UNFCCC). https://unfccc.int/topics/land-use/workstreams/land-use--land-use-change-and-forestry-lulucf.

UNFCCC, 2021a: Reporting and Review under the Paris Agreement. United Nations Framework Convention on Climate Change (UNFCCC). https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-paris-agreement.

UNFCCC, 2021b: Reporting and accounting of LULUCF activities under the Kyoto Protocol. United Nations Framework Convention on Climate Change (UNFCCC). https://unfccc.int/topics/land-use/workstreams/land-use-land-use-change-and-forestry-lulucf/reporting-and-accounting-of-lulucf-activities-under-the-kyoto-protocol.

UNGA, 2016: *Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction*. United Nations General Assembly (UNGA), 41 pp. https://www.preventionweb.net/files/50683_oiewgreportenglish.pdf.

UNISDR, 2009: *2009 UNISDR Terminology on Disaster Risk Reduction*. United Nations International Strategy for Disaster Reduction (UNISDR), Geneva, Switzerland, 30 pp. https://www.unisdr.org/we/inform/publications/7817.

WCED, 1987: *Our Common Future*. World Commission on Environment and Development (WCED) Oxford University Press, Oxford, UK, 400 pp.

WHO, 2018: Malnutrition. World Health Organization (WHO). https://www.who.int/health-topics/malnutrition#tab=tab_1 (Accessed October 11, 2021).

Wiedmann, T. and J. Minx, 2008: A Definition of "Carbon Footprint." In: *Ecological Economics Research Trends* [C.C. Pertsova (ed.)], Nova Science Publishers, New York, NY, USA, pp. 1–11.

Wiener, J.B. and J.D. Graham, 2009: *Risk vs Risk: Tradeoffs in Protecting Health and the Environment*. [Wiener, J.B. and J.D. Graham (eds.)]. Harvard University Press, Cambridge, MA, USA, 352 pp.

Willems, S. and K. Baumert, 2003: *Institutional Capacity and Climate Actions*. Organisation for Economic Co-operation and Development (OECD) International Energy Agency (IEA), Paris, France, 50 pp. Retrieved from: http://www.oecd.org/env/cc/21018790.pdf.

WOCAT, [undated]: Glossary. World Overview of Conservation Approaches and Technologies (WOCAT). https://www.wocat.net/en/glossary.