INTERGOVERNMENTAL PANEL ON climate change

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

Summary for Policymakers

This Summary for Policymakers was formally approved at the First Joint Session of Working Groups I, II and III of the IPCC and accepted by the 48th Session of the IPCC, Incheon, Republic of Korea, 6 October 2018.

SUBJECT TO COPY EDIT

WMO UNEP

Summary for Policymakers

Drafting Authors: Myles Allen (UK), Mustafa Babiker (Sudan), Yang Chen (China), Heleen de Coninck (Netherlands), Sarah Connors (UK), Renée van Diemen (Netherlands), Opha Pauline Dube (Botswana), Kris Ebi (USA), Francois Engelbrecht (South Africa), Marion Ferrat (UK/France), James Ford (UK), Piers Forster (UK), Sabine Fuss (Germany), Tania Guillen (Germany/Nicaragua), Jordan Harold (UK), Ove Hoegh-Guldberg (Australia), Jean-Charles Hourcade (France), Daniel Huppmann (Austria), Daniela Jacob (Germany), Kejun Jiang (China), Tom Gabriel Johansen (Norway), Mikiko Kainuma (Japan), Kiane de Kleijne (Netherlands), Elmar Kriegler (Germany), Debora Ley (Guatemala/Mexico), Diana Liverman (USA), Natalie Mahowald (USA), Valérie Masson-Delmotte (France), Robin Matthews (UK), Reinhard Melcher (Austria), Richard Millar (UK), Katja Mintenbeck (Germany), Angela Morelli (Norway/Italy), Wilfran Moufouma-Okia (France/Congo), Luis Mundaca (Sweden/Chile), Maike Nicolai (Germany), Chukwumerije Okereke (UK/Nigeria), Minal Pathak (India), Anthony Payne (UK), Roz Pidcock (UK), Anna Pirani (Italy), Elvira Poloczanska (UK/Australia), Hans-Otto Pörtner (Germany), Aromar Revi (India), Keywan Riahi (Austria), Debra C. Roberts (South Africa), Joeri Rogelj (Austria/Belgium), Joyashree Roy (India), Sonia Seneviratne (Switzerland), Priyadarshi R.Shukla (India), James Skea (UK), Raphael Slade (UK), Drew Shindell (USA), Chandni Singh (India), William Solecki (USA), Linda Steg (Netherlands), Michael Taylor (Jamaica), Petra Tschakert (Australia/Austria), Henri Waisman (France), Rachel Warren (UK), Panmao Zhai (China), Kirsten Zickfeld (Canada)

Acknowledgements

We are very grateful for the expertise, rigour and dedication shown throughout by the volunteer Coordinating Lead Authors and Lead Authors, with important help by the many Contributing Authors. Working across scientific disciplines in each chapter of the Special Report on Global Warming of 1.5°C. The Review Editors have played a critical role in assisting the author teams and ensuring the integrity of the review process. We express our sincere appreciation to all the expert and government reviewers. A special thanks goes to the Chapter Scientists of this report who went above and beyond what was expected of them: Neville Ellis, Tania Guillén Bolaños, Daniel Huppmann, Kiane de Kleijne, Richard Millar and Chandni Singh.

We would also like to thank the three IPCC Vice-Chairs Ko Barrett, Thelma Krug, and Youba Sokona as well as the members of the WGI, WGII and WGIII Bureaus for their assistance, guidance, and wisdom throughout the preparation of the report: Amjad Abdulla, Edvin Aldrian, Carlo Carraro, Diriba Korecha Dadi, Fatima Driouech, Andreas Fischlin, Gregory Flato, Jan Fuglestvedt, Mark Howden, Nagmeldin G. E. Mahmoud, Carlos Mendez, Joy Jacqueline Pereira, Ramón Pichs-Madruga, Andy Reisinger, Roberto Sánchez Rodríguez, Sergey Semenov, Muhammad I. Tariq, Diana Ürge-Vorsatz, Carolina Vera, Pius Yanda, Noureddine Yassaa, and Taha Zatari.

Our heartfelt thanks go to the hosts and organizers of the scoping meeting and the four Special Report on 1.5°C Lead Author Meetings. We gratefully acknowledge the support from the host countries and institutions: World Meteorological Organisation, Switzerland; Ministry of Foreign

Affairs, and the National Institute for Space Research (INPE), Brazil; Met Office and the University of Exeter, The United Kingdom; Swedish Meteorological and Hydrological Institute (SMHI), Sweden; the Ministry of Environment Natural Resources Conservation and Tourism, the National Climate Change Committee in the Department of Meteorological Services and the Botswana Global Environmental Change Committee at the University of Botswana, Botswana; and the government of the Republic of Korea. The support provided by governments and institutions, as well as through contributions to the IPCC Trust Fund, is thankfully acknowledged as it enabled the participation of the author teams in the preparation of the report. The efficient operation of the Working Group I Technical Support Unit was made possible by the generous financial support provided by the government of France and administrative and information technology support from the University Paris Saclay (France), Institut Pierre Simon Laplace (IPSL) and the Laboratoire des Sciences du Climat et de l'Environnement (LSCE). We thank the Norwegian Environment Agency for supporting the preparation of the graphics for the Summary for Policymakers.

We would also like to thank Abdalah Mokssit, Secretary of the IPCC, and the staff of the IPCC Secretariat: Kerstin Stendahl, Jonathan Lynn, Sophie Schlingemann, Judith Ewa, Mxolisi Shongwe, Jesbin Baidya, Werani Zabula, Nina Peeva, Joelle Fernandez, Annie Courtin, Laura Biagioni and Oksana Ekzarho. Thanks are due to Elhousseine Gouaini who served as the conference officer for the 48th Session of the IPCC.

Finally, our particular appreciation goes to the Working Group Technical Support Units whose tireless dedication, professionalism and enthusiasm led the production of this special report. This report could not have been prepared without the commitment of members of the Working Group I Technical Support Unit, all new to the IPCC, who rose to the unprecedented AR6 challenge, and were pivotal in all aspects of the preparation of the report: Yang Chen, Sarah Connors, Melissa Gomez, Elisabeth Lonnoy, Robin Matthews, Wilfran-Moufouma-Okia, Clotilde Péan, Roz Pidcock, Anna Pirani, Nicholas Reay, Tim Waterfield, and Xiao Zhou. Our warmest thanks go to the collegial and collaborative support provided by Marlies Craig, Andrew Okem, Jan Petzold, Melinda Tignor and Nora Weyer from the WGII Technical Support Unit and Bhushan Kankal, Suvadip Neogi, Joana Portugal Pereira from the WGIII Technical Support Unit. A special thanks goes to Kenny Coventry, Harmen Gudde, Irene Lorenzoni, and Steve Jenkins for their support with the figures in the Summary for Policymakers, as well as Nigel Hawtin for graphical support of the report. In addition, the following contributions are gratefully acknowledged: Tom Maycock (operational support and copy edit), Jatinder Padda (copy edit), Melissa Dawes (copy edit), Marilyn Anderson (index), Vincent Grégoire (layout) and Sarah le Rouzic (intern).

Date of Summary for Policymakers: 6 October 2018

Introduction

This report responds to the invitation for IPCC '... to provide a Special Report in 2018 on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways' contained in the Decision of the 21st Conference of Parties of the United Nations Framework Convention on Climate Change to adopt the Paris Agreement.[1]

The IPCC accepted the invitation in April 2016, deciding to prepare this Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

This Summary for Policy Makers (SPM) presents the key findings of the Special Report, based on the assessment of the available scientific, technical and socio-economic literature[2] relevant to global warming of 1.5°C and for the comparison between global warming of 1.5°C and 2°C above pre-industrial levels. The level of confidence associated with each key finding is reported using the IPCC calibrated language.[3] The underlying scientific basis of each key finding is indicated by references provided to chapter elements. In the SPM, knowledge gaps are identified associated with the underlying chapters of the report.

---

[1] Decision 1/CP.21, paragraph 21.

[2] The assessment covers literature accepted for publication by 15 May 2018.

[3] Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not >50–100%, more unlikely than likely 0–<50%, extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, for example, *very likely*. This is consistent with AR5.

A. Understanding Global Warming of 1.5°C[4]

A1. Human activities are estimated to have caused approximately 1.0°C of global warming[5] above pre-industrial levels, with a *likely* range of 0.8°C to 1.2°C. Global warming is *likely* to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. (*high confidence*) {1.2, Figure SPM.1}

A1.1. Reflecting the long-term warming trend since pre-industrial times, observed global mean surface temperature (GMST) for the decade 2006–2015 was 0.87°C (*likely* between 0.75°C and 0.99°C)[6] higher than the average over the 1850–1900 period (*very high confidence*). Estimated anthropogenic global warming matches the level of observed warming to within ±20% (*likely* range). Estimated anthropogenic global warming is currently increasing at 0.2°C (*likely* between 0.1°C and 0.3°C) per decade due to past and ongoing emissions (*high confidence*). {1.2.1, Table 1.1, 1.2.4}

A1.2. Warming greater than the global annual average is being experienced in many land regions and seasons, including two to three times higher in the Arctic. Warming is generally higher over land than over the ocean. (*high confidence*) {1.2.1, 1.2.2, Figure 1.1, Figure 1.3, 3.3.1, 3.3.2}

A1.3. Trends in intensity and frequency of some climate and weather extremes have been detected over time spans during which about 0.5°C of global warming occurred (*medium confidence*). This assessment is based on several lines of evidence, including attribution studies for changes in extremes since 1950. {3.3.1, 3.3.2, 3.3.3}

A.2. Warming from anthropogenic emissions from the pre-industrial period to the present will persist for centuries to millennia and will continue to cause further long-term changes in the climate system, such as sea level rise, with associated impacts (*high confidence*), but these emissions alone are *unlikely* to cause global warming of 1.5°C (*medium confidence*) {1.2, 3.3, Figure 1.5, Figure SPM.1}

A2.1. Anthropogenic emissions (including greenhouse gases, aerosols and their precursors) up to the present are *unlikely* to cause further warming of more than 0.5°C over the next two to three decades (*high confidence*) or on a century time scale (*medium confidence*). {1.2.4, Figure 1.5}

---

[4] SPM BOX.1: Core Concepts

[5] Present level of global warming is defined as the average of a 30-year period centered on 2017 assuming the recent rate of warming continues.

[6] This range spans the four available peer-reviewed estimates of the observed GMST change and also accounts for additional uncertainty due to possible short-term natural variability. {1.2.1, Table 1.1}

A2.2. Reaching and sustaining net-zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal timescales (*high confidence*). The maximum temperature reached is then determined by cumulative net global anthropogenic CO_2 emissions up to the time of net zero CO_2 emissions (*high confidence*) and the level of non-CO_2 radiative forcing in the decades prior to the time that maximum temperatures are reached (*medium confidence*). On longer timescales, sustained net negative global anthropogenic CO_2 emissions and/or further reductions in non-CO_2 radiative forcing may still be required to prevent further warming due to Earth system feedbacks and reverse ocean acidification (*medium confidence*) and will be required to minimise sea level rise (*high confidence*). {Cross-Chapter Box 2 in Chapter 1, 1.2.3, 1.2.4, Figure 1.4, 2.2.1, 2.2.2, 3.4.4.8, 3.4.5.1, 3.6.3.2}

Cumulative emissions of CO_2 and future non-CO_2 radiative forcing determine the probability of limiting warming to 1.5°C

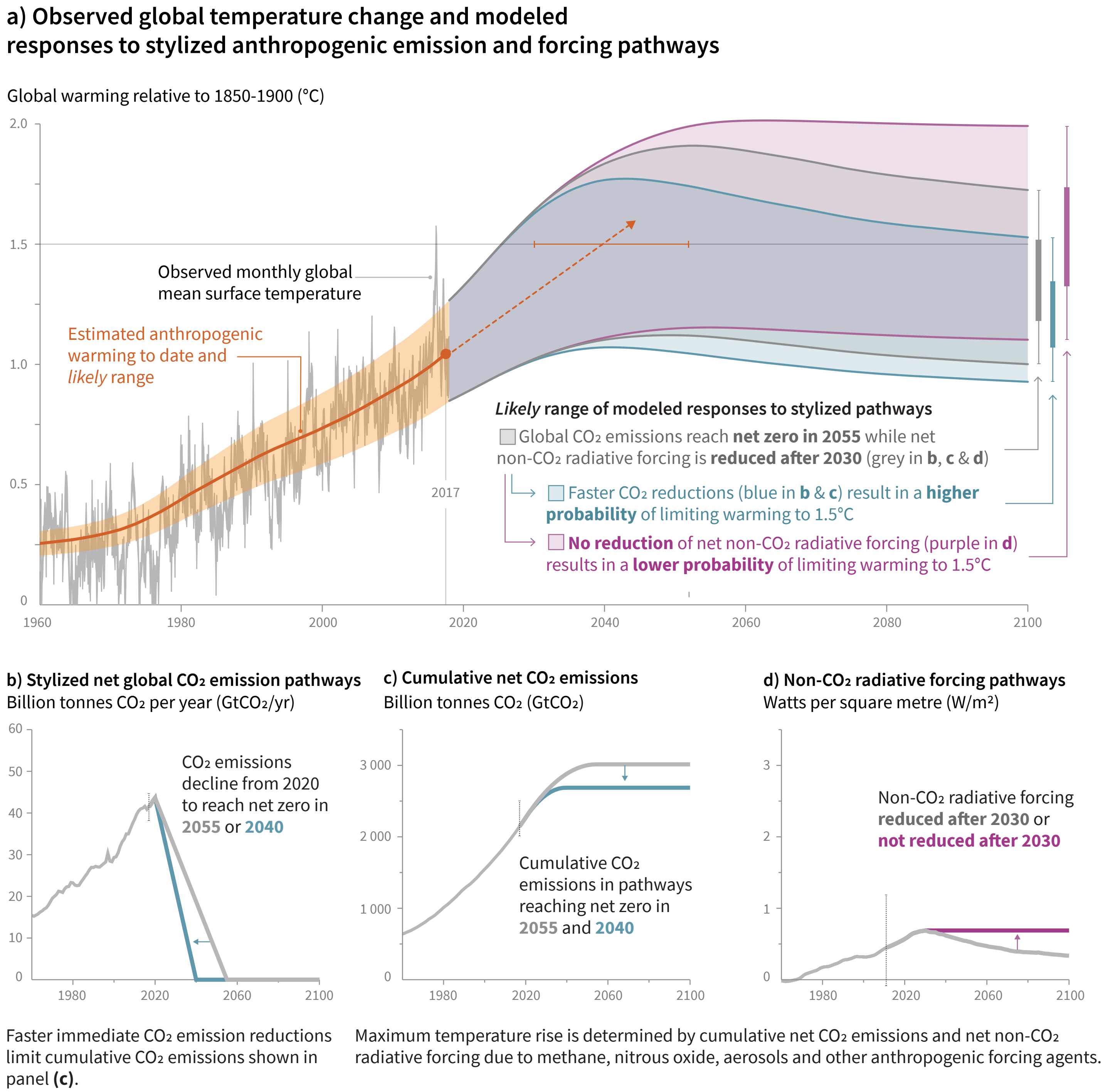


Figure SPM.1: Panel a: Observed monthly global mean surface temperature (GMST) change grey line up to 2017, from the HadCRUT4, GISTEMP, Cowtan–Way, and NOAA datasets) and estimated anthropogenic global warming (solid orange line up to 2017, with orange shading indicating assessed *likely* range). Orange dashed arrow and horizontal orange error bar show respectively central estimate and *likely* range of the time at which 1.5°C is reached if the current rate of warming continues. The grey plume on the right of Panel a) shows the *likely* range of warming responses, computed with a simple climate model, to a stylized pathway (hypothetical future) in which net CO_2 emissions (grey line in panels b and c) decline in a straight line from 2020 to reach net zero in 2055 and net non-CO_2 radiative forcing (grey line in panel d) increases to 2030 and then declines. The blue plume in panel a) shows the response to faster CO_2 emissions reductions (blue line in panel b), reaching net zero in 2040, reducing cumulative CO_2 emissions (panel c). The purple plume shows the response to net CO_2 emissions declining to zero in 2055, with net non-CO_2 forcing remaining constant after 2030. The vertical error bars on right of panel a) show the *likely* ranges (thin lines) and central terciles (33rd – 66th percentiles, thick lines) of the estimated distribution of warming in 2100 under these three stylized pathways. Vertical dotted error bars in panels b, c and d show the *likely* range of historical annual and cumulative global net CO_2 emissions in 2017 (data from the Global Carbon Project) and of net non-CO_2 radiative forcing in 2011 from AR5, respectively. Vertical axes in panels c and d are scaled to represent approximately equal effects on GMST. {1.2.1, 1.2.3, 1.2.4, 2.3, Chapter 1 Figure 1.2 & Chapter 1 Supplementary Material, Cross-Chapter Box 2}

A3. Climate-related risks for natural and human systems are higher for global warming of 1.5°C than at present, but lower than at 2°C (*high confidence*). These risks depend on the magnitude and rate of warming, geographic location, levels of development and vulnerability, and on the choices and implementation of adaptation and mitigation options (*high confidence*) (Figure SPM.2). {1.3, 3.3, 3.4, 5.6}

A3.1. Impacts on natural and human systems from global warming have already been observed (*high confidence*). Many land and ocean ecosystems and some of the services they provide have already changed due to global warming (*high confidence*). {1.4, 3.4, 3.5, Figure SPM.2}

A3.2. Future climate-related risks depend on the rate, peak and duration of warming. In the aggregate they are larger if global warming exceeds 1.5°C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5°C, especially if the peak temperature is high (e.g., about 2°C) (*high confidence*). Some impacts may be long-lasting or irreversible, such as the loss of some ecosystems (*high confidence*). {3.2, 3.4.4, 3.6.3, Cross-Chapter Box 8}

A3.3. Adaptation and mitigation are already occurring (*high confidence*). Future climate-related risks would be reduced by the upscaling and acceleration of far-reaching, multi-level and cross-sectoral climate mitigation and by both incremental and transformational adaptation (*high confidence*). {1.2, 1.3, Table 3.5, 4.2.2, Cross-Chapter Box 9 in Chapter 4, Box 4.2, Box 4.3, Box 4.6, 4.3.1, 4.3.2, 4.3.3, 4.3.4, 4.3.5, 4.4.1, 4.4.4, 4.4.5, 4.5.3}

B. Projected Climate Change, Potential Impacts and Associated Risks

B1. Climate models project robust[7] differences in regional climate characteristics between present-day and global warming of 1.5°C,[8] and between 1.5°C and 2°C.[8] These differences include increases in: mean temperature in most land and ocean regions (*high confidence*), hot extremes in most inhabited regions (*high confidence*), heavy precipitation in several regions (*medium confidence*), and the probability of drought and precipitation deficits in some regions (*medium confidence*). {3.3}

B1.1. Evidence from attributed changes in some climate and weather extremes for a global warming of about 0.5°C supports the assessment that an additional 0.5°C of warming compared to present is associated with further detectable changes in these extremes (*medium confidence*). Several regional changes in climate are assessed to occur with global warming up to 1.5°C compared to pre-industrial levels, including warming of extreme temperatures in many regions (*high confidence*), increases in frequency, intensity, and/or amount of heavy precipitation in several regions (*high confidence*), and an increase in intensity or frequency of droughts in some regions (*medium confidence*). {3.2, 3.3.1, 3.3.2, 3.3.3, 3.3.4, Table 3.2}

B1.2. Temperature extremes on land are projected to warm more than GMST (*high confidence*): extreme hot days in mid-latitudes warm by up to about 3°C at global warming of 1.5°C and about

---

[7] Robust is here used to mean that at least two thirds of climate models show the same sign of changes at the grid point scale, and that differences in large regions are statistically significant.

[8] Projected changes in impacts between different levels of global warming are determined with respect to changes in global mean surface air temperature.

4°C at 2°C, and extreme cold nights in high latitudes warm by up to about 4.5°C at 1.5°C and about 6°C at 2°C (*high confidence*). The number of hot days is projected to increase in most land regions, with highest increases in the tropics (*high confidence*). {3.3.1, 3.3.2, Cross-Chapter Box 8 in Chapter 3}

B1.3. Risks from droughts and precipitation deficits are projected to be higher at 2°C compared to 1.5°C global warming in some regions (*medium confidence*). Risks from heavy precipitation events are projected to be higher at 2°C compared to 1.5°C global warming in several northern hemisphere high-latitude and/or high-elevation regions, eastern Asia and eastern North America (*medium confidence*). Heavy precipitation associated with tropical cyclones is projected to be higher at 2°C compared to 1.5°C global warming (*medium confidence*). There is generally *low confidence* in projected changes in heavy precipitation at 2°C compared to 1.5°C in other regions. Heavy precipitation when aggregated at global scale is projected to be higher at 2.0°C than at 1.5°C of global warming (*medium confidence*). As a consequence of heavy precipitation, the fraction of the global land area affected by flood hazards is projected to be larger at 2°C compared to 1.5°C of global warming (*medium confidence*). {3.3.1, 3.3.3, 3.3.4, 3.3.5, 3.3.6}

B2. By 2100, global mean sea level rise is projected to be around 0.1 metre lower with global warming of 1.5°C compared to 2°C (*medium confidence*). Sea level will continue to rise well beyond 2100 (*high confidence*), and the magnitude and rate of this rise depends on future emission pathways. A slower rate of sea level rise enables greater opportunities for adaptation in the human and ecological systems of small islands, low-lying coastal areas and deltas (*medium confidence*). {3.3, 3.4, 3.6 }

B2.1. Model-based projections of global mean sea level rise (relative to 1986-2005) suggest an indicative range of 0.26 to 0.77 m by 2100 for 1.5°C global warming, 0.1 m (0.04-0.16 m) less than for a global warming of 2°C (*medium confidence*). A reduction of 0.1 m in global sea level rise implies that up to 10 million fewer people would be exposed to related risks, based on population in the year 2010 and assuming no adaptation (*medium confidence*). {3.4.4, 3.4.5, 4.3.2}

B2.2. Sea level rise will continue beyond 2100 even if global warming is limited to 1.5°C in the 21st century (*high confidence*). Marine ice sheet instability in Antarctica and/or irreversible loss of the Greenland ice sheet could result in multi-metre rise in sea level over hundreds to thousands of years. These instabilities could be triggered around 1.5°C to 2°C of global warming (*medium confidence*). {3.3.9, 3.4.5, 3.5.2, 3.6.3, Box 3.3, Figure SPM.2}

B2.3. Increasing warming amplifies the exposure of small islands, low-lying coastal areas and deltas to the risks associated with sea level rise for many human and ecological systems, including increased saltwater intrusion, flooding and damage to infrastructure (*high confidence*). Risks associated with sea level rise are higher at 2°C compared to 1.5°C. The slower rate of sea level rise at global warming of 1.5°C reduces these risks enabling greater opportunities for adaptation including managing and restoring natural coastal ecosystems, and infrastructure reinforcement (*medium confidence*). {3.4.5, Figure SPM.2, Box 3.5}

B3. On land, impacts on biodiversity and ecosystems, including species loss and extinction, are projected to be lower at 1.5°C of global warming compared to 2°C. Limiting global warming to 1.5°C compared to 2°C is projected to lower the impacts on terrestrial, freshwater, and coastal ecosystems and to retain more of their services to humans (*high confidence*). (Figure SPM.2) {3.4, 3.5, Box 3.4, Box 4.2, Cross-Chapter Box 8 in Chapter 3}

B3.1. Of 105,000 species studied,[9] 6% of insects, 8% of plants and 4% of vertebrates are projected to lose over half of their climatically determined geographic range for global warming of 1.5°C, compared with 18% of insects, 16% of plants and 8% of vertebrates for global warming of 2°C (*medium confidence*). Impacts associated with other biodiversity-related risks such as forest fires, and the spread of invasive species, are lower at 1.5°C compared to 2°C of global warming (*high confidence*). {3.4.3, 3.5.2}

B3.2. Approximately 4% (interquartile range 2–7%) of the global terrestrial land area is projected to undergo a transformation of ecosystems from one type to another at 1ºC of global warming, compared with 13% (interquartile range 8–20%) at 2°C (*medium confidence*). This indicates that the area at risk is projected to be approximately 50% lower at 1.5°C compared to 2°C (*medium confidence*). {3.4.3.1, 3.4.3.5}

B3.3. High-latitude tundra and boreal forests are particularly at risk of climate change-induced degradation and loss, with woody shrubs already encroaching into the tundra (*high confidence*) and will proceed with further warming. Limiting global warming to 1.5°C rather than 2°C is projected to prevent the thawing over centuries of a permafrost area in the range of 1.5 to 2.5 million km^2 (*medium confidence*). {3.3.2, 3.4.3, 3.5.5}

B4. Limiting global warming to 1.5°C compared to 2ºC is projected to reduce increases in ocean temperature as well as associated increases in ocean acidity and decreases in ocean oxygen levels (*high confidence*). Consequently, limiting global warming to 1.5°C is projected to reduce risks to marine biodiversity, fisheries, and ecosystems, and their functions and services to humans, as illustrated by recent changes to Arctic sea ice and warm water coral reef ecosystems (*high confidence*). {3.3, 3.4, 3.5, Boxes 3.4, 3.5}

B4.1. There is *high confidence* that the probability of a sea-ice-free Arctic Ocean during summer is substantially lower at global warming of 1.5°C when compared to 2°C. With 1.5°C of global warming, one sea ice-free Arctic summer is projected per century. This likelihood is increased to at least one per decade with 2°C global warming. Effects of a temperature overshoot are reversible for Arctic sea ice cover on decadal time scales (*high confidence*). {3.3.8, 3.4.4.7}

B4.2. Global warming of 1.5°C is projected to shift the ranges of many marine species, to higher latitudes as well as increase the amount of damage to many ecosystems. It is also expected to drive the loss of coastal resources, and reduce the productivity of fisheries and aquaculture (especially at low latitudes). The risks of climate-induced impacts are projected to be higher at 2°C than those at global warming of 1.5°C (*high confidence*). Coral reefs, for example, are projected to decline by a further 70–90% at 1.5°C (*high confidence*) with larger losses (>99%) at 2ºC (*very high confidence*). The risk of irreversible loss of many marine and coastal ecosystems increases with global warming, especially at 2°C or more (*high confidence*). {3.4.4, Box 3.4}

B4.3. The level of ocean acidification due to increasing CO_2 concentrations associated with global warming of 1.5°C is projected to amplify the adverse effects of warming, and even further at 2°C,

[9] Consistent with earlier studies, illustrative numbers were adopted from one recent meta-study.

impacting the growth, development, calcification, survival, and thus abundance of a broad range of species, e.g., from algae to fish (*high confidence*). {3.3.10, 3.4.4}

B4.4. Impacts of climate change in the ocean are increasing risks to fisheries and aquaculture via impacts on the physiology, survivorship, habitat, reproduction, disease incidence, and risk of invasive species (*medium confidence)* but are projected to be less at 1.5ºC of global warming than at 2ºC. One global fishery model, for example, projected a decrease in global annual catch for marine fisheries of about 1.5 million tonnes for 1.5°C of global warming compared to a loss of more than 3 million tonnes for 2°C of global warming (*medium confidence*). {3.4.4, Box 3.4}

B5. Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C. (Figure SPM.2) {3.4, 3.5, 5.2, Box 3.2, Box 3.3, Box 3.5, Box 3.6, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5, 5.2}

B5.1. Populations at disproportionately higher risk of adverse consequences of global warming of 1.5°C and beyond include disadvantaged and vulnerable populations, some indigenous peoples, and local communities dependent on agricultural or coastal livelihoods (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small-island developing states, and least developed countries (*high confidence)*. Poverty and disadvantages are expected to increase in some populations as global warming increases; limiting global warming to 1.5°C, compared with 2°C, could reduce the number of people both exposed to climate-related risks and susceptible to poverty by up to several hundred million by 2050 (*medium confidence*). {3.4.10, 3.4.11, Box 3.5, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5, 4.2.2.2, 5.2.1, 5.2.2, 5.2.3, 5.6.3}

B5.2. Any increase in global warming is projected to affect human health, with primarily negative consequences (*high confidence*). Lower risks are projected at 1.5°C than at 2°C for heat-related morbidity and mortality (*very high confidence*) and for ozone-related mortality if emissions needed for ozone formation remain high (*high confidence)*. Urban heat islands often amplify the impacts of heatwaves in cities (*high confidence*). Risks from some vector-borne diseases, such as malaria and dengue fever, are projected to increase with warming from 1.5°C to 2°C, including potential shifts in their geographic range (*high confidence*). {3.4.7, 3.4.8, 3.5.5.8}

B5.3. Limiting warming to 1.5°C, compared with 2ºC, is projected to result in smaller net reductions in yields of maize, rice, wheat, and potentially other cereal crops, particularly in sub-Saharan Africa, Southeast Asia, and Central and South America; and in the CO_2 dependent, nutritional quality of rice and wheat (*high confidence*). Reductions in projected food availability are larger at 2ºC than at 1.5°C of global warming in the Sahel, southern Africa, the Mediterranean, central Europe, and the Amazon (*medium confidence*). Livestock are projected to be adversely affected with rising temperatures, depending on the extent of changes in feed quality, spread of diseases, and water resource availability (*high confidence*). {3.4.6, 3.5.4, 3.5.5, Box 3.1, Cross-Chapter Box 6 in Chapter 3, Cross-Chapter Box 9 in Chapter 4}

B5.4. Depending on future socioeconomic conditions, limiting global warming to 1.5°C, compared to 2°C, may reduce the proportion of the world population exposed to a climate-change induced increase in water stress by up to 50%, although there is considerable variability between regions (*medium confidence*). Many small island developing states would experience lower water stress as a result of projected changes in aridity when global warming is limited to 1.5°C, as compared to 2°C (*medium confidence*). {3.3.5, 3.4.2, 3.4.8, 3.5.5, Box 3.2, Box 3.5, Cross-Chapter Box 9 in Chapter 4}

B5.5. Risks to global aggregated economic growth due to climate change impacts are projected to be lower at 1.5°C than at 2°C by the end of this century[10] (*medium confidence*). This excludes the costs of mitigation, adaptation investments and the benefits of adaptation. Countries in the tropics and Southern Hemisphere subtropics are projected to experience the largest impacts on economic growth due to climate change should global warming increase from 1.5°C to 2 °C (*medium confidence*). {3.5.2, 3.5.3}

B5.6. Exposure to multiple and compound climate-related risks increases between 1.5°C and 2°C of global warming, with greater proportions of people both so exposed and susceptible to poverty in Africa and Asia (*high confidence*). For global warming from 1.5°C to 2°C, risks across energy, food, and water sectors could overlap spatially and temporally, creating new and exacerbating current hazards, exposures, and vulnerabilities that could affect increasing numbers of people and regions (*medium confidence*). {Box 3.5, 3.3.1, 3.4.5.3, 3.4.5.6, 3.4.11, 3.5.4.9}

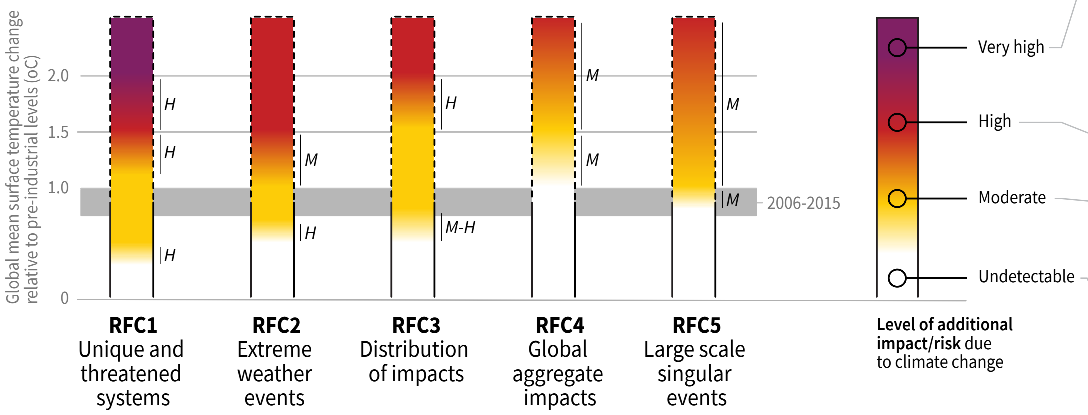
B5.7. There are multiple lines of evidence that since the AR5 the assessed levels of risk increased for four of the five Reasons for Concern (RFCs) for global warming to 2°C (*high confidence*). The risk transitions by degrees of global warming are now: from high to very high between 1.5°C and 2°C for RFC1 (Unique and threatened systems) (*high confidence*); from moderate to high risk between 1.0°C and 1.5°C for RFC2 (Extreme weather events) (*medium confidence*); from moderate to high risk between 1.5°C and 2°C for RFC3 (Distribution of impacts) (*high confidence*); from moderate to high risk between 1.5°C and 2.5°C for RFC4 (Global aggregate impacts) (*medium confidence*); and from moderate to high risk between 1°C and 2.5°C for RFC5 (Large-scale singular events) (*medium confidence*). (Figure SPM.2) {3.4.13; 3.5, 3.5.2}

[10] Here, impacts on economic growth refer to changes in GDP. Many impacts, such as loss of human lives, cultural heritage, and ecosystem services, are difficult to value and monetize.

How the level of global warming affects impacts and/or risks associated with the Reasons for Concern (RFCs) and selected natural, managed and human systems

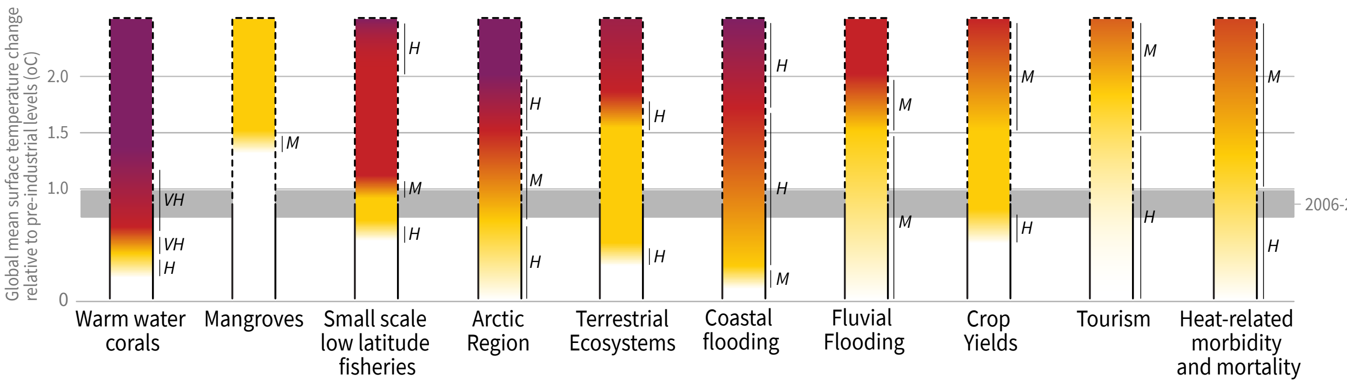
Five Reasons For Concern (RFCs) illustrate the impacts and risks of different levels of global warming for people, economies and ecosystems across sectors and regions.

Impacts and risks associated with the Reasons for Concern (RFCs)



Purple indicates very high risks of severe impacts/risks and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks.
Red indicates severe and widespread impacts/risks.
Yellow indicates that impacts/risks are detectable and attributable to climate change with at least medium confidence.
White indicates that no impacts are detectable and attributable to climate change.

Impacts and risks for selected natural, managed and human systems



Confidence level for transition: *L*=Low, *M*=Medium, *H*=High and *VH*=Very high

Figure SPM.2: Five integrative reasons for concern (RFCs) provide a framework for summarizing key impacts and risks across sectors and regions, and were introduced in the IPCC Third Assessment Report. RFCs illustrate the implications of global warming for people, economies, and ecosystems. Impacts and/or risks for each RFC are based on assessment of the new literature that has appeared. As in the AR5, this literature was used to make expert judgments to assess the levels of global warming at which levels of impact and/or risk are undetectable, moderate, high or very high. The selection of impacts and risks to natural, managed and human systems in the lower panel is illustrative and is not intended to be fully comprehensive. **RFC1 Unique and threatened systems:** ecological and human systems that have restricted geographic ranges constrained by climate related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its indigenous people, mountain glaciers, and biodiversity hotspots. **RFC2 Extreme weather events**: risks/impacts to human health, livelihoods, assets, and ecosystems from extreme weather events such as heat waves, heavy rain, drought and associated wildfires, and coastal flooding. **RFC3 Distribution of impacts:** risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. **RFC4 Global aggregate impacts:** global monetary damage, global scale degradation and loss of ecosystems and biodiversity. **RFC5 Large-scale singular events:** are relatively large, abrupt and sometimes irreversible changes in systems that are caused by global warming. Examples include disintegration of the Greenland and Antarctic ice sheets. {3.4, 3.5, 3.5.2.1, 3.5.2.2, 3.5.2.3, 3.5.2.4, 3.5.2.5, 5.4.1 5.5.3, 5.6.1, Box 3.4}

B6. Most adaptation needs will be lower for global warming of 1.5°C compared to 2°C (*high confidence*). There are a wide range of adaptation options that can reduce the risks of climate change (*high confidence*). There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5°C, with associated losses (*medium confidence*). The number and availability of adaptation options vary by sector (*medium confidence*). {Table 3.5, 4.3, 4.5, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 12 in Chapter 5}

B6.1. A wide range of adaptation options are available to reduce the risks to natural and managed ecosystems (e.g., ecosystem-based adaptation, ecosystem restoration and avoided degradation and deforestation, biodiversity management, sustainable aquaculture, and local knowledge and indigenous knowledge), the risks of sea level rise (e.g., coastal defence and hardening), and the risks to health, livelihoods, food, water, and economic growth, especially in rural landscapes (e.g., efficient irrigation, social safety nets, disaster risk management, risk spreading and sharing, community-based adaptation) and urban areas (e.g., green infrastructure, sustainable land use and planning, and sustainable water management) (*medium confidence*). {4.3.1, 4.3.2, 4.3.3, 4.3.5, 4.5.3, 4.5.4, 5.3.2, Box 4.2, Box 4.3, Box 4.6, Cross-Chapter Box 9 in Chapter 4}.

B6.2. Adaptation is expected to be more challenging for ecosystems, food and health systems at 2°C of global warming than for 1.5°C (*medium confidence*). Some vulnerable regions, including small islands and Least Developed Countries, are projected to experience high multiple interrelated climate risks even at global warming of 1.5°C (*high confidence*). {3.3.1, 3.4.5, Box 3.5, Table 3.5, Cross-Chapter Box 9 in Chapter 4, 5.6, Cross-Chapter Box 12 in Chapter 5, Box 5.3}

B6.3. Limits to adaptive capacity exist at 1.5°C of global warming, become more pronounced at higher levels of warming and vary by sector, with site-specific implications for vulnerable regions, ecosystems, and human health (*medium confidence*) {Cross-Chapter Box 12 in Chapter 5, Box 3.5, Table 3.5}

C. Emission Pathways and System Transitions Consistent with 1.5°C Global Warming

C1. In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range). For limiting global warming to below 2°C[11] CO_2 emissions are projected to decline by about 20% by 2030 in most pathways (10–30% interquartile range) and reach net zero around 2075 (2065–2080 interquartile range). Non-CO_2 emissions in pathways that limit global warming to 1.5°C show deep reductions that are similar to those in pathways limiting warming to 2°C. (*high confidence*) (Figure SPM.3a) {2.1, 2.3, Table 2.4}

C1.1. CO_2 emissions reductions that limit global warming to 1.5°C with no or limited overshoot can involve different portfolios of mitigation measures, striking different balances between lowering energy and resource intensity, rate of decarbonization, and the reliance on carbon dioxide removal. Different portfolios face different implementation challenges, and potential synergies and trade-offs with sustainable development. (*high confidence*). (Figure SPM.3b) {2.3.2, 2.3.4, 2.4, 2.5.3}

[11] References to pathways limiting global warming to 2°C are based on a 66% probability of staying below 2°C.

C1.2. Modelled pathways that limit global warming to 1.5°C with no or limited overshoot involve deep reductions in emissions of methane and black carbon (35% or more of both by 2050 relative to 2010). These pathways also reduce most of the cooling aerosols, which partially offsets mitigation effects for two to three decades. Non-CO_2 emissions[12] can be reduced as a result of broad mitigation measures in the energy sector. In addition, targeted non-CO_2 mitigation measures can reduce nitrous oxide and methane from agriculture, methane from the waste sector, some sources of black carbon, and hydrofluorocarbons. High bioenergy demand can increase emissions of nitrous oxide in some 1.5°C pathways, highlighting the importance of appropriate management approaches. Improved air quality resulting from projected reductions in many non-CO_2 emissions provide direct and immediate population health benefits in all 1.5°C model pathways. (*high confidence*) (Figure SPM.3a) {2.2.1, 2.3.3, 2.4.4, 2.5.3, 4.3.6, 5.4.2}

C1.3. Limiting global warming requires limiting the total cumulative global anthropogenic emissions of CO_2 since the preindustrial period, i.e. staying within a total carbon budget (*high confidence*).[13] By the end of 2017, anthropogenic CO_2 emissions since the preindustrial period are estimated to have reduced the total carbon budget for 1.5°C by approximately 2200 ± 320 $GtCO_2$ (*medium confidence*). The associated remaining budget is being depleted by current emissions of 42 ± 3 $GtCO_2$ per year (*high confidence*). The choice of the measure of global temperature affects the estimated remaining carbon budget. Using global mean surface air temperature, as in AR5, gives an estimate of the remaining carbon budget of 580 $GtCO_2$ for a 50% probability of limiting warming to 1.5°C, and 420 $GtCO_2$ for a 66% probability (*medium confidence*).[14] Alternatively, using GMST gives estimates of 770 and 570 $GtCO_2$, for 50% and 66% probabilities,[15] respectively (*medium confidence*). Uncertainties in the size of these estimated remaining carbon budgets are substantial and depend on several factors. Uncertainties in the climate response to CO_2 and non-CO_2 emissions contribute ±400 $GtCO_2$ and the level of historic warming contributes ±250 $GtCO_2$ (*medium confidence*). Potential additional carbon release from future permafrost thawing and methane release from wetlands would reduce budgets by up to 100 $GtCO_2$ over the course of this century and more thereafter (*medium confidence*). In addition, the level of non-CO_2 mitigation in the future could alter the remaining carbon budget by 250 $GtCO_2$ in either direction (*medium confidence*). {1.2.4, 2.2.2, 2.6.1, Table 2.2, Chapter 2 Supplementary Material}

C1.4. Solar radiation modification (SRM) measures are not included in any of the available assessed pathways. Although some SRM measures may be theoretically effective in reducing an overshoot, they face large uncertainties and knowledge gaps as well as substantial risks,

---

[12] Non-CO_2 emissions included in this report are all anthropogenic emissions other than CO_2 that result in radiative forcing. These include short-lived climate forcers, such as methane, some fluorinated gases, ozone precursors, aerosols or aerosol precursors, such as black carbon and sulphur dioxide, respectively, as well as long-lived greenhouse gases, such as nitrous oxide or some fluorinated gases. The radiative forcing associated with non-CO_2 emissions and changes in surface albedo is referred to as non-CO_2 radiative forcing. {x.y}

[13] There is a clear scientific basis for a total carbon budget consistent with limiting global warming to 1.5°C. However, neither this total carbon budget nor the fraction of this budget taken up by past emissions were assessed in this report.

[14] Irrespective of the measure of global temperature used, updated understanding and further advances in methods have led to an increase in the estimated remaining carbon budget of about 300 $GtCO_2$ compared to AR5. (*medium confidence*) {x.y}

[15] These estimates use observed GMST to 2006–2015 and estimate future temperature changes using near surface air temperatures.

institutional and social constraints to deployment related to governance, ethics, and impacts on sustainable development. They also do not mitigate ocean acidification. (*medium confidence*). {4.3.8, Cross-Chapter Box 10 in Chapter 4}

Global emissions pathway characteristics

General characteristics of the evolution of anthropogenic net emissions of CO_2, and total emissions of methane, black carbon, and nitrous oxide in model pathways that limit global warming to 1.5°C with no or limited overshoot. Net emissions are defined as anthropogenic emissions reduced by anthropogenic removals. Reductions in net emissions can be achieved through different portfolios of mitigation measures illustrated in Figure SPM3B.

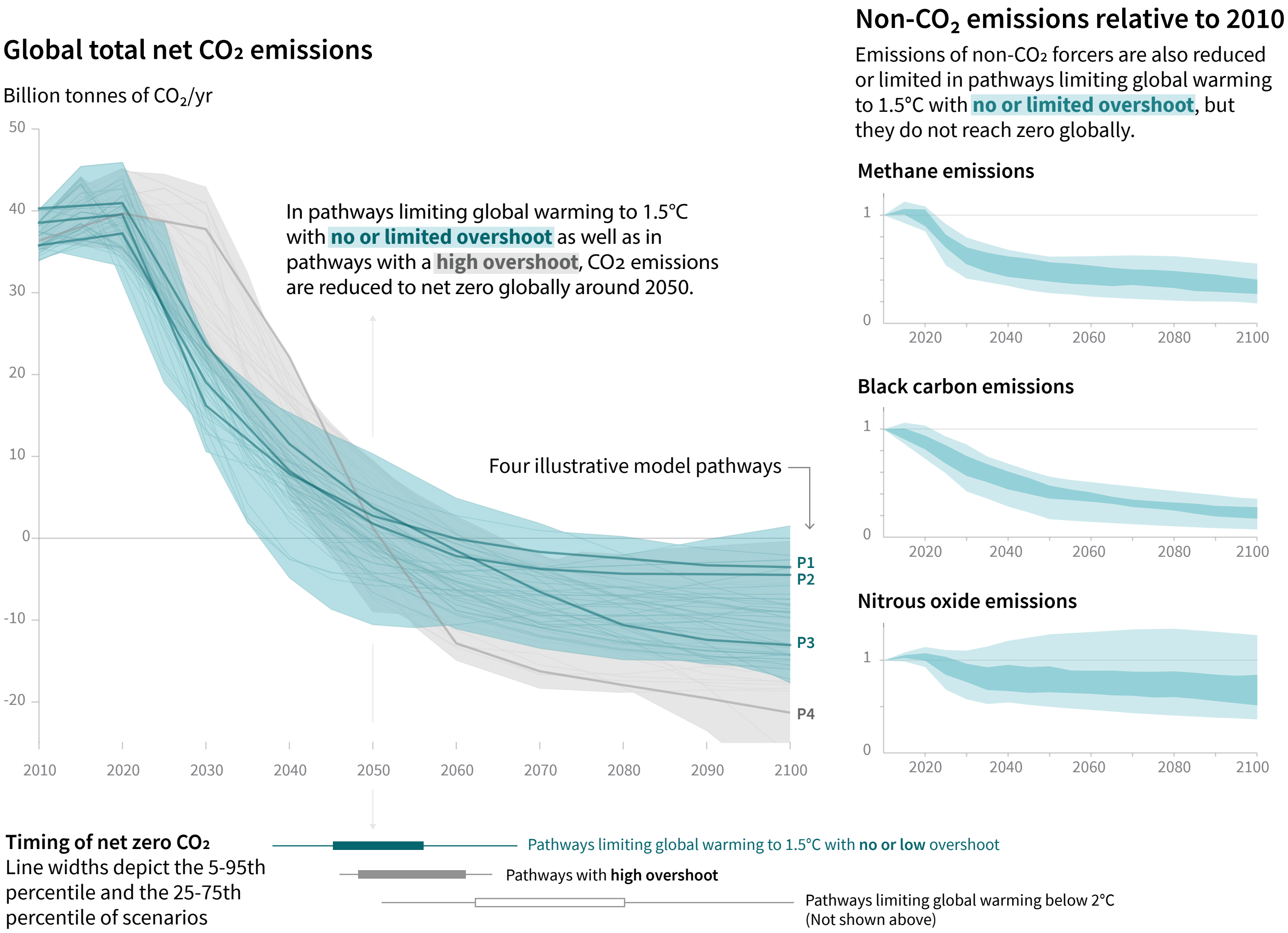
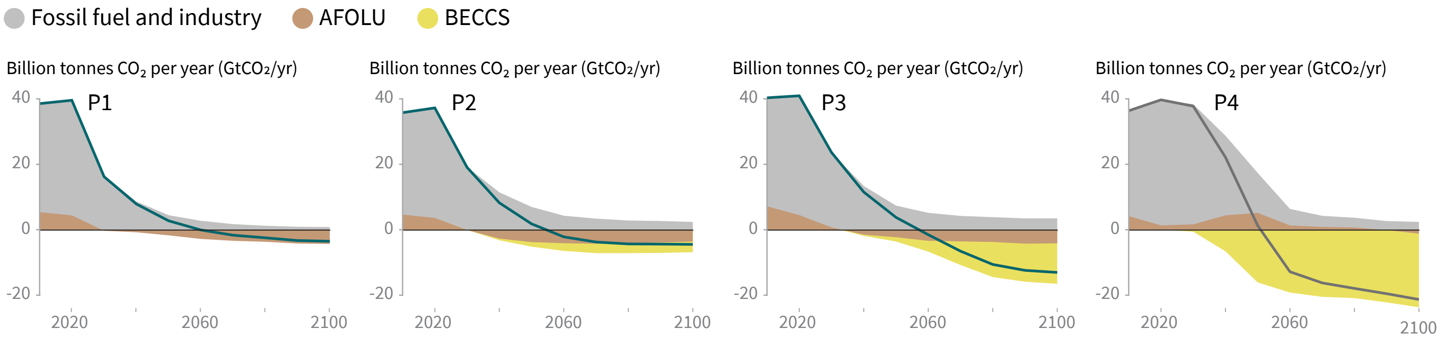


Figure SPM.3a: Global emissions pathway characteristics. The main panel shows global net anthropogenic CO_2 emissions in pathways limiting global warming to 1.5°C with no or limited (less than 0.1°C) overshoot and pathways with higher overshoot. The shaded area shows the full range for pathways analysed in this report. The panels on the right show non-CO_2 emissions ranges for three compounds with large historical forcing and a substantial portion of emissions coming from sources distinct from those central to CO_2 mitigation. Shaded areas in these panels show the 5–95% (light shading) and interquartile (dark shading) ranges of pathways limiting global warming to 1.5°C with no or limited overshoot. Box and whiskers at the bottom of the figure show the timing of pathways reaching global net zero CO_2 emission levels, and a comparison with pathways limiting global warming to 2°C with at least 66% probability. Four illustrative model pathways are highlighted in the main panel and are labelled P1, P2, P3 and P4, corresponding to the LED, S1, S2, and S5 pathways assessed in Chapter 2. Descriptions and characteristics of these pathways are available in Figure SPM3b. {2.1, 2.2, 2.3, Figure 2.5, Figure 2.10, Figure 2.11}

Characteristics of four illustrative model pathways

Different mitigation strategies can achieve the net emissions reductions that would be required to follow a pathway that limit global warming to 1.5°C with no or limited overshoot. All pathways use Carbon Dioxide Removal (CDR), but the amount varies across pathways, as do the relative contributions of Bioenergy with Carbon Capture and Storage (BECCS) and removals in the Agriculture, Forestry and Other Land Use (AFOLU) sector. This has implications for the emissions and several other pathway characteristics.

Breakdown of contributions to global net CO_2 emissions in four illustrative model pathways



P1: A scenario in which social, business, and technological innovations result in lower energy demand up to 2050 while living standards rise, especially in the global South. A down-sized energy system enables rapid decarbonisation of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used.

P2: A scenario with a broad focus on sustainability including energy intensity, human development, economic convergence and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS.

P3: A middle-of-the-road scenario in which societal as well as technological development follows historical patterns. Emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand.

P4: A resource and energy-intensive scenario in which economic growth and globalization lead to widespread adoption of greenhouse-gas intensive lifestyles, including high demand for transportation fuels and livestock products. Emissions reductions are mainly achieved through technological means, making strong use of CDR through the deployment of BECCS.

Global indicators	P1	P2	P3	P4	**Interquartile range**
Pathway classification	No or low overshoot	No or low overshoot	No or low overshoot	High overshoot	No or low overshoot
CO_2 emission change in 2030 (% rel to 2010)	-58	-47	-41	4	(-59,-40)
↳ in 2050 (% rel to 2010)	-93	-95	-91	-97	(-104,-91)
Kyoto-GHG emissions in 2030 (% rel to 2010)*	-50	-49	-35	-2	(-55,-38)
↳ in 2050 (% rel to 2010)	-82	-89	-78	-80	(-93,-81)
*Final energy demand** in 2030 (% rel to 2010)*	-15	-5	17	39	(-12, 7)
↳ in 2050 (% rel to 2010)	-32	2	21	44	(-11, 22)
Renewable share in electricity in 2030 (%)	60	58	48	25	(47, 65)
↳ in 2050 (%)	77	81	63	70	(69, 87)
Primary energy from coal in 2030 (% rel to 2010)	-78	-61	-75	-59	(-78, -59)
↳ in 2050 (% rel to 2010)	-97	-77	-73	-97	(-95, -74)
from oil in 2030 (% rel to 2010)	-37	-13	-3	86	(-34,3)
↳ in 2050 (% rel to 2010)	-87	-50	-81	-32	(-78,-31)
from gas in 2030 (% rel to 2010)	-25	-20	33	37	(-26,21)
↳ in 2050 (% rel to 2010)	-74	-53	21	-48	(-56,6)
from nuclear in 2030 (% rel to 2010)	59	83	98	106	(44,102)
↳ in 2050 (% rel to 2010)	150	98	501	468	(91,190)
from biomass in 2030 (% rel to 2010)	-11	0	36	-1	(29,80)
↳ in 2050 (% rel to 2010)	-16	49	121	418	(123,261)
from non-biomass renewables in 2030 (% rel to 2010)	430	470	315	110	(243,438)
↳ in 2050 (% rel to 2010)	832	1327	878	1137	(575,1300)
Cumulative CCS until 2100 ($GtCO_2$)	0	348	687	1218	(550, 1017)
↳ of which BECCS ($GtCO_2$)	0	151	414	1191	(364, 662)
Land area of bioenergy crops in 2050 (million hectare)	22	93	283	724	(151, 320)
Agricultural CH_4 emissions in 2030 (% rel to 2010)	-24	-48	1	14	(-30,-11)
in 2050 (% rel to 2010)	-33	-69	-23	2	(-46,-23)
Agricultural N_2O emissions in 2030 (% rel to 2010)	5	-26	15	3	(-21,4)
in 2050 (% rel to 2010)	6	-26	0	39	(-26,1)

NOTE: Indicators have been selected to show global trends identified by the Chapter 2 assessment. National and sectoral characteristics can differ substantially from the global trends shown above.

** Kyoto-gas emissions are based on SAR GWP-100*
*** Changes in energy demand are associated with improvements in energy efficiency and behaviour change*

Figure SPM.3b: Characteristics of four illustrative model pathways in relation to global warming of 1.5°C introduced in Figure SPM3a. These pathways were selected to show a range of potential mitigation approaches and vary widely in their projected energy and land use, as well as their assumptions about future socioeconomic developments, including economic and population growth, equity and sustainability. A breakdown of the global net anthropogenic CO_2 emissions into the contributions in terms of CO_2 emissions from fossil fuel and industry, agriculture, forestry and other land use (AFOLU), and bioenergy with carbon capture and storage (BECCS) is shown. AFOLU estimates reported here are not necessarily comparable with countries' estimates. Further characteristics for each of these pathways are listed below each pathway. These pathways illustrate relative global differences in mitigation strategies, but do not represent central estimates, national strategies, and do not indicate requirements. For comparison, the right-most column shows the interquartile ranges across pathways with no or limited overshoot of 1.5°C. Pathways P1, P2, P3 and P4, correspond to the LED, S1, S2, and S5 pathways assessed in Chapter 2. (Figure SPM.3a) {2.2.1, 2.3.1, 2.3.2, 2.3.3, 2.3.4, 2.4.1, 2.4.2, 2.4.4, 2.5.3, Figure 2.5, Figure 2.6, Figure 2.9, Figure 2.10, Figure 2.11, Figure 2.14, Figure 2.15, Figure 2.16, Figure 2.17, Figure 2.24, Figure 2.25, Table 2.4, Table 2.6, Table 2.7, Table 2.9, Table 4.1}

C2. Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (*high confidence*). These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (*medium confidence*). {2.3, 2.4, 2.5, 4.2, 4.3, 4.4, 4.5}

C2.1. Pathways that limit global warming to 1.5°C with no or limited overshoot show system changes that are more rapid and pronounced over the next two decades than in 2°C pathways (*high confidence*). The rates of system changes associated with limiting global warming to 1.5°C with no or limited overshoot have occurred in the past within specific sectors, technologies and spatial contexts, but there is no documented historic precedent for their scale (*medium confidence*). {2.3.3, 2.3.4, 2.4, 2.5, 4.2.1, 4.2.2, Cross-Chapter Box 11 in Chapter 4}

C2.2. In energy systems, modelled global pathways (considered in the literature) limiting global warming to 1.5°C with no or limited overshoot (for more details see Figure SPM.3b), generally meet energy service demand with lower energy use, including through enhanced energy efficiency, and show faster electrification of energy end use compared to 2°C (*high confidence*). In 1.5°C pathways with no or limited overshoot, low-emission energy sources are projected to have a higher share, compared with 2°C pathways, particularly before 2050 (*high confidence*). In 1.5°C pathways with no or limited overshoot, renewables are projected to supply 70–85% (interquartile range) of electricity in 2050 (*high confidence*). In electricity generation, shares of nuclear and fossil fuels with carbon dioxide capture and storage (CCS) are modelled to increase in most 1.5°C pathways with no or limited overshoot. In modelled 1.5°C pathways with limited or no overshoot, the use of CCS would allow the electricity generation share of gas to be approximately 8% (3–11% interquartile range) of global electricity in 2050, while the use of coal shows a steep reduction in all pathways and would be reduced to close to 0% (0–2%) of electricity (*high confidence*). While acknowledging the challenges, and differences between the options and national circumstances, political, economic, social and technical feasibility of solar energy, wind energy and electricity storage technologies have substantially improved over the past few years (*high confidence*). These improvements signal a potential system transition in electricity generation (Figure SPM.3b) {2.4.1, 2.4.2, Figure 2.1, Table 2.6, Table 2.7, Cross-Chapter Box 6 in Chapter 3, 4.2.1, 4.3.1, 4.3.3, 4.5.2}

C2.3. CO_2 emissions from industry in pathways limiting global warming to 1.5°C with no or limited overshoot are projected to be about 75–90% (interquartile range) lower in 2050 relative to 2010, as compared to 50–80% for global warming of 2°C (*medium confidence*). Such reductions can be achieved through combinations of new and existing technologies and practices, including electrification, hydrogen, sustainable bio-based feedstocks, product substitution, and carbon capture, utilization and storage (CCUS). These options are technically proven at various scales but their large-scale deployment may be limited by economic, financial, human capacity and institutional constraints in specific contexts, and specific characteristics of large-scale industrial installations. In industry, emissions reductions by energy and process efficiency by themselves are insufficient for limiting warming to 1.5°C with no or limited overshoot (*high confidence*). {2.4.3, 4.2.1, Table 4.1, Table 4.3, 4.3.3, 4.3.4, 4.5.2}

C2.4. The urban and infrastructure system transition consistent with limiting global warming to 1.5°C with no or limited overshoot would imply, for example, changes in land and urban planning practices, as well as deeper emissions reductions in transport and buildings compared to pathways that limit global warming below 2°C (see 2.4.3; 4.3.3; 4.2.1) (*medium confidence*). Technical measures and practices enabling deep emissions reductions include various energy efficiency options. In pathways limiting global warming to 1.5°C with no or limited overshoot, the electricity share of energy demand in buildings would be about 55–75% in 2050 compared to 50–70% in 2050 for 2°C global warming (*medium confidence*). In the transport sector, the share of low-emission final energy would rise from less than 5% in 2020 to about 35–65% in 2050 compared to 25–45% for 2°C global warming (*medium confidence*). Economic, institutional and socio-cultural barriers may inhibit these urban and infrastructure system transitions, depending on national, regional and local circumstances, capabilities and the availability of capital (*high confidence*). {2.3.4, 2.4.3, 4.2.1, Table 4.1, 4.3.3, 4.5.2}.

C2.5. Transitions in global and regional land use are found in all pathways limiting global warming to 1.5°C with no or limited overshoot, but their scale depends on the pursued mitigation portfolio. Model pathways that limit global warming to 1.5°C with no or limited overshoot project the conversion of 0.5–8 million km^2 of pasture and 0–5 million km^2 of non-pasture agricultural land for food and feed crops into 1–7 million km^2 for energy crops and a 1 million km^2 reduction to 10 million km^2 increase in forests by 2050 relative to 2010 (*medium confidence*).[16] Land use transitions of similar magnitude can be observed in modelled 2°C pathways (*medium confidence*). Such large transitions pose profound challenges for sustainable management of the various demands on land for human settlements, food, livestock feed, fibre, bioenergy, carbon storage, biodiversity and other ecosystem services (*high confidence*). Mitigation options limiting the demand for land include sustainable intensification of land use practices, ecosystem restoration and changes towards less resource-intensive diets (*high confidence*). The implementation of land-based mitigation options would require overcoming socio-economic, institutional, technological, financing and environmental barriers that differ across regions (*high confidence*). {2.4.4, Figure 2.24, 4.3.2, 4.5.2, Cross-Chapter Box 7 in Chapter 3}

C2.6 Total annual average energy-related mitigation investment for the period 2015 to 2050 in pathways limiting warming to 1.5°C is estimated to be around 900 billion USD2015 (range of 180 billion to 1800 billion USD2015 across six models[17]). This corresponds to total annual average energy supply investments of 1600 to 3800 billion USD2015 and total annual average energy demand investments of 700 to 1000 billion USD2015 for the period 2015 to 2050, and an increase in total energy-related investments of about 12% (range of 3% to 23%) in 1.5°C pathways relative to 2°C pathways. Average annual investment in low-carbon energy technologies and energy efficiency are upscaled by roughly a factor of five (range of factor of 4 to 5) by 2050 compared to 2015 (*medium confidence*). {2.5.2, Box 4.8, Figure 2.27}

C2.7. Modelled pathways limiting global warming to 1.5°C with no or limited overshoot project a wide range of global average discounted marginal abatement costs over the 21st century. They are roughly 3-4 times higher than in pathways limiting global warming to below 2°C (*high confidence*). The economic literature distinguishes marginal abatement costs from total mitigation costs in the economy. The literature on total mitigation costs of 1.5°C mitigation pathways is limited and was not assessed in this report. Knowledge gaps remain in the integrated assessment of the economy wide costs and benefits of mitigation in line with pathways limiting warming to 1.5°C. {2.5.2; 2.6; Figure 2.26}

---

[16] The projected land use changes presented are not deployed to their upper limits simultaneously in a single pathway.

[17] Including two pathways limiting warming to 1.5°C with no or limited overshoot and four pathways with high overshoot.

C3. All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the 21st century. CDR would be used to compensate for residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5°C following a peak (*high confidence*). CDR deployment of several hundreds of $GtCO_2$ is subject to multiple feasibility and sustainability constraints (*high confidence*). Significant near-term emissions reductions and measures to lower energy and land demand can limit CDR deployment to a few hundred $GtCO_2$ without reliance on bioenergy with carbon capture and storage (BECCS) (*high confidence*). {2.3, 2.4, 3.6.2, 4.3, 5.4}

C3.1. Existing and potential CDR measures include afforestation and reforestation, land restoration and soil carbon sequestration, BECCS, direct air carbon capture and storage (DACCS), enhanced weathering and ocean alkalinization. These differ widely in terms of maturity, potentials, costs, risks, co-benefits and trade-offs (*high confidence*). To date, only a few published pathways include CDR measures other than afforestation and BECCS. {2.3.4, 3.6.2, 4.3.2, 4.3.7}

C3.2. In pathways limiting global warming to 1.5°C with limited or no overshoot, BECCS deployment is projected to range from 0–1, 0–8, and 0–16 $GtCO_2\ yr^{-1}$ in 2030, 2050, and 2100, respectively, while agriculture, forestry and land-use (AFOLU) related CDR measures are projected to remove 0–5, 1–11, and 1–5 $GtCO_2\ yr^{-1}$ in these years (*medium confidence*). The upper end of these deployment ranges by mid-century exceeds the BECCS potential of up to 5 $GtCO_2\ yr^{-1}$ and afforestation potential of up to 3.6 $GtCO_2\ yr^{-1}$ assessed based on recent literature (*medium confidence*). Some pathways avoid BECCS deployment completely through demand-side measures and greater reliance on AFOLU-related CDR measures (*medium confidence*). The use of bioenergy can be as high or even higher when BECCS is excluded compared to when it is included due to its potential for replacing fossil fuels across sectors (*high confidence*). (Figure SPM.3b) {2.3.3, 2.3.4, 2.4.2, 3.6.2, 4.3.1, 4.2.3, 4.3.2, 4.3.7, 4.4.3, Table 2.4}

C3.3. Pathways that overshoot 1.5°C of global warming rely on CDR exceeding residual CO_2 emissions later in the century to return to below 1.5°C by 2100, with larger overshoots requiring greater amounts of CDR (Figure SPM.3b). (*high confidence*). Limitations on the speed, scale, and societal acceptability of CDR deployment hence determine the ability to return global warming to below 1.5°C following an overshoot. Carbon cycle and climate system understanding is still limited about the effectiveness of net negative emissions to reduce temperatures after they peak (*high confidence*). {2.2, 2.3.4, 2.3.5, 2.6, 4.3.7, 4.5.2, Table 4.11}

C3.4. Most current and potential CDR measures could have significant impacts on land, energy, water, or nutrients if deployed at large scale (*high confidence*). Afforestation and bioenergy may compete with other land uses and may have significant impacts on agricultural and food systems, biodiversity and other ecosystem functions and services (*high confidence*). Effective governance is needed to limit such trade-offs and ensure permanence of carbon removal in terrestrial, geological and ocean reservoirs (*high confidence*). Feasibility and sustainability of CDR use could be enhanced by a portfolio of options deployed at substantial, but lesser scales, rather than a single option at very large scale (*high confidence*). (Figure SPM.3b). {2.3.4, 2.4.4, 2.5.3, 2.6, 3.6.2, 4.3.2, 4.3.7, 4.5.2, 5.4.1, 5.4.2; Cross-Chapter Boxes 7 and 8 in Chapter 3, Table 4.11, Table 5.3, Figure 5.3}

C3.5. Some AFOLU-related CDR measures such as restoration of natural ecosystems and soil carbon sequestration could provide co-benefits such as improved biodiversity, soil quality, and local food security. If deployed at large scale, they would require governance systems enabling sustainable land management to conserve and protect land carbon stocks and other ecosystem functions and services (*medium confidence*). (Figure SPM.4) {2.3.3, 2.3.4, 2.4.2, 2.4.4, 3.6.2, 5.4.1, Cross-Chapter Boxes 3 in Chapter 1 and 7 in Chapter 3, 4.3.2, 4.3.7, 4.4.1, 4.5.2, Table 2.4}

D. Strengthening the Global Response in the Context of Sustainable Development and Efforts to Eradicate Poverty

D1. Estimates of the global emissions outcome of current nationally stated mitigation ambitions as submitted under the Paris Agreement would lead to global greenhouse gas emissions[18] in 2030 of 52–58 $GtCO_2eq\ yr^{-1}$ (*medium confidence)*. Pathways reflecting these ambitions would not limit global warming to 1.5°C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030 (*high confidence*). Avoiding overshoot and reliance on future large-scale deployment of carbon dioxide removal (CDR) can only be achieved if global CO_2 emissions start to decline well before 2030 (*high confidence*). {1.2, 2.3, 3.3, 3.4, 4.2, 4.4, Cross-Chapter Box 11 in Chapter 4}

D1.1. Pathways that limit global warming to 1.5°C with no or limited overshoot show clear emission reductions by 2030 (*high confidence*). All but one show a decline in global greenhouse gas emissions to below 35 $GtCO_2eq\ yr^{-1}$ in 2030, and half of available pathways fall within the 25–30 $GtCO_2eq\ yr^{-1}$ range (interquartile range), a 40–50% reduction from 2010 levels (*high confidence*). Pathways reflecting current nationally stated mitigation ambition until 2030 are broadly consistent with cost-effective pathways that result in a global warming of about 3°C by 2100, with warming continuing afterwards (*medium confidence*). {2.3.3, 2.3.5, Cross-Chapter Box 11 in Chapter 4, 5.5.3.2}

D1.2. Overshoot trajectories result in higher impacts and associated challenges compared to pathways that limit global warming to 1.5°C with no or limited overshoot (*high confidence*). Reversing warming after an overshoot of 0.2°C or larger during this century would require upscaling and deployment of CDR at rates and volumes that might not be achievable given considerable implementation challenges (*medium confidence*). {1.3.3, 2.3.4, 2.3.5, 2.5.1, 3.3, 4.3.7, Cross-Chapter Box 8 in Chapter 3, Cross-Chapter Box 11 in Chapter 4}

D1.3. The lower the emissions in 2030, the lower the challenge in limiting global warming to 1.5°C after 2030 with no or limited overshoot (*high confidence*). The challenges from delayed actions to reduce greenhouse gas emissions include the risk of cost escalation, lock-in in carbon-emitting infrastructure, stranded assets, and reduced flexibility in future response options in the medium to long-term (*high confidence*). These may increase uneven distributional impacts between countries at different stages of development (*medium confidence*). {2.3.5, 4.4.5, 5.4.2}

D2. The avoided climate change impacts on sustainable development, eradication of poverty and reducing inequalities would be greater if global warming were limited to 1.5°C rather than 2°C, if mitigation and adaptation synergies are maximized while trade-offs are minimized (*high confidence*). {1.1, 1.4, 2.5, 3.3, 3.4, 5.2, Table 5.1}

---

[18] GHG emissions have been aggregated with 100-year GWP values as introduced in the IPCC Second Assessment Report

D2.1. Climate change impacts and responses are closely linked to sustainable development which balances social well-being, economic prosperity and environmental protection. The United Nations Sustainable Development Goals (SDGs), adopted in 2015, provide an established framework for assessing the links between global warming of 1.5°C or 2°C and development goals that include poverty eradication, reducing inequalities, and climate action (*high confidence*) {Cross-Chapter Box 4 in Chapter 1, 1.4, 5.1}

D2.2. The consideration of ethics and equity can help address the uneven distribution of adverse impacts associated with 1.5°C and higher levels of global warming, as well as those from mitigation and adaptation, particularly for poor and disadvantaged populations, in all societies (*high confidence*). {1.1.1, 1.1.2, 1.4.3, 2.5.3, 3.4.10, 5.1, 5.2, 5.3. 5.4, Cross-Chapter Box 4 in Chapter 1, Cross-Chapter Boxes 6 and 8 in Chapter 3, and Cross-Chapter Box 12 in Chapter 5}

D2.3. Mitigation and adaptation consistent with limiting global warming to 1.5°C are underpinned by enabling conditions, assessed in SR1.5 across the geophysical, environmental-ecological, technological, economic, socio-cultural and institutional dimensions of feasibility. Strengthened multi-level governance, institutional capacity, policy instruments, technological innovation and transfer and mobilization of finance, and changes in human behaviour and lifestyles are enabling conditions that enhance the feasibility of mitigation and adaptation options for 1.5°C consistent systems transitions. *(high confidence*) {1.4, Cross-Chapter Box 3 in Chapter 1, 4.4, 4.5, 5.6}

D3. Adaptation options specific to national contexts, if carefully selected together with enabling conditions, will have benefits for sustainable development and poverty reduction with global warming of 1.5°C, although trade-offs are possible (*high confidence*). {1.4, 4.3, 4.5}

D3.1. Adaptation options that reduce the vulnerability of human and natural systems have many synergies with sustainable development, if well managed, such as ensuring food and water security, reducing disaster risks, improving health conditions, maintaining ecosystem services and reducing poverty and inequality (*high confidence*). Increasing investment in physical and social infrastructure is a key enabling condition to enhance the resilience and the adaptive capacities of societies. These benefits can occur in most regions with adaptation to 1.5°C of global warming (*high confidence*). {1.4.3, 4.2.2, 4.3.1, 4.3.2, 4.3.3, 4.3.5, 4.4.1, 4.4.3, 4.5.3, 5.3.1, 5.3.2}

D3.2. Adaptation to 1.5°C global warming can also result in trade–offs or maladaptations with adverse impacts for sustainable development. For example, if poorly designed or implemented, adaptation projects in a range of sectors can increase greenhouse gas emissions and water use, increase gender and social inequality, undermine health conditions, and encroach on natural ecosystems (*high confidence*). These trade-offs can be reduced by adaptations that include attention to poverty and sustainable development (*high confidence*). {4.3.2, 4.3.3, 4.5.4, 5.3.2; Cross-Chapter Boxes 6 and 7 in Chapter 3}

D3.3. A mix of adaptation and mitigation options to limit global warming to 1.5°C, implemented in a participatory and integrated manner, can enable rapid, systemic transitions in urban and rural areas (*high confidence*). These are most effective when aligned with economic and sustainable development, and when local and regional governments and decision makers are supported by national governments (*medium confidence*) {4.3.2, 4.3.3, 4.4.1, 4.4.2}

D3.4. Adaptation options that also mitigate emissions can provide synergies and cost savings in most sectors and system transitions, such as when land management reduces emissions and disaster risk, or when low carbon buildings are also designed for efficient cooling. Trade-offs between mitigation and adaptation, when limiting global warming to 1.5°C, such as when bioenergy crops, reforestation or afforestation encroach on land needed for agricultural adaptation, can undermine food security, livelihoods, ecosystem functions and services and other aspects of sustainable development. (*high confidence*) {3.4.3, 4.3.2, 4.3.4, 4.4.1, 4.5.2, 4.5.3, 4.5.4}

D4. Mitigation options consistent with 1.5°C pathways are associated with multiple synergies and trade-offs across the Sustainable Development Goals (SDGs). While the total number of possible synergies exceeds the number of trade-offs, their net effect will depend on the pace and magnitude of changes, the composition of the mitigation portfolio and the management of the transition. *(high confidence*) (Figure SPM.4) {2.5, 4.5, 5.4}

D4.1. 1.5°C pathways have robust synergies particularly for the SDGs 3 (health), 7 (clean energy), 11 (cities and communities), 12 (responsible consumption and production), and 14 (oceans) (*very high confidence*). Some 1.5°C pathways show potential trade-offs with mitigation for SDGs 1 (poverty), 2 (hunger), 6 (water), and 7 (energy access), if not carefully managed (*high confidence*) (Figure SPM.4). {5.4.2; Figure 5.4, Cross-Chapter Boxes 7 and 8 in Chapter 3}

D4.2. 1.5°C pathways that include low energy demand (e.g., see P1 in Figure SPM.3a and SPM.3b), low material consumption, and low GHG-intensive food consumption have the most pronounced synergies and the lowest number of trade-offs with respect to sustainable development and the SDGs (*high confidence*). Such pathways would reduce dependence on CDR. In modelled pathways sustainable development, eradicating poverty and reducing inequality can support limiting warming to 1.5◦C. (*high confidence*) (Figure SPM.3b, Figure SPM.4) {2.4.3, 2.5.1, 2.5.3, Figure 2.4, Figure 2.28, 5.4.1, 5.4.2, Figure 5.4}

D4.3. 1.5°C and 2°C modelled pathways often rely on the deployment of large-scale land-related measures like afforestation and bioenergy supply, which, if poorly managed, can compete with food production and hence raise food security concerns (*high confidence*). The impacts of carbon dioxide removal (CDR) options on SDGs depend on the type of options and the scale of deployment (*high confidence*). If poorly implemented, CDR options such as BECCS and AFOLU options would lead to trade-offs. Context-relevant design and implementation requires considering people's needs, biodiversity, and other sustainable development dimensions (*very high confidence*). {Figure SPM.4, 5.4.1.3, Cross-Chapter Box 7 in Chapter 3}

D4.4. Mitigation consistent with 1.5°C pathways creates risks for sustainable development in regions with high dependency on fossil fuels for revenue and employment generation (*high confidence*). Policies that promote diversification of the economy and the energy sector can address the associated challenges (*high confidence*). {5.4.1.2, Box 5.2}

D4.5. Redistributive policies across sectors and populations that shield the poor and vulnerable can resolve trade-offs for a range of SDGs, particularly hunger, poverty and energy access. Investment needs for such complementary policies are only a small fraction of the overall mitigation investments in 1.5°C pathways. (*high confidence*) {2.4.3, 5.4.2, Figure 5.5}

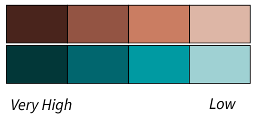
Indicative linkages between mitigation options and sustainable development using SDGs (The linkages do not show costs and benefits)

Mitigation options deployed in each sector can be associated with potential positive effects (synergies) or negative effects (trade-offs) with the Sustainable Development Goals (SDGs). The degree to which this potential is realized will depend on the selected portfolio of mitigation options, mitigation policy design, and local circumstances and context. Particularly in the energy-demand sector, the potential for synergies is larger than for trade-offs. The bars group individually assessed options by level of confidence and take into account the relative strength of the assessed mitigation-SDG connections.

Length shows strength of connection

The overall **size of the coloured bars** depict **the relative** for synergies and trade-offs between the sectoral mitigation options and the SDGs.

Shades show level of confidence



The shades depict **the level of confidence** of the assessed potential for **Trade-offs**/**Synergies**.

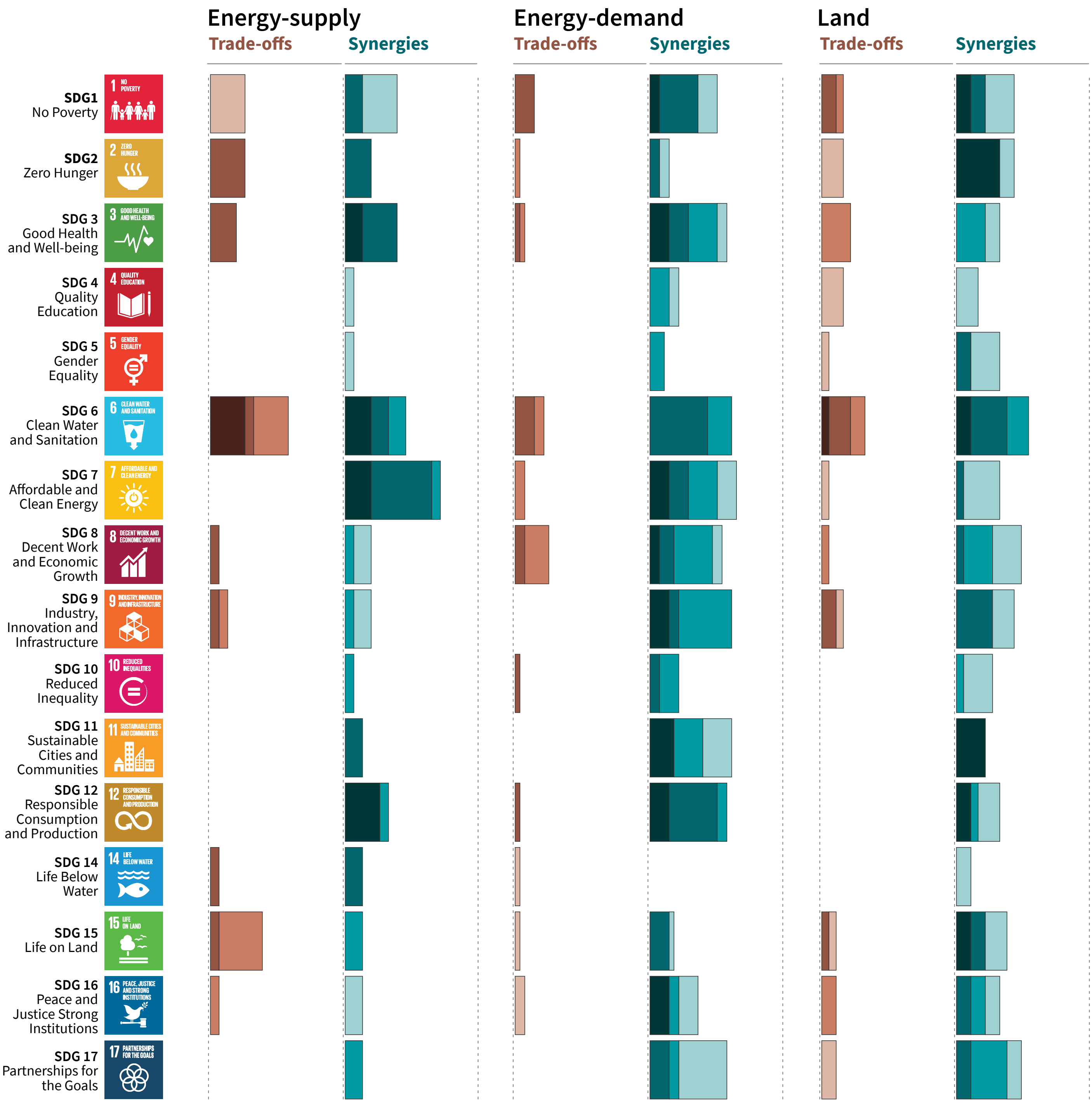


Figure SPM.4: Potential synergies and trade-offs between the sectoral portfolio of climate change mitigation options and the Sustainable Development Goals (SDGs). The SDGs serve as an analytical framework for the assessment of the different sustainable development dimensions, which extend beyond the time frame of the 2030 SDG targets. The assessment is based on literature on mitigation options that are considered relevant for 1.5ºC. The assessed strength of the SDG interactions is based on the qualitative and quantitative assessment of individual mitigation options listed in Table 5.2. For each mitigation option, the strength of the SDG-connection as well as the associated confidence of the underlying literature (shades of green and red) was assessed. The strength of positive connections (synergies) and negative connections (trade-offs) across all individual options within a sector (see Table 5.2) are aggregated into sectoral potentials for the whole mitigation portfolio. The (white) areas outside the bars, which indicate no interactions, have *low confidence* due to the uncertainty and limited number of studies exploring indirect effects. The strength of the connection considers only the effect of mitigation and does not include benefits of avoided impacts. SDG 13 (climate action) is not listed because mitigation is being considered in terms of interactions with SDGs and not vice versa. The bars denote the strength of the connection, and do not consider the strength of the impact on the SDGs. The energy demand sector comprises behavioural responses, fuel switching and efficiency options in the transport, industry and building sector as well as carbon capture options in the industry sector. Options assessed in the energy supply sector comprise biomass and non-biomass renewables, nuclear, CCS with bio-energy, and CCS with fossil fuels. Options in the land sector comprise agricultural and forest options, sustainable diets & reduced food waste, soil sequestration, livestock & manure management, reduced deforestation, afforestation & reforestation, responsible sourcing. In addition to this figure, options in the ocean sector are discussed in the underlying report. {5.4, Table 5.2, Figure 5.2}

Statement for knowledge gap:
Information about the net impacts of mitigation on sustainable development in 1.5°C pathways is available only for a limited number of SDGs and mitigation options. Only a limited number of studies have assessed the benefits of avoided climate change impacts of 1.5°C pathways for the SDGs, and the co-effects of adaptation for mitigation and the SDGs. The assessment of the indicative mitigation potentials in Figure SPM.4 is a step further from AR5 towards a more comprehensive and integrated assessment in the future.

D5. Limiting the risks from global warming of 1.5°C in the context of sustainable development and poverty eradication implies system transitions that can be enabled by an increase of adaptation and mitigation investments, policy instruments, the acceleration of technological innovation and behaviour changes (*high confidence*). {2.3, 2.4, 2.5, 3.2, 4.2, 4.4, 4.5, 5.2, 5.5, 5.6}

D5.1. Directing finance towards investment in infrastructure for mitigation and adaptation could provide additional resources. This could involve the mobilization of private funds by institutional investors, asset managers and development or investment banks, as well as the provision of public funds. Government policies that lower the risk of low-emission and adaptation investments can facilitate the mobilization of private funds and enhance the effectiveness of other public policies. Studies indicate a number of challenges including access to finance and mobilisation of funds (*high confidence*) {2.5.2, 4.4.5}

D5.2. Adaptation finance consistent with global warming of 1.5°C is difficult to quantify and compare with 2°C. Knowledge gaps include insufficient data to calculate specific climate resilience-enhancing investments, from the provision of currently underinvested basic infrastructure. Estimates of the costs of adaptation might be lower at global warming of 1.5°C than for 2°C. Adaptation needs have typically been supported by public sector sources such as national and subnational government budgets, and in developing countries together with support from development assistance, multilateral development banks, and UNFCCC channels (*medium confidence*). More recently there is a growing understanding of the scale and increase in NGO and private funding in some regions (*medium confidence*). Barriers include the scale of adaptation financing, limited capacity and access to adaptation finance (*medium confidence*).{4.4.5, 4.6}

D5.3. Global model pathways limiting global warming to 1.5°C are projected to involve the annual average investment needs in the energy system of around 2.4 trillion USD2010 between 2016 and 2035 representing about 2.5% of the world GDP (*medium confidence*). {2.5.2, 4.4.5, Box 4.8}

D5.4. Policy tools can help mobilise incremental resources, including through shifting global investments and savings and through market and non-market based instruments as well as accompanying measures to secure the equity of the transition, acknowledging the challenges related with implementation including those of energy costs, depreciation of assets and impacts on international competition, and utilizing the opportunities to maximize co-benefits (*high confidence*) {1.3.3, 2.3.4, 2.3.5, 2.5.1, 2.5.2, Cross-Chapter Box 8 in Chapter 3 and 11 in Chapter 4, 4.4.5, 5.5.2}

D5.5. The systems transitions consistent with adapting to and limiting global warming to 1.5°C include the widespread adoption of new and possibly disruptive technologies and practices and enhanced climate-driven innovation. These imply enhanced technological innovation capabilities, including in industry and finance. Both national innovation policies and international cooperation can contribute to the development, commercialization and widespread adoption of mitigation and adaptation technologies. Innovation policies may be more effective when they combine public support for research and development with policy mixes that provide incentives for technology diffusion. (*high confidence*) {4.4.4, 4.4.5}.

D5.6. Education, information, and community approaches, including those that are informed by Indigenous knowledge and local knowledge, can accelerate the wide scale behaviour changes consistent with adapting to and limiting global warming to 1.5°C. These approaches are more effective when combined with other policies and tailored to the motivations, capabilities, and resources of specific actors and contexts (*high confidence*). Public acceptability can enable or inhibit the implementation of policies and measures to limit global warming to 1.5°C and to adapt to the consequences. Public acceptability depends on the individual's evaluation of expected policy consequences, the perceived fairness of the distribution of these consequences, and perceived fairness of decision procedures (*high confidence*). {1.1, 1.5, 4.3.5, 4.4.1, 4.4.3, Box 4.3, 5.5.3, 5.6.5}

D6. Sustainable development supports, and often enables, the fundamental societal and systems transitions and transformations that help limit global warming to 1.5°C. Such changes facilitate the pursuit of climate-resilient development pathways that achieve ambitious mitigation and adaptation in conjunction with poverty eradication and efforts to reduce inequalities *(high confidence)*. {Box 1.1, 1.4.3, Figure 5.1, 5.5.3, Box 5.3}

D6.1. Social justice and equity are core aspects of climate-resilient development pathways that aim to limit global warming to 1.5°C as they address challenges and inevitable trade-offs, widen opportunities, and ensure that options, visions, and values are deliberated, between and within countries and communities, without making the poor and disadvantaged worse off (*high confidence*). {5.5.2, 5.5.3, Box 5.3, Figure 5.1, Figure 5.6, Cross-Chapter Boxes 12 and 13 in Chapter 5}

D6.2. The potential for climate-resilient development pathways differs between and within regions and nations, due to different development contexts and systemic vulnerabilities (*very high confidence*). Efforts along such pathways to date have been limited (*medium confidence*) and enhanced efforts would involve strengthened and timely action from all countries and non-state actors (*high confidence*). {5.5.1, 5.5.3, Figure 5.1}

D6.3. Pathways that are consistent with sustainable development show fewer mitigation and adaptation challenges and are associated with lower mitigation costs. The large majority of modelling studies could not construct pathways characterized by lack of international cooperation, inequality and poverty that were able to limit global warming to 1.5°C. (*high confidence*) {2.3.1, 2.5.3, 5.5.2}

D7. Strengthening the capacities for climate action of national and sub-national authorities, civil society, the private sector, indigenous peoples and local communities can support the implementation of ambitious actions implied by limiting global warming to 1.5°C (*high confidence*). International cooperation can provide an enabling environment for this to be achieved in all countries and for all people, in the context of sustainable development. International cooperation is a critical enabler for developing countries and vulnerable regions (*high confidence*). {1.4, 2.3, 2.5, 4.2, 4.4, 4.5, 5.3, 5.4, 5.5, 5.6, 5, Box 4.1, Box 4.2, Box 4.7, Box 5.3, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter Box 13 in Chapter 5}

D7.1. Partnerships involving non-state public and private actors, institutional investors, the banking system, civil society and scientific institutions would facilitate actions and responses consistent with limiting global warming to 1.5°C (*very high confidence*). {1.4, 4.4.1, 4.2.2, 4.4.3, 4.4.5, 4.5.3, 5.4.1, 5.6.2, Box 5.3}.

D7.2. Cooperation on strengthened accountable multilevel governance that includes non-state actors such as industry, civil society and scientific institutions, coordinated sectoral and cross-sectoral policies at various governance levels, gender-sensitive policies, finance including innovative financing and cooperation on technology development and transfer can ensure participation, transparency, capacity building, and learning among different players (*high confidence*). {2.5.2, 4.2.2, 4.4.1, 4.4.2, 4.4.3, 4.4.4, 4.5.3, Cross-Chapter Box 9 in Chapter 4, 5.3.1, 4.4.5, 5.5.3, Cross-Chapter Box 13 in Chapter 5, 5.6.1, 5.6.3}

D7.3. International cooperation is a critical enabler for developing countries and vulnerable regions to strengthen their action for the implementation of 1.5°C-consistent climate responses, including through enhancing access to finance and technology and enhancing domestic capacities, taking into account national and local circumstances and needs (*high confidence*). {2.3.1, 4.4.1, 4.4.2, 4.4.4, 4.4.5, 5.4.1 5.5.3, 5.6.1, Box 4.1, Box 4.2, Box 4.7}.

D7.4. Collective efforts at all levels, in ways that reflect different circumstances and capabilities, in the pursuit of limiting global warming to 1.5ºC, taking into account equity as well as effectiveness, can facilitate strengthening the global response to climate change, achieving sustainable development and eradicating poverty (*high confidence*). {1.4.2, 2.3.1, 2.5.2, 4.2.2, 4.4.1, 4.4.2, 4.4.3, 4.4.4, 4.4.5, 4.5.3, 5.3.1, 5.4.1, 5.5.3, 5.6.1, 5.6.2, 5.6.3}

Box SPM 1: Core Concepts Central to this Special Report

Global mean surface temperature (GMST): Estimated global average of near-surface air temperatures over land and sea-ice, and sea surface temperatures over ice-free ocean regions, with changes normally expressed as departures from a value over a specified reference period.
When estimating changes in GMST, near-surface air temperature over both land and oceans are also used.[19] {1.2.1.1}

Pre-industrial: The multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial GMST. {1.2.1.2}

Global warming: The estimated increase in GMST averaged over a 30-year period, or the 30-year period centered on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified. For 30-year periods that span past and future years, the current multi-decadal warming trend is assumed to continue. {1.2.1}

Net zero CO_2 emissions: Net-zero carbon dioxide (CO_2) emissions are achieved when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2 removals over a specified period.

Carbon dioxide removal (CDR): Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities.

Total carbon budget: Estimated cumulative net global anthropogenic CO_2 emissions from the preindustrial period to the time that anthropogenic CO_2 emissions reach net zero that would result, at some probability, in limiting global warming to a given level, accounting for the impact of other anthropogenic emissions. {2.2.2}

Remaining carbon budget: Estimated cumulative net global anthropogenic CO_2 emissions from a given start date to the time that anthropogenic CO_2 emissions reach net zero that would result, at some probability, in limiting global warming to a given level, accounting for the impact of other anthropogenic emissions. {2.2.2}

Temperature overshoot: The temporary exceedance of a specified level of global warming.

Emission pathways: In this Summary for Policymakers, the modelled trajectories of global anthropogenic emissions over the 21st century are termed emission pathways. Emission pathways are classified by their temperature trajectory over the 21st century: pathways giving at least 50% probability based on current knowledge of limiting global warming to below 1.5°C are classified as 'no overshoot'; those limiting warming to below 1.6°C and returning to 1.5°C by 2100 are classified as '1.5°C limited-overshoot'; while those exceeding 1.6°C but still returning to 1.5°C by 2100 are classified as 'higher-overshoot'.

[19] Past IPCC reports, reflecting the literature, have used a variety of approximately equivalent metrics of GMST change.

Impacts: Effects of climate change on human and natural systems. Impacts can have beneficial or adverse outcomes for livelihoods, health and well-being, ecosystems and species, services, infrastructure, and economic, social and cultural assets.

Risk: The potential for adverse consequences from a climate-related hazard for human and natural systems, resulting from the interactions between the hazard and the vulnerability and exposure of the affected system. Risk integrates the likelihood of exposure to a hazard and the magnitude of its impact. Risk also can describe the potential for adverse consequences of adaptation or mitigation responses to climate change.

Climate-resilient development pathways (CRDPs): Trajectories that strengthen sustainable development at multiple scales and efforts to eradicate poverty through equitable societal and systems transitions and transformations while reducing the threat of climate change through ambitious mitigation, adaptation, and climate resilience.

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

Headline Statements

A. Understanding Global Warming of 1.5°C4

A1. Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate (*high confidence*).

A.2. Warming from anthropogenic emissions from the pre-industrial period to the present will persist for centuries to millennia and will continue to cause further long-term changes in the climate system, such as sea level rise, with associated impacts (*high confidence*), but these emissions alone are unlikely to cause global warming of 1.5°C (*medium confidence*).

A3. Climate-related risks for natural and human systems are higher for global warming of 1.5°C than at present, but lower than at 2°C (*high confidence*). These risks depend on the magnitude and rate of warming, geographic location, levels of development and vulnerability, and on the choices and implementation of adaptation and mitigation options (*high confidence*).

B. Projected Climate Change, Potential Impacts and Associated Risks

B1. Climate models project robust7 differences in regional climate characteristics between present-day and global warming of 1.5°C, and between 1.5°C and 2°C. These differences include increases in: mean temperature in most land and ocean regions (*high confidence*), hot extremes in most inhabited regions (*high confidence*), heavy precipitation in several regions (*medium confidence*), and the probability of drought and precipitation deficits in some regions (*medium confidence*).

B2. By 2100, global mean sea level rise is projected to be around 0.1 metre lower with global warming of 1.5°C compared to 2°C (*medium confidence*). Sea level will continue to rise well beyond 2100 (*high confidence*), and the magnitude and rate of this rise depends on future emission pathways. A slower rate of sea level rise enables greater opportunities for adaptation in the human and ecological systems of small islands, low-lying coastal areas and deltas (*medium confidence*).

B3. On land, impacts on biodiversity and ecosystems, including species loss and extinction, are projected to be lower at 1.5°C of global warming compared to 2°C. Limiting global warming to 1.5°C compared to 2°C is projected to lower the impacts on terrestrial, freshwater, and coastal ecosystems and to retain more of their services to humans (*high confidence*).

B4. Limiting global warming to 1.5°C compared to 2ºC is projected to reduce increases in ocean temperature as well as associated increases in ocean acidity and decreases in ocean oxygen levels (*high confidence*). Consequently, limiting global warming to 1.5°C is projected to reduce risks to marine biodiversity, fisheries, and ecosystems, and their functions and services to humans, as illustrated by recent changes to Arctic sea ice and warm water coral reef ecosystems (*high confidence*).

B5. Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C.

B6. Most adaptation needs will be lower for global warming of 1.5°C compared to 2°C (*high confidence*). There are a wide range of adaptation options that can reduce the risks of climate change (*high confidence*). There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5°C, with associated losses (*medium confidence*). The number and availability of adaptation options vary by sector (*medium confidence*).

C. Emission Pathways and System Transitions Consistent with 1.5°C Global Warming

C1. In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range). For limiting global warming to below 2°C, CO2 emissions are projected to decline by about 20% by 2030 in most pathways (10–30% interquartile range) and reach net zero around 2075 (2065–2080 interquartile range). Non-CO2 emissions in pathways that limit global warming to 1.5°C show deep reductions that are similar to those in pathways limiting warming to 2°C (*high confidence*).

C2. Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (*high confidence*). These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (*medium confidence*).

C3. All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 GtCO2 over the 21st century. CDR would be used to compensate for residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5°C following a peak (*high confidence*). CDR deployment of several hundreds of GtCO2 is subject to multiple feasibility and sustainability constraints (*high confidence*). Significant near-term emissions reductions and measures to lower energy and land demand can limit CDR deployment to a few hundred GtCO2 without reliance on bioenergy with carbon capture and storage (BECCS) (*high confidence*).

D. Strengthening the Global Response in the Context of Sustainable Development and Efforts to Eradicate Poverty

D1. Estimates of the global emissions outcome of current nationally stated mitigation ambitions as submitted under the Paris Agreement would lead to global greenhouse gas emissions in 2030 of 52–58 GtCO2eq yr-1 (*medium confidence*). Pathways reflecting these ambitions would not limit global warming to 1.5°C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030 (*high confidence*). Avoiding overshoot and reliance on future largescale deployment of carbon dioxide removal (CDR) can only be achieved if global CO2 emissions start to decline well before 2030 (*high confidence*).

D2. The avoided climate change impacts on sustainable development, eradication of poverty and reducing inequalities would be greater if global warming were limited to 1.5°C rather than 2°C, if mitigation and adaptation synergies are maximized while trade-offs are minimized (*high confidence*).

D3. Adaptation options specific to national contexts, if carefully selected together with enabling conditions, will have benefits for sustainable development and poverty reduction with global warming of 1.5°C, although trade-offs are possible (*high confidence*).

D4. Mitigation options consistent with 1.5°C pathways are associated with multiple synergies and trade-offs across the Sustainable Development Goals (SDGs). While the total number of possible synergies exceeds the number of trade-offs, their net effect will depend on the pace and magnitude of changes, the composition of the mitigation portfolio and the management of the transition (*high confidence*).

D5. Limiting the risks from global warming of 1.5°C in the context of sustainable development and poverty eradication implies system transitions that can be enabled by an increase of adaptation and mitigation investments, policy instruments, the acceleration of technological innovation and behaviour changes (*high confidence*).

D6. Sustainable development supports, and often enables, the fundamental societal and systems transitions and transformations that help limit global warming to 1.5°C. Such changes facilitate the pursuit of climate-resilient development pathways that achieve ambitious mitigation and adaptation in conjunction with poverty eradication and efforts to reduce inequalities (*high confidence*).

D7. Strengthening the capacities for climate action of national and sub-national authorities, civil society, the private sector, indigenous peoples and local communities can support the implementation of ambitious actions implied by limiting global warming to 1.5°C (*high confidence*). International cooperation can provide an enabling environment for this to be achieved in all countries and for all people, in the context of sustainable development. International cooperation is a critical enabler for developing countries and vulnerable regions (*high confidence*).

Chapter 1: Framing and Context

Coordinating Lead Authors: Myles Allen (UK), Opha Pauline Dube (Botswana), William Solecki (USA)

Lead Authors: Fernando Aragón–Durand (Mexico), Wolfgang Cramer (France/Germany), Stephen Humphreys (UK/Ireland), Mikiko Kainuma (Japan), Jatin Kala (Australia), Natalie Mahowald (USA), Yacob Mulugetta (UK/Ethiopia), Rosa Perez (Philippines), Morgan Wairiu (Solomon Islands), Kirsten Zickfeld (Canada)

Contributing Authors: Purnamita Dasgupta (India), Haile Eakin (USA), Bronwyn Hayward (New Zealand), Diana Liverman (USA/UK), Richard Millar (UK), Graciela Raga (Argentina), Aurélien Ribes (France), Mark Richardson (USA/UK), Maisa Rojas (Chile), Roland Séférian (France), Sonia Seneviratne (Switzerland), Christopher Smith (UK), Will Steffen (Australia), Peter Thorne (Ireland/UK)

Review Editors: Ismail Elgizouli Idris (Sudan), Andreas Fischlin (Switzerland), Xuejie Gao (China)

Chapter Scientist: Richard Millar (UK)

Date of Draft: 4/06/18

Notes: TSU compiled version

Table of Content

Executive Summary 4

1.1 Assessing the knowledge base for a 1.5°C warmer world 7

Box 1.1: The Anthropocene: Strengthening the global response to 1.5°C global warming 8

1.1.1 Equity and a 1.5°C warmer world 9

1.1.2 Eradication of poverty 10

1.1.3 Sustainable development and a 1.5°C warmer world 11

1.2 Understanding 1.5°C: reference levels, probability, transience, overshoot, stabilization 12

1.2.1 Working definitions of 1.5°C and 2°C warming relative to pre-industrial levels 12

1.2.1.1 Definition of global average temperature 12

1.2.1.2 Choice of reference period 14

1.2.1.3 Total versus human–induced warming and warming rates 15

1.2.2 Global versus regional and seasonal warming 16

1.2.3 Definition of 1.5°C-consistent pathways: probability, transience, stabilization and overshoot 17

1.2.3.1 Pathways remaining below 1.5°C 18

1.2.3.2 Pathways temporarily exceeding 1.5°C 19

1.2.3.3 Impacts at 1.5°C warming associated with different pathways: transience versus stabilisation 19

Cross-Chapter Box 1: Scenarios and Pathways 21

1.2.4 Geophysical warming commitment 23

Cross-Chapter Box 2: Measuring progress to net zero emissions combining long-lived and short-lived climate forcers 26

1.3 Impacts at 1.5°C and beyond 28

1.3.1 Definitions 28

1.3.2 Drivers of Impacts 29

1.3.3 Uncertainty and non-linearity of impacts 30

1.4 Strengthening the global response 31

1.4.1 Classifying Response Options 31

1.4.2 Governance, implementation and policies 32

Cross-Chapter Box 3: Framing feasibility: Key concepts and conditions for limiting global temperature increases to 1.5°C 33

1.4.3 Transformation, transformation pathways, and transition: evaluating trade-offs and synergies between mitigation, adaptation and sustainable development goals 35

Cross-Chapter Box 4: Sustainable Development and the Sustainable Development Goals 36

1.5 Assessment frameworks and emerging methodologies that integrate climate change mitigation and adaptation with sustainable development 38

1.5.1 Knowledge sources and evidence used in the report 38

1.5.2 Assessment frameworks and methodologies 39

1.6 Confidence, uncertainty and risk 40
1.7 Storyline of the report 41
Frequently Asked Questions 43
FAQ 1.1: Why are we talking about 1.5°C? 43
FAQ 1.2: How close are we to 1.5°C? 45
References 47

Executive Summary

This chapter frames the context, knowledge-base and assessment approaches used to understand the impacts of 1.5°C global warming above pre-industrial levels and related global greenhouse gas emission pathways, building on the IPCC Fifth Assessment Report (AR5), in the context of strengthening the global response to the threat of climate change, sustainable development and efforts to eradicate poverty.

Human-induced warming reached approximately 1°C (±0.2°C *likely* range) above pre-industrial levels in 2017, increasing at 0.2°C (±0.1°C) per decade (*high confidence*). Global warming is defined in this report as an increase in combined surface air and sea surface temperatures averaged over the globe and a 30-year period. Unless otherwise specified, warming is expressed relative to the period 1850-1900, used as an approximation of pre-industrial temperatures in AR5. For periods shorter than 30 years, warming refers to the estimated average temperature over the 30 years centered on that shorter period, accounting for the impact of any temperature fluctuations or trend within those 30 years. Accordingly, warming up to the decade 2006-2015 is assessed at 0.87°C (±0.12°C *likely* range). Since 2000, the estimated level of human-induced warming has been equal to the level of observed warming with a *likely* range of ±20% accounting for uncertainty due to contributions from solar and volcanic activity over the historical period (*high confidence*). {1.2.1}

Warming greater than the global average has already been experienced in many regions and seasons, with average warming over land higher than over the ocean (*high confidence*). Most land regions are experiencing greater warming than the global average, while most ocean regions are warming at a slower rate. Depending on the temperature dataset considered, 20-40% of the global human population live in regions that, by the decade 2006-2015, had already experienced warming of more than 1.5°C above pre-industrial in at least one season (*medium confidence*). {1.2.1 & 1.2.2}

Past emissions alone are *unlikely* to raise global-mean temperature to 1.5°C above pre-industrial levels but past emissions do commit to other changes, such as further sea level rise (*high confidence*)**.** If all anthropogenic emissions (including aerosol-related) were reduced to zero immediately, any further warming beyond the 1°C already experienced would *likely* be less than 0.5°C over the next two to three decades (*high confidence*), and *likely* less than 0.5°C on a century timescale (*medium confidence*), due to the opposing effects of different climate processes and drivers. A warming greater than 1.5°C is therefore not geophysically unavoidable: whether it will occur depends on future rates of emission reductions. {1.2.3, 1.2.4}

1.5°C-consistent emission pathways are defined as those that, given current knowledge of the climate response, provide a one-in-two to two-in-three chance of warming either remaining below 1.5°C, or returning to 1.5°C by around 2100 following an overshoot. Overshoot pathways are characterized by the peak magnitude of the overshoot, which may have implications for impacts. All 1.5°C-consistent pathways involve limiting cumulative emissions of long-lived greenhouse gases, including carbon dioxide and nitrous oxide, and substantial reductions in other climate forcers (*high confidence*). Limiting cumulative emissions requires either reducing net global emissions of long-lived greenhouse gases to zero before the cumulative limit is reached, or net negative global emissions (anthropogenic removals) after the limit is exceeded. {1.2.3, 1.2.4, Cross-Chapter Boxes 1 and 2}

This report assesses projected impacts at a global average warming of 1.5°C and higher levels of warming. Global warming of 1.5°C is associated with global average surface temperatures fluctuating naturally on either side of 1.5°C, together with warming substantially greater than 1.5°C in many regions and seasons (*high confidence*), all of which must be taken into account in the assessment of impacts. Impacts at 1.5°C of warming also depend on the emission pathway to 1.5°C. Very different impacts result from pathways that remain below 1.5°C versus pathways that return to

1.5°C after a substantial overshoot, and when temperatures stabilize at 1.5°C versus a transient warming past 1.5°C. (*medium confidence*) {1.2.3, 1.3}

Ethical considerations, and the principle of equity in particular, are central to this report, recognising that many of the impacts of warming up to and beyond 1.5°C, and some potential impacts of mitigation actions required to limit warming to 1.5°C, fall disproportionately on the poor and vulnerable (*high confidence*). Equity has procedural and distributive dimensions and requires fairness in burden sharing, between generations, and between and within nations. In framing the objective of holding the increase in the global average temperature rise to well below 2°C above pre-industrial levels, and to pursue efforts to limit warming to 1.5°C, the Paris Agreement associates the principle of equity with the broader goals of poverty eradication and sustainable development, recognising that effective responses to climate change require a global collective effort that may be guided by the 2015 United Nations Sustainable Development Goals. {1.1.1}

Climate adaptation refers to the actions taken to manage impacts of climate change by reducing vulnerability and exposure to its harmful effects and exploiting any potential benefits. Adaptation takes place at international, national and local levels. Subnational jurisdictions and entities, including urban and rural municipalities, are key to developing and reinforcing measures for reducing weather- and climate-related risks. Adaptation implementation faces several barriers including unavailability of up-to-date and locally-relevant information, lack of finance and technology, social values and attitudes, and institutional constraints (*high confidence*). Adaptation is more likely to contribute to sustainable development when polices align with mitigation and poverty eradication goals (*medium confidence*) {1.1, 1.4}

Ambitious mitigation actions are indispensable to limit warming to 1.5°C while achieving sustainable development and poverty eradication (*high confidence*). Ill-designed responses, however, could pose challenges especially—but not exclusively—for countries and regions contending with poverty and those requiring significant transformation of their energy systems. This report focuses on 'climate-resilient development pathways' , which aim to meet the goals of sustainable development, including climate adaptation and mitigation, poverty eradication and reducing inequalities. But any feasible pathway that remains within 1.5°C involves synergies and trade-offs (*high confidence*). Significant uncertainty remains as to which pathways are more consistent with the principle of equity. {1.1.1, 1.4}

Multiple forms of knowledge, including scientific evidence, narrative scenarios and prospective pathways, inform the understanding of 1.5°C. This report is informed by traditional evidence of the physical climate system and associated impacts and vulnerabilities of climate change, together with knowledge drawn from the perceptions of risk and the experiences of climate impacts and governance systems. Scenarios and pathways are used to explore conditions enabling goal-oriented futures while recognizing the significance of ethical considerations, the principle of equity, and the societal transformation needed. {1.2.3, 1.5.2}

There is no single answer to the question of whether it is feasible to limit warming to 1.5°C and adapt to the consequences. Feasibility is considered in this report as the capacity of a system as a whole to achieve a specific outcome. The global transformation that would be needed to limit warming to 1.5°C requires enabling conditions that reflect the links, synergies and trade-offs between mitigation, adaptation and sustainable development. These enabling conditions have many systemic dimensions—geophysical, environmental-ecological, technological, economic, socio-cultural and institutional—that may be considered through the unifying lens of the Anthropocene, acknowledging profound, differential but increasingly geologically significant human influences on the Earth system as a whole. This framing also emphasises the global interconnectivity of past, present and future human–environment relations, highlighing the need and opportunities for integrated responses to achieve the goals of the Paris Agreement. {1.1, Cross-Chapter Box 1}

1.1 Assessing the knowledge base for a 1.5°C warmer world

Human influence on climate has been the dominant cause of observed warming since the mid-20th century, while global average surface temperature warmed by 0.85°C between 1880 and 2012, as reported in the IPCC Fifth Assessment Report, or AR5 (IPCC, 2013b). Many regions of the world have already experienced greater regional-scale warming, with 20-40% of the global population (depending on the temperature dataset used) having experienced over 1.5°C of warming in at least one season (Figure 1.1 and Chapter 3 Section 3.3). Temperature rise to date has already resulted in profound alterations to human and natural systems, bringing increases in some types of extreme weather, droughts, floods, sea level rise and biodiversity loss, and causing unprecedented risks to vulnerable persons and populations (IPCC, 2012a, 2014b; Mysiak et al., 2016), Chapter 3 Section 3.4). The most affected people live in low and middle income countries, some of which have already experienced a decline in food security, linked in turn to rising migration and poverty (IPCC, 2012a). Small islands, megacities, coastal regions and high mountain ranges are likewise among the most affected (Albert et al., 2017). Worldwide, numerous ecosystems are at risk of severe impacts, particularly warm-water tropical reefs and Arctic ecosystems (IPCC, 2014d).

This report assesses current knowledge of the environmental, technical, economic, financial, socio-cultural, and institutional dimensions of a 1.5°C warmer world (meaning, unless otherwise specified, a world in which warming has been limited to 1.5°C relative to pre-industrial levels). Differences in vulnerability and exposure arise from numerous non-climatic factors (IPCC, 2014b). Global economic growth has been accompanied by increased life expectancy and income in much of the world - but in addition to environmental degradation and pollution, many regions remain characterised by significant poverty, severe inequity in income distribution and access to resources, amplifying vulnerability to climate change (Dryzek, 2016; Pattberg and Zelli, 2016; Bäckstrand et al., 2017; Lövbrand et al., 2017). World population continues to rise, notably in hazard-prone small and medium-sized cities in low- and moderate-income countries (Birkmann et al., 2016). The spread of fossil-fuel-based material consumption and changing lifestyles is a major driver of global resource use, and the main contributor to rising greenhouse gas (GHG) emissions (Fleurbaey et al., 2014).

The overarching context of this report is this: human influence has become a principal agent of change on the planet, shifting the world out of the relatively stable Holocene period into a new geological era, often termed the Anthropocene (Box 1.1). Responding to climate change in the Anthropocene will require approaches that integrate multiple levels of inter-connectivity across the global community.

This chapter is composed of seven sections linked to the remaining four chapters of the report. The introductory section 1.1 situates the basic elements of the assessment within the context of sustainable development, considerations of ethics, equity and human rights, and their link to poverty. Section 1.2 focuses on understanding 1.5°C, global versus regional warming, 1.5°C–consistent pathways and associated emissions. Section 1.3 frames the impacts at 1.5°C and beyond on natural and human systems. The section on strengthening the global response (1.4) frames different responses, governance and implementation, and trade-offs and synergies between mitigation, adaptation and the Sustainable Development Goals (SDGs) under transformation, transformation pathways, and transition. Section 1.5 provides assessment frameworks and emerging methodologies that integrate climate change mitigation and adaptation with sustainable development. Section 1.6 defines approaches used to communicate confidence, uncertainty and risk, while 1.7 presents the storyline of the whole report.

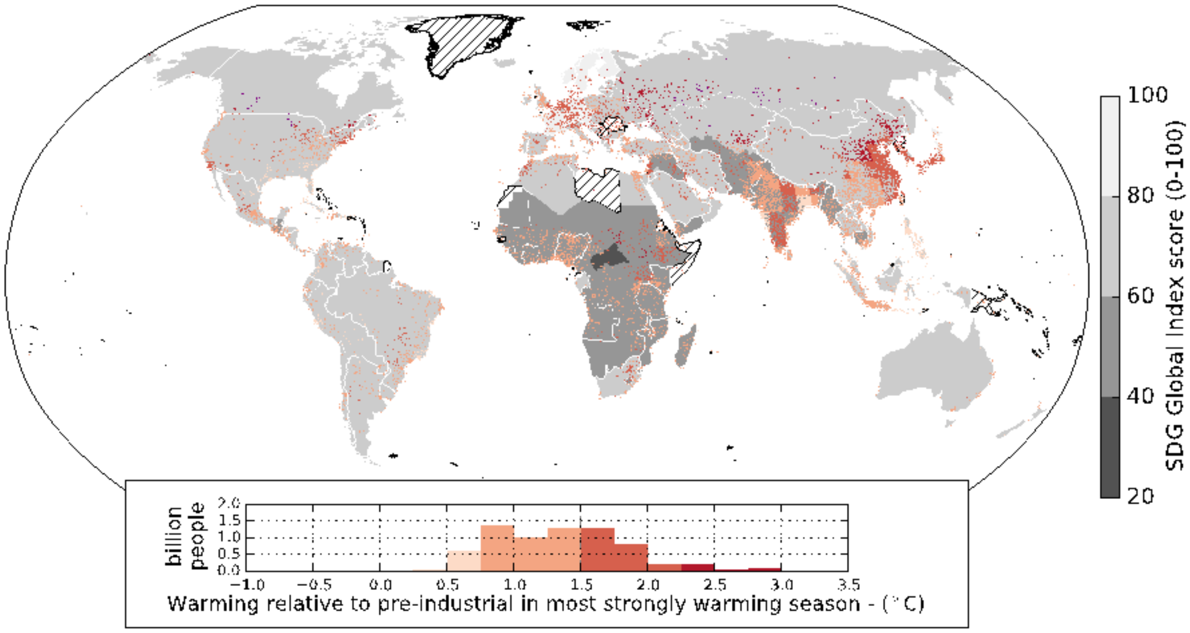


Figure 1.1: Human experience of present–day warming. Colours indicated by the inset histogram show estimated warming for the season that has warmed the most at a given location between the periods 1850-1900 and 2006–2015, during which global average temperatures rose by 0.91°C in this dataset (Cowtan and Way, 2014), and 0.87°C in the multi-dataset average (Table 1.1 and Figure 1.3). The density of dots indicates the population (in 2010) in any 1°x1° grid box. The underlay shows national SDG Global Index Scores indicating performance across the 17 Sustainable Development Goals. Hatching indicates missing SDG index data (e.g., Greenland). The histogram shows the number of people of the 2010 global population living in regions experiencing different levels of warming (at 0.25°C increments). See Technical Annex 1.A for further details.

Box 1.1: The Anthropocene: Strengthening the global response to 1.5°C global warming

Introduction

The concept of the Anthropocene can be linked to the aspiration of the Paris Agreement. The abundant empirical evidence of the unprecedented rate and global scale of impact of human influence on the Earth System (Steffen et al., 2016; Waters et al., 2016) has led many scientists to call for an acknowledgement that the Earth has entered a new geological epoch: the Anthropocene (Crutzen and Stoermer, 2000; Crutzen, 2002; Gradstein et al., 2012). Although rates of change in the Anthropocene are necessarily assessed over much shorter periods than those used to calculate long-term baseline rates of change, and therefore present challenges for direct comparison, they are nevertheless striking. The rise in global CO_2 concentration since 2000 is about 20 ppm/decade, which is up to 10 times faster than any sustained rise in CO_2 during the past 800,000 years (Lüthi et al., 2008; Bereiter et al., 2015). AR5 found that the last geological epoch with similar atmospheric CO_2 concentration was the Pliocene, 3.3 to 3.0 Ma (Masson-Delmotte et al., 2013). Since 1970 the global average temperature has been rising at a rate of 1.7°C per century, compared to a long-term decline over the past 7,000 years at a baseline rate of 0.01°C per century (NOAA 2016, Marcott et al. 2013). These global-level rates of human-driven change far exceed the rates of change driven by geophysical or biosphere forces that have altered the Earth System trajectory in the past (e.g., Summerhayes 2015; Foster et al. 2017); even abrupt geophysical events do not approach current rates of human-driven change.

The geological dimension of the Anthropocene and 1.5°C global warming
The process of formalising the Anthropocene is on-going (Zalasiewicz et al., 2017), but a strong majority of the Anthropocene Working Group (AWG) established by the Sub–Committee on Quaternary Stratigraphy of the International Commission on Stratigraphy have agreed that: (i) the Anthropocene has a geological merit; (ii) it should follow the Holocene as a formal epoch in the Geological Time Scale; and, that (iii) its onset should be defined as the mid–20th century. Potential markers in the stratigraphic record include an array of novel manufactured materials of human origin, and "these combined signals render the Anthropocene stratigraphically distinct from the Holocene and earlier epochs" (Waters et al., 2016). The Holocene period, which itself was formally adopted in 1885 by geological science community, began 11,700 years ago with a more stable warm climate providing for emergence of human civilisation and growing human-nature interactions that have expanded to give rise to the Anthropocene (Waters et al., 2016).

The Anthropocene and the Challenge of a 1.5° C warmer world
The Anthropocene can be employed as a "boundary concept" (Brondizio et al., 2016) that frames critical insights into understanding the drivers, dynamics and specific challenges in responding to the ambition of keeping global temperature well below 2°C while pursuing efforts towards and adapting to a 1.5°C warmer world. The UNFCCC and its Paris Accord recognize the ability of humans to influence geophysical planetary processes (Chapter 2, Cross-Chapter Box 1 in this Chapter). The Anthropocene offers a structured understanding of the culmination of past and present human–environmental relations and provides an opportunity to better visualize the future to minimize pitfalls (Pattberg and Zelli, 2016; Delanty and Mota, 2017), while acknowledging the differentiated responsibility and opportunity to limit global warming and invest in prospects for climate-resilient sustainable development (Harrington, 2016) (Chapter 5). The Anthropocene also provides an opportunity to raise questions regarding the regional differences, social inequities and uneven capacities and drivers of global social–environmental changes, which in turn inform the search for solutions as explored in Chapter 4 of this report (Biermann et al., 2016). It links uneven influences of human actions on planetary functions to an uneven distribution of impacts (assessed in Chapter 3) as well as the responsibility and response capacity to for example, limiting global warming to no more than a 1.5°C rise above pre–industrial levels. Efforts to curtail greenhouse gas emissions without incorporating the intrinsic interconnectivity and disparities associated with the Anthropocene world may themselves negatively affect the development ambitions of some regions more than others and negate sustainable development efforts (see Chapter 2 and Chapter 5).

1.1.1 Equity and a 1.5°C warmer world

The AR5 suggested that equity, sustainable development, and poverty eradication are best understood as mutually supportive and co-achievable within the context of climate action, and are underpinned by various other international hard and soft law instruments (Denton et al., 2014; Fleurbaey et al., 2014; Klein et al., 2014; Olsson et al., 2014; Porter et al., 2014; Stavins et al., 2014). The aim of the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) to 'pursue efforts to limit' the rise in global temperatures to 1.5°C above pre-industrial levels raises ethical concerns that have long been central to climate debates (Fleurbaey et al., 2014; Kolstad et al., 2014). The Paris Agreement makes particular reference to the principle of equity, within the context of broader international goals of sustainable development and poverty eradication. Equity is a long-standing principle within international law and climate change law in particular (Dinah, 2008; Bodansky et al., 2017).

The AR5 describes equity as having three dimensions: intergenerational (fairness between generations), international (fairness between states), and national (fairness between individuals) (Fleurbaey et al., 2014). The principle is generally agreed to involve both procedural justice (i.e.

participation in decision making) and distributive justice (i.e. how the costs and benefits of climate actions are distributed) (Kolstad et al., 2014; Savaresi, 2016; Reckien et al., 2017). Concerns regarding equity have frequently been central to debates around mitigation, adaptation and climate governance (Caney, 2005; Schroeder et al., 2012; Ajibade, 2016; Reckien et al., 2017; Shue, 2018). Hence, equity provides a framework for understanding the asymmetries between the distributions of benefits and costs relevant to climate action (Schleussner et al., 2016; Aaheim et al., 2017).

Four key framing asymmetries associated with the conditions of 1.5°C warmer world have been noted (Okereke, 2010; Harlan et al., 2015; Ajibade, 2016; Savaresi, 2016; Reckien et al., 2017) and are reflected in the report's assessment. The first concerns differential contributions to the problem: the observation that the benefits from industrialization have been unevenly distributed and those who benefited most historically also have contributed most to the current climate problem and so bear greater responsibility (Shue, 2013; Otto et al., 2017; Skeie et al., 2017). The second asymmetry concerns differential impact: the worst impacts tend to fall on those least responsible for the problem, within states, between states, and between generations (Fleurbaey et al., 2014; Shue, 2014; Ionesco et al., 2016). The third is the asymmetry in capacity to shape solutions and response strategies, such that the worst-affected states, groups and individuals are not always well-represented (Robinson and Shine, 2018). Fourth, there is an asymmetry in future response capacity: some states, groups and places are at risk of being left behind as the world progresses to a low-carbon economy (Fleurbaey et al., 2014; Shue, 2014; Humphreys, 2017).

A sizeable and growing literature exists on how best to operationalize climate equity considerations, drawing on other concepts mentioned in the Paris Agreement, notably its explicit reference to human rights (OHCHR, 2009; Caney, 2010; Adger et al., 2014; Fleurbaey et al., 2014; IBA, 2014; Knox, 2015; Duyck et al., 2018; Robinson and Shine, 2018). Human rights comprise internationally agreed norms that align with the Paris ambitions of poverty eradication, sustainable development and the reduction of vulnerability (Caney, 2010; Fleurbaey et al., 2014; OHCHR, 2015). In addition to defining substantive rights (such as to life, health and shelter) and procedural rights (such as to information and participation), human rights instruments prioritise the rights of marginalised, children, vulnerable and indigenous persons, and those discriminated against on grounds such as gender, race, age or disability (OHCHR, 2017). Several international human rights obligations that are relevant to the implementation of climate actions and consonant with UNFCCC undertakings in the areas of mitigation, adaptation, finance, and technology transfer (Knox, 2015; OHCHR, 2015; Humphreys, 2017).

Much of this literature is still new and evolving (Holz et al., 2017; Dooley et al., 2018; Klinsky and Winkler, 2018), permitting the present report to examine some broader equity concerns raised both by possible failure to limit warming to 1.5°C and by the range of ambitious mitigation efforts that may be undertaken to achieve that limit. Any comparison between 1.5°C and higher levels of warming implies risk assessments and value judgements, and cannot straightforwardly be reduced to a cost-benefit analysis (Kolstad et al., 2014). However, different levels of warming can nevertheless be understood in terms of their different implications for equity – that is, in the comparative distribution of benefits and burdens for specific states, persons or generations, and in terms of their likely impacts on sustainable development and poverty (see especially sections 2.2.2.3, 2.3.3.1, 3.4.5-3.4.11, 3.6, 5.4.1, 5.4.2, 5.6 and Cross-Chapter boxes 6 in Chapter 3 and 12 in Chapter 5).

1.1.2 Eradication of poverty

This report assesses the role of poverty and its eradication in the context of strengthening the global response to the threat of climate change and sustainable development. A wide range of definitions for *poverty* exist. The AR5 discussed 'poverty' in terms of its multidimensionality, referring to 'material circumstances' (e.g. needs, patterns of deprivation, or limited resources), as well as to economic conditions (e.g. standard of living, inequality, or economic position), and/or social relationships (e.g. social class, dependency, lack of basic security, exclusion, or lack of entitlement – Olsson et al., 2014). The UNDP now uses a Multidimensional Poverty Index, and estimates that about 1.5 billion people globally live in multidimensional poverty, especially in rural areas of South Asia and Sub-Saharan Africa, with an additional billion at risk of falling into poverty (UNDP, 2016).

A large and rapidly growing body of knowledge explores the connections between climate change and poverty. Climatic variability and climate change are widely recognized as factors that may exacerbate poverty, particularly in countries and regions where poverty levels are high (Leichenko and Silva, 2014). The AR5 noted that climate change-driven impacts often act as a threat multiplier in that the impacts of climate change compound other drivers of poverty (Olsson et al., 2014). Many vulnerable and poor people are dependent on activities such as agriculture that are highly susceptible to temperature increases and variability in precipitation patterns (Shiferaw et al., 2014; Miyan, 2015). Even modest changes in rainfall and temperature patterns can push marginalized people into poverty as they lack the means to recover from shocks. Extreme events, such as floods, droughts, and heat waves, especially when they occur in series, can significantly erode poor people's assets and further undermine their livelihoods in terms of labour productivity, housing, infrastructure, and social networks (Olsson et al., 2014).

1.1.3 Sustainable development and a 1.5°C warmer world

AR5 noted with *high confidence* that 'equity is an integral dimension of sustainable development' and that 'mitigation and adaptation measures can strongly affect broader sustainable development and equity objectives' (Fleurbaey et al., 2014). Limiting global warming to 1.5°C will require substantial societal and technological transformations, dependent in turn on global and regional sustainable development pathways. A range of pathways, both sustainable and not, are explored in this report, including implementation strategies to understand the enabling conditions and challenges required for such a transformation. These pathways and connected strategies are framed within the context of sustainable development, and in particular the United Nations 2030 Agenda for Sustainable Development (UNGA, 2015) and Cross-Chapter Box 4 on SDGs (in this Chapter). The feasibility of staying within 1.5°C depends upon a range of enabling conditions with geophysical, environmental-ecological, technological, economic, socio-cultural, and institutional enabling conditions. Limiting warming to 1.5°C also involves identifying technology and policy levers to accelerate the pace of transformation (see Chapter 4). Some pathways are more consistent than others with the requirements for sustainable development (see Chapter 5). Overall, the three-pronged emphasis on sustainable development, resilience, and transformation provides Chapter 5 an opportunity to assess the conditions of simultaneously reducing societal vulnerabilities, addressing entrenched inequalities, and breaking the circle of poverty.

The feasibility of any global commitment to a 1.5°C pathway depends, in part, on the cumulative influence of the nationally determined contributions (NDCs), committing nation states to specific GHG emission reductions. The current NDCs, extending only to 2030, do not limit warming to 1.5°C. Depending on mitigation decisions after 2030, they cumulatively track toward a warming of 3-4°C above preindustrial temperatures by 2100, with the potential for further warming thereafter (Rogelj et al., 2016a; UNFCCC, 2016). The analysis of pathways in this report reveals opportunities for greater decoupling of economic growth from GHG emissions. Progress towards limiting warming to 1.5°C requires a significant acceleration of this trend. AR5 (IPCC, 2014a) concluded that climate change constrains possible development paths, that synergies and trade-offs exist between climate responses and socio-economic contexts, and that opportunities for effective climate responses overlap with opportunities for sustainable development, noting that many existing societal patterns of consumption are intrinsically unsustainable (Fleurbaey et al., 2014).

1.2 Understanding 1.5°C: reference levels, probability, transience, overshoot, stabilization

1.2.1 Working definitions of 1.5°C and 2°C warming relative to pre-industrial levels

What is meant by 'the increase in global average temperature … above pre–industrial levels' referred to in the Paris Agreement depends on the choice of pre–industrial reference period, whether 1.5°C refers to total warming or the human–induced component of that warming, and which variables and geographical coverage are used to define global average temperature change. The cumulative impact of these definitional ambiguities (e.g. Hawkins et al., 2017; Pfleiderer et al., 2018) is comparable to natural multi–decadal temperature variability on continental scales (Deser et al., 2012) and primarily affects the historical period, particularly that prior to the early 20th century when data is sparse and of less certain quality. Most practical mitigation and adaptation decisions do not depend on quantifying historical warming to this level of precision, but a consistent working definition is necessary to ensure consistency across chapters and figures. We adopt definitions that are as consistent as possible with key findings of AR5 with respect to historical warming.

This report defines 'warming', unless otherwise qualified, as an increase in multi-decade global mean surface temperature (GMST) above pre–industrial levels. Specifically, warming at a given point in time is defined as the global average of combined land surface air and sea surface temperatures for a 30–year period centred on that time, expressed relative to the reference period 1850-1900 (adopted for consistency with Box SPM.1 Figure 1 of IPCC (2014e) 'as an approximation of pre–industrial levels', excluding the impact of natural climate fluctuations within that 30–year period and assuming any secular trend continues throughout that period, extrapolating into the future if necessary. There are multiple ways of accounting for natural fluctuations and trends (e.g., Foster and Rahmstorf, 2011; Haustein et al., 2017; Medhaug et al., 2017), but all give similar results. A major volcanic eruption might temporarily reduce observed global temperatures, but would not reduce warming as defined here (Bethke et al., 2017). Likewise, given that the level of warming is currently increasing at 0.3-0.7°C per 30 years (Kirtman et al., 2013), the level of warming in 2017 is 0.15-0.35°C higher than average warming over the 30–year period 1988-2017.

In summary, this report adopts a working definition of '1.5°C relative to pre–industrial levels' that corresponds to global average combined land surface air and sea surface temperatures either 1.5°C warmer than the average of the 51-year period 1850-1900, 0.87°C warmer than the 20-year period 1986–2005, or 0.63°C warmer than the decade 2006–2015. These offsets are based on all available published global datasets, combined and updated, which show that 1986-2005 was 0.63°C (±0.06°C 5–95% range based on observational uncertainties alone), and 2006-2015 was 0.87°C (±0.12°C *likely* range also accounting for the possible impact of natural fluctuations), warmer than 1850–1900. Where possible, estimates of impacts and mitigation pathways are evaluated relative to these more recent periods.

1.2.1.1 Definition of global average temperature

The IPCC has traditionally defined changes in observed GMST as a weighted average of near-surface air temperature (SAT) changes over land and sea surface temperature (SST) changes over the oceans (Morice et al., 2012; Hartmann et al., 2013), while modelling studies have typically used a simple global average SAT. For ambitious mitigation goals, and under conditions of rapid warming, the difference can be significant. Cowtan et al. (2015) and Richardson et al. (2016) show that the use of blended SAT/SST data and incomplete coverage together can give approximately 0.2°C less warming from the 19th century to the present relative to the use of complete global-average SAT (Stocker et al. , 2013), Figure TFE8.1 and Figure 1.2). However, Richardson et al. (2018) show that this is primarily an issue for the interpretation of the historical record to date, not for projection of future changes or for estimated emissions budgets consistent with future changes, particularly under ambitious mitigation scenarios.

The three GMST reconstructions used in AR5 differ in their treatment of missing data. GISTEMP (Hansen et al., 2010) uses interpolation to infer trends in poorly-observed regions like the Arctic (although even this product is spatially incomplete in the early record), while NOAA (Vose et al., 2012) and HadCRUT (Morice et al., 2012) are progressively closer to a simple average of available observations. Since the AR5, considerable effort has been devoted to more sophisticated statistical modelling to account for the impact of incomplete observation coverage (Rohde et al., 2013; Cowtan and Way, 2014; Jones, 2016). The main impact of statistical infilling is to increase estimated warming to date by about 0.1°C (Richardson et al., 2018 and Table 1.1).

We adopt a working definition of warming over the historical period based on an average of the four available global datasets that are supported by peer-reviewed publications: the three datasets used in the AR5, updated (Karl et al., 2015), together with the Cowtan-Way infilled dataset (Cowtan and Way, 2014). A further two datasets, Berkeley Earth (Rohde et al., 2013) and JMA, are provided in Table 1.1. This working definition provides an updated estimate of 0.86°C for the warming 1880-2012 based on a linear trend that was quoted as 0.85°C in the AR5. Hence the inclusion of the Cowtan-Way dataset does not introduce any inconsistency with the AR5, whereas redefining GMST to represent global SAT could increase this figure by up to 20%, (Table 1.1, Figure 1.2 Richardson et al., 2016).

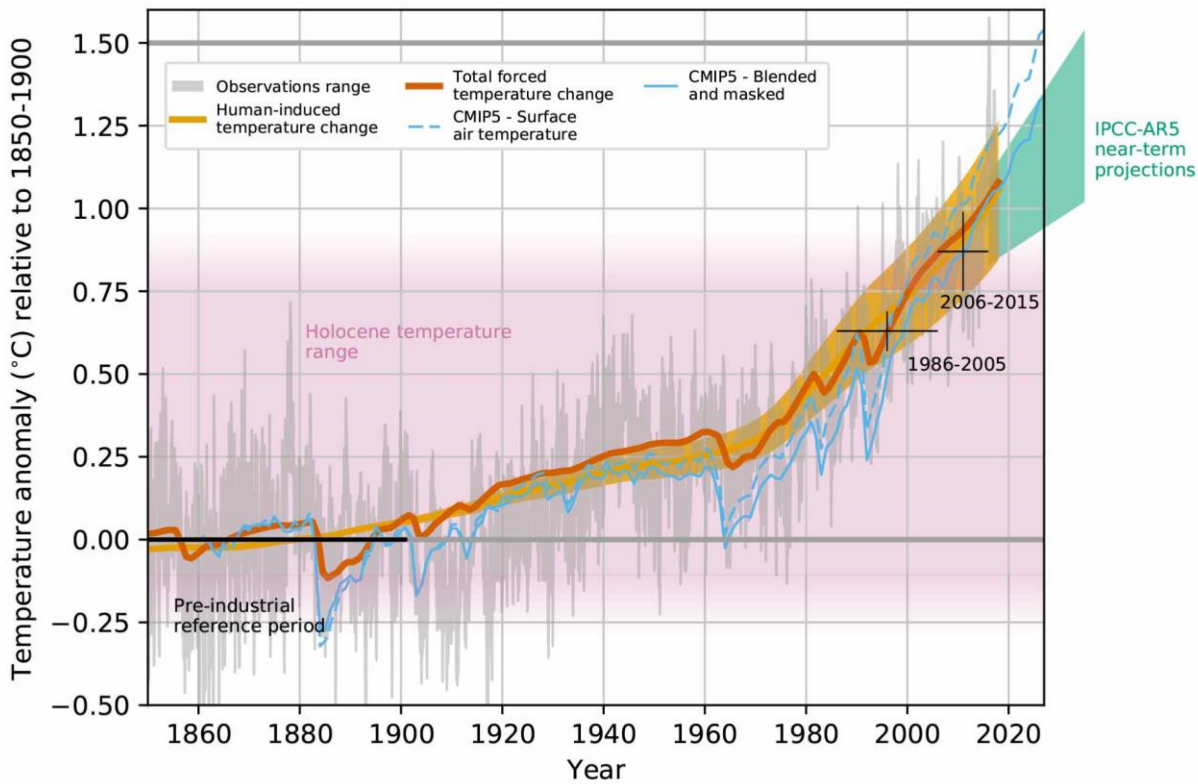


Figure 1.2: Evolution of global mean surface temperature (GMST) over the period of instrumental observations. Grey line shows monthly mean GMST in the HadCRUT4, NOAA, GISTEMP and Cowtan-Way datasets, expressed as departures from 1850–1900, with line thickness indicating inter–dataset range. All observational datasets shown represent GMST as a weighted average of near surface air temperature over land and sea surface temperature over oceans. Human–induced (yellow) and total (human– and naturally–forced, orange) contributions to these GMST changes

are shown calculated following Otto et al. (2015) and Haustein et al. (2017). Fractional uncertainty in the level of human–induced warming in 2017 is set equal to ±20%. Thin blue lines show the modelled global–mean surface air temperature (dashed) and blended surface air and sea surface temperature accounting for observational coverage (solid) from the CMIP5 historical ensemble average extended with RCP8.5 forcing (Cowtan et al., 2015; Richardson et al., 2018). The pink shading indicates a range for temperature fluctuations over the Holocene (Marcott et al., 2013). Light green plume shows AR5 prediction for average GMST over 2016–2035 (Kirtman et al., 2013). See Technical Annex 1.A of this chapter for further details.

1.2.1.2 Choice of reference period

Any choice of reference period used to approximate 'pre–industrial' conditions is a compromise between data coverage and representativeness of typical pre-industrial solar and volcanic forcing conditions. This report adopts the 51-year reference period, 1850–1900 inclusive, assessed as an approximation of pre-industrial conditions in AR5 (Box TS.5, Figure 1 of Field et al., 2014). The years 1880–1900 are subject to strong but uncertain volcanic forcing, but in the HadCRUT4 dataset, average temperatures over 1850–1879, prior to the largest eruptions, are less than 0.01°C from the average for 1850–1900. Temperatures rose by 0.0–0.2°C from 1720–1800 to 1850–1900 (Hawkins et al., 2017), but the anthropogenic contribution to this warming is uncertain (Schurer et al., 2017). The 18th century represents a relatively cool period in the context of temperatures since the mid-Holocene (Marcott et al., 2013; Marsicek et al., 2018), as indicated by the pink shaded region in Figure 1.2.

Projections of responses to emission scenarios, and associated impacts, may use a more recent reference period, offset by historical observations, to avoid conflating uncertainty in past and future changes (e.g. Hawkins et al., 2017; Millar et al., 2017b; Simmons et al., 2017). Two recent reference periods are used in this report: 1986–2005 and 2006–2015. In the latter case, when using a single decade to represent a 30-year average centred on that decade, it is important to consider the potential impact of internal climate variability. The years 2008–2013 were characterised by persistent cool conditions in the Eastern Pacific (Kosaka and Xie, 2013; Medhaug et al., 2017), related to both the El Niño / Southern Oscillation (ENSO) and, potentially, multi–decadal Pacific variability (e.g., England et al., 2014), but these were partially compensated for by El Niño conditions in 2006 and 2015. Likewise, volcanic activity depressed temperatures in 1986–2005, partly offset by the very strong El Niño event in 1998. Figure 1.2 indicates that natural variability (internally generated and externally driven) had little net impact on average temperatures over 2006–2015, in that the average temperature of the decade is similar to the estimated externally–driven warming. When solar, volcanic and ENSO-related variability is taken into account following the procedure of Foster and Rahmstorf (2011), there is no indication of average temperatures in either 1986–2005 or 2006–2015 being substantially biased by short-term variability (see Technical Appendix). The temperature difference between these two reference periods (0.21–0.27°C over 15 years across available datasets) is also consistent with the AR5 assessment of the current warming rate of 0.3–0.7°C over 30 years (Kirtman et al., 2013).

On the definition of warming used here, warming to the decade 2006–2015 comprises an estimate of the 30-year average centered on this decade, or 1996–2025, assuming the current trend continues and that any volcanic eruptions that might occur over the final seven years are corrected for. Given this element of extrapolation, we use the AR5 near-term projection to provide a conservative uncertainty range. Combining the uncertainty in observed warming to 1986–2005 (±0.06°C) with the *likely* range in the current warming trend as assessed by AR5 (±0.2°C/30 years), assuming these are uncorrelated, and using observed warming relative to 1850–1900 to provide the central estimate (no evidence of bias from short-term variability), gives an assessed warming to the decade 2006–2015 of 0.87°C with a ±0.12°C *likely* range. This estimate has the advantage of traceability to the AR5, but more formal methods of quantifying externally-driven warming (e.g., Bindoff et al., 2013; Jones et al., 2016; Haustein et al., 2017; Ribes et al., 2017), which typically give smaller ranges of uncertainty, may be adopted in future.

Table 1.1: Observed increase in global average surface temperature in various datasets. Numbers in square brackets correspond to 5-95% uncertainty ranges from individual datasets, encompassing known sources of observational uncertainty only.

Diagnostic / dataset	1850-1900 to (1) 2006-2015	1850-1900 to (2) 1986-2005	1986-2005 to (3) 2006-2015	1850-1900 to (4) 1981-2010	1850-1900 to (5) 1998-2017	trend (6) 1880-2012	trend (6) 1880-2015
HadCRUT4.6	0.84 [0.79—0.89]	0.60 [0.57—0.66]	0.22 [0.21—0.23]	0.62 [0.58—0.67]	0.83 [0.78—0.88]	0.83 [0.77—0.90]	0.88 [0.83—0.95]
NOAA (7)	0.86	0.62	0.22	0.63	0.85	0.85	0.91
GISTEMP (7)	0.89	0.65	0.23	0.66	0.88	0.89	0.94
Cowtan-Way	0.91 [0.85—0.99]	0.65 [0.60—0.72]	0.26 [0.25—0.27]	0.65 [0.60—0.72]	0.88 [0.82—0.96]	0.88 [0.79—0.98]	0.93 [0.85—1.03]
Average (8)	**0.87**	0.63	0.23	0.64	0.86	0.86	0.92
Berkeley (9)	0.98	0.73	0.25	0.73	0.97	0.97	1.02
JMA (9)	0.82	0.59	0.17	0.60	0.81	0.82	0.87
ERA-Interim	N/A	N/A	0.26	N/A	N/A	N/A	N/A
JRA-55	N/A	N/A	0.23	N/A	N/A	N/A	N/A
CMIP5 global SAT (10)	0.99 [0.65—1.37]	0.62 [0.38—0.94]	0.38 [0.24—0.62]	0.62 [0.34—0.93]	0.89 [0.62—1.29]	0.81 [0.58—1.31]	0.86 [0.63—1.39]
CMIP5 SAT/SST blend—masked	0.86 [0.54—1.18]	0.50 [0.31—0.79]	0.34 [0.19—0.54]	0.48 [0.26—0.79]	0.75 [0.52—1.11]	0.68 [0.45—1.08]	0.74 [0.51—1.14]

Notes:
1) Most recent reference period used in this report.
2) Most recent reference period used in AR5.
3) Difference between recent reference periods.
4) Current WMO standard reference periods.
5) Most recent 20-year period.
6) Linear trends estimated by a straight-line fit, expressed in degrees yr^{-1} multiplied by 133 or 135 years respectively, with uncertainty ranges incorporating observational uncertainty only.
7) To estimate changes in the NOAA and GISTEMP datasets relative to the 1850–1900 reference period, warming is computed relative to 1850–1900 using the HadCRUT4.6 dataset and scaled by the ratio of the linear trend 1880–2015 in the NOAA or GISTEMP dataset with the corresponding linear trend computed from HadCRUT4.
8) Average of diagnostics derived – see (7) – from four peer-reviewed global datasets, HadCRUT4.6, NOAA, GISTEMP & Cowtan-Way. Note that differences between averages may not coincide with average differences because of rounding.
9) No peer-reviewed publication available for these global combined land-sea datasets.
10) CMIP5 changes estimated relative to 1861–80 plus 0.02°C for the offset in HadCRUT4.6 from 1850–1900. CMIP5 values are the mean of the RCP8.5 ensemble, with 5–95% ensemble range. They are included to illustrate the difference between a complete global surface air temperature record (SAT) and a blended surface air and sea surface temperature (SST) record accounting for incomplete coverage (masked), following Richardson et al. (2016). Note that 1986–2005 temperatures in CMIP5 appear to have been depressed more than observed temperatures by the eruption of Mount Pinatubo.

1.2.1.3 Total versus human–induced warming and warming rates

Total warming refers to the actual temperature change, irrespective of cause, while human–induced warming refers to the component of that warming that is attributable to human activities. Mitigation studies focus on human-induced warming (that is not subject to internal climate variability), while studies of climate change impacts typically refer to total warming (often with the impact of internal variability minimised through the use of multi–decade averages).

In the absence of strong natural forcing due to changes in solar or volcanic activity, the difference between total and human-induced warming is small: assessing empirical studies quantifying solar and volcanic contributions to GMST from 1890 to 2010, AR5 (Fig. 10.6 of Bindoff et al., 2013) found their net impact on warming over the full period to be less than ±0.1°C. Figure 1.2 shows that the level of human–induced warming has been indistinguishable from total observed warming since 2000, including over the decade 2006–2015. Bindoff et al. (2013) assessed the magnitude of human-induced warming over the period 1951–2010 to be 0.7°C±0.1°C, slightly greater than the 0.65°C observed warming over this period (Figures 10.4 & 10.5) and a *likely* range of ±14%. The key surface temperature attribution studies underlying this finding finding (Gillett et al., 2013; Jones et al., 2013; Ribes and Terray, 2013) used temperatures since the 19th century to constrain human-induced warming, and so their results are equally applicable to the attribution of causes of warming over longer periods. Jones et al. (2016) show (Figure 10) human-induced warming trends over the period 1905–2005 to be indistinguishable from the corresponding total observed warming trend accounting for natural variability using spatio-temporal detection patterns from 12 out of 15 CMIP5 models and from the multi-model average. Figures from Ribes and Terray (2013), show the anthropogenic contribution to the observed linear warming trend 1880-2012 in the HadCRUT4 dataset (0.83°C in Table 1.1) to be 0.86°C using a multi-model average global diagnostic, with a 5-95% confidence interval of 0.72-1.00°C. In all cases, since 2000 the estimated combined contribution of solar and volcanic activity to warming relative to 1850–1900 is found to be less than ±0.1°C (Gillett et al., 2013), while anthropogenic warming is indistinguishable from, and if anything slightly greater than, the total observed warming, with 5–95% confidence intervals typically around ±20%.

Haustein et al. (2017) give a 5–95% confidence interval for human-induced warming in 2017 of 0.87–1.22°C, with a best estimate of 1.02°C, based on the HadCRUT4 dataset accounting for observational and forcing uncertainty and internal variability. Applying their method to the average of the 4 datasets shown in figure 1.2 gives an average level of human-induced warming in 2017 of 1.04°C. They also estimate a human-induced warming trend over the past 20 years of 0.17°C (0.13–0.33°C) per decade, consistent with estimates of the total observed trend of Foster and Rahmstorf (2011) (0.17±0.03°C/decade uncertainty in linear trend only) and Kirtman et al. (2013) (0.3–0.7°C over 30 years, or 0.1–0.23°C/decade, *likely* range), and a best-estimate warming rate over the past five years of 0.215°C/decade (Leach et al., 2018). Drawing on these multiple lines of evidence, human-induced warming is assessed to have reached 1.0°C in 2017, having increased by 0.13°C from the mid-point of 2006–2015, with a *likely* range of ±0.2°C (reduced from 5–95% to account for additional forcing and model uncertainty), increasing at 0.2°C (±0.1°C) per decade (estimates of human-induced warming given to 0.1°C precision only).

Since warming is here defined in terms of a 30-year average, corrected for short-term natural fluctuations, when warming is considered to be at 1.5°C, global temperatures would fluctuate equally on either side of 1.5°C in the absence of a large cooling volcanic eruption (Bethke et al, 2017). Figure 1.2 indicates there is a substantial chance of GMST in a single month fluctuating over 1.5°C between now and 2020, but this would not constitute temperatures ‘reaching 1.5°C’ on our working definition. Rogelj et al. (2017) show limiting the probability of annual GMST exceeding 1.5°C to less than one-year-in-20 would require limiting warming, on the definition used here, to 1.31°C or lower.

1.2.2 Global versus regional and seasonal warming

Warming is not observed or expected to be spatially or seasonally uniform (IPCC, 2013b). A 1.5°C increase in GMST will be associated with warming substantially greater than 1.5°C in many land regions, and less than 1.5°C in most ocean regions. This is illustrated by Figure 1.3, which shows an estimate of the observed change in annual and seasonal average temperatures between the 1850-1900 pre-industrial reference period and the decade 2006–2015 in the Cowtan-Way dataset. These regional changes are associated with an observed GMST increase of 0.91°C in the dataset shown here, or

0.87°C in the 4-dataset average (Table 1.1). This observed pattern reflects an on-going transient warming: features such as enhanced warming over land may be less pronounced, but still present, in equilibrium (IPCC, 2013b). This figure illustrates the magnitude of these differences, with many locations, particularly in Northern-Hemisphere mid-latitude winter (December–February), already experiencing regional warming more than double the global average. Individual seasons may be substantially warmer, or cooler, than these expected long–term average changes.

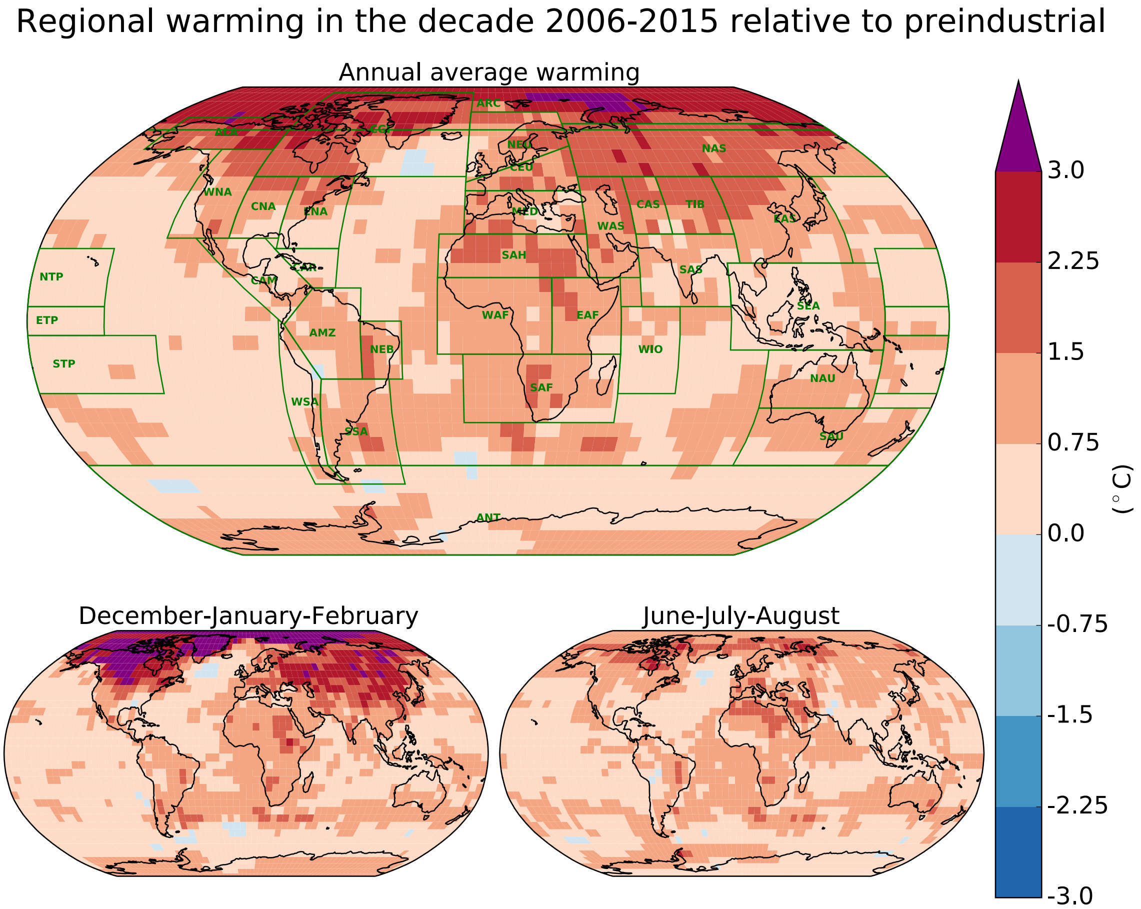


Figure 1.3: Spatial and seasonal pattern of present-day warming: Regional warming for the 2006–2015 decade relative to 1850–1900 for the annual mean (top), the average of December, January and February (bottom left) and for June, July and August (bottom right). Warming is evaluated by regressing regional changes in the (Cowtan and Way, 2014) dataset onto the total (combined human and natural) externally-forced warming (yellow line in Figure 1.2). See Technical Annex 1.A of this chapter for further details and versions using alternative datasets. The definition of regions (green boxes and labels in top panel) is adopted from the AR5 (Christensen et al., 2013).

1.2.3 Definition of 1.5°C-consistent pathways: probability, transience, stabilization and overshoot

Pathways considered in this report, consistent with available literature on 1.5°C, primarily focus on the timescale up to 2100, recognising that the evolution of GMST after 2100 is also important. Two broad categories of 1.5°C-consistent pathways can be used to characterise mitigation options and impacts: pathways in which warming (defined as 30-year averaged GMST relative to pre-industrial levels, see section 1.2.1) remains below 1.5°C throughout the 21st century, and pathways in which warming temporarily exceeds ('overshoots') 1.5°C and returns to 1.5°C either before or soon after

2100. Pathways in which warming exceeds 1.5°C before 2100, but might return to that level in some future century, are not considered 1.5°C-consistent.

Because of uncertainty in the climate response, a 'prospective' mitigation pathway (see Cross-Chapter Box 1 in this Chapter), in which emissions are prescribed, can only provide a level of probability of warming remaining below a temperature threshold. This probability cannot be quantified precisely since estimates depend on the method used (Rogelj et al., 2016b; Millar et al., 2017b; Goodwin et al., 2018; Tokarska and Gillett, 2018). This report defines a '1.5°C-consistent pathway' as a pathway of emissions and associated possible temperature responses in which the majority of approaches using presently-available information assign a probability in the range of approximately one-in-two to two-in-three to warming remaining below 1.5°C or, in the case of an overshoot pathway, returning to 1.5°C by around 2100 or earlier. In Chapter 2, the classification of pathways is based on one modeling approach to avoid ambiguity, but probabilities of exceeding 1.5°C are checked against other approaches to verify that they lie within this approximate range. All these absolute probabilities are imprecise, depend on the information used to constrain them, and hence are expected to evolve in the future. Imprecise probabilities can nevertheless be useful for decision-making, provided the imprecision is acknowledged (Hall et al., 2007; Kriegler et al., 2009; Simpson et al., 2016). Relative and rank probabilities can be assessed much more consistently: approaches may differ on the absolute probability assigned to individual outcomes, but typically agree on which outcomes are more probable.

Importantly, 1.5°C-consistent pathways allow a substantial (up to one-in-two) chance of warming still exceeding 1.5°C. An 'adaptive' mitigation pathway in which emissions are continuously adjusted to achieve a specific temperature outcome (e.g. Millar et al., 2017b) reduces uncertainty in the temperature outcome while increasing uncertainty in the emissions required to achieve it. It has been argued (Otto et al., 2015; Xu and Ramanathan, 2017) that achieving very ambitious temperature goals will require such an adaptive approach to mitigation, but very few studies have been performed taking this approach (e.g. Jarvis et al., 2012).

Figure 1.4 illustrates these categories of (a) 1.5°C-consistent temperature pathways and associated (b) annual and (c) cumulative emissions of CO_2. It also shows (d) a 'time-integrated impact' that continues to increase even after GMST has stabilised, such as sea-level rise. This schematic assumes for illustration that the fractional contribution of non-CO_2 climate forcers to total anthropogenic forcing (which is currently increasing, Myhre et al., 2017) is approximately constant from now on. Consequently, total human-induced warming is proportional to cumulative CO_2 emissions (solid line in c), and GMST stabilises when emissions reach zero. This is only the case in the most ambitious scenarios for non-CO_2 mitigation (Leach et al., 2018). A simple way of accounting for varying non-CO_2 forcing in Figure 1.4 would be to note that every 1 W/m^2 increase in non-CO_2 forcing between now and the decade or two immediately prior to the time of peak warming reduces cumulative CO_2 emissions consistent with the same peak warming by approximately 1200±300 $GtCO_2$ (using values from AR5: Myhre et al, 2013; Jenkins et al, 2018; Allen et al, 2018; Cross-Chapter Box 2 in this Chapter).

1.2.3.1 Pathways remaining below 1.5°C

In this category of 1.5°C-consistent pathways, human-induced warming either rises monotonically to stabilise at 1.5°C (Figure 1.4, brown lines) or peaks at or below 1.5°C and then declines (yellow lines). Figure 1.4, panel b demonstrates that pathways remaining below 1.5°C require net annual CO_2 emissions to peak and decline to near zero or below, depending on the long-term adjustment of the carbon cycle and non-CO_2 emissions (Bowerman et al., 2013; Wigley, 2018). Reducing emissions to zero corresponds to stabilizing cumulative CO_2 emissions (panel c, solid lines) and falling concentrations of CO_2 in the atmosphere (panel c dashed lines) (Matthews and Caldeira, 2008;

Solomon et al., 2009), which is required to stabilize GMST if non-CO_2 climate forcings are constant and positive. Stabilizing atmospheric greenhouse gas concentrations would result in continued warming (see Section 1.2.4).

If starting emission reductions is delayed until temperatures are close to the proposed limit, pathways remaining below 1.5°C necessarily involve much faster rates of net CO_2 emission reductions (Figure 1.4, green lines), combined with rapid reductions in non-CO_2 forcing, and also reach 1.5°C earlier. Note that the emissions associated with these schematic temperature pathways may not correspond to feasible emission scenarios, but they do illustrate the fact that the timing of net zero emissions does not in itself determine peak warming: what matters is total cumulative emissions up to that time. Hence every year's delay before initiating emission reductions reduces by approximately two years the remaining time available to reduce emissions to zero on a pathway remaining below 1.5°C (Allen and Stocker, 2013; Leach et al., 2018).

1.2.3.2 Pathways temporarily exceeding 1.5°C

With the pathways in this category, also referred to as overshoot pathways, GMST rises above 1.5°C before peaking and returning to 1.5°C around or before 2100 (Figure 1.4, blue lines), subsequently either stabilising or continuing to fall. This allows initially slower or delayed emission reductions but lowering GMST requires net negative global CO_2 emissions (net anthropogenic removal of CO_2; Figure 1.4, panel b). Cooling, or reduced warming, through sustained reductions of net non-CO_2 climate forcing (Cross-Chapter Box 2 in this Chapter) is also required, but their role is limited because emissions of most non-CO_2 forcers cannot be reduced to below zero. Hence the feasibility and availability of large–scale CO_2 removal limits the possible rate and magnitude of temperature decline. In this report, overshoot pathways are referred to as 1.5°C-consistent, but qualified by the amount of the temperature overshoot, which can have a substantial impact on irreversible climate change impacts (Mathesius et al., 2015; Tokarska and Zickfeld, 2015).

1.2.3.3 Impacts at 1.5°C warming associated with different pathways: transience versus stabilisation

Figure 1.4 also illustrates timescales associated with different impacts. While many impacts scale with the change in GMST itself, some (such as those associated with ocean acidification) scale with the change in atmospheric CO_2 concentration, indicated by the fraction of cumulative CO_2 emissions remaining in the atmosphere (dotted lines in panel c). Others may depend on the rate of change of GMST, while 'time-integrated impacts', such as sea-level rise, shown in panel (d) continue to increase even after GMST has stabilised.

Hence impacts that occur when GMST reaches 1.5°C could be very different depending on the pathway to 1.5°C. CO_2 concentrations will be higher as GMST rises past 1.5°C (transient warming) than when GMST has stabilized at 1.5°C while sea level and, potentially, global mean precipitation (Pendergrass et al., 2015) would both be lower (see Figure 1.4). These differences could lead to very different impacts on agriculture, on some forms of extreme weather (e.g., Baker et al., 2018), and on marine and terrestrial ecosystems (e.g., Mitchell et al., 2017,)Box 3.1). Sea level would be higher still if GMST returns to 1.5°C after an overshoot (Figure 1.4, panel d), with potentially significantly different impacts in vulnerable regions. Temperature overshoot could also cause irreversible impacts (see Chapter 3).

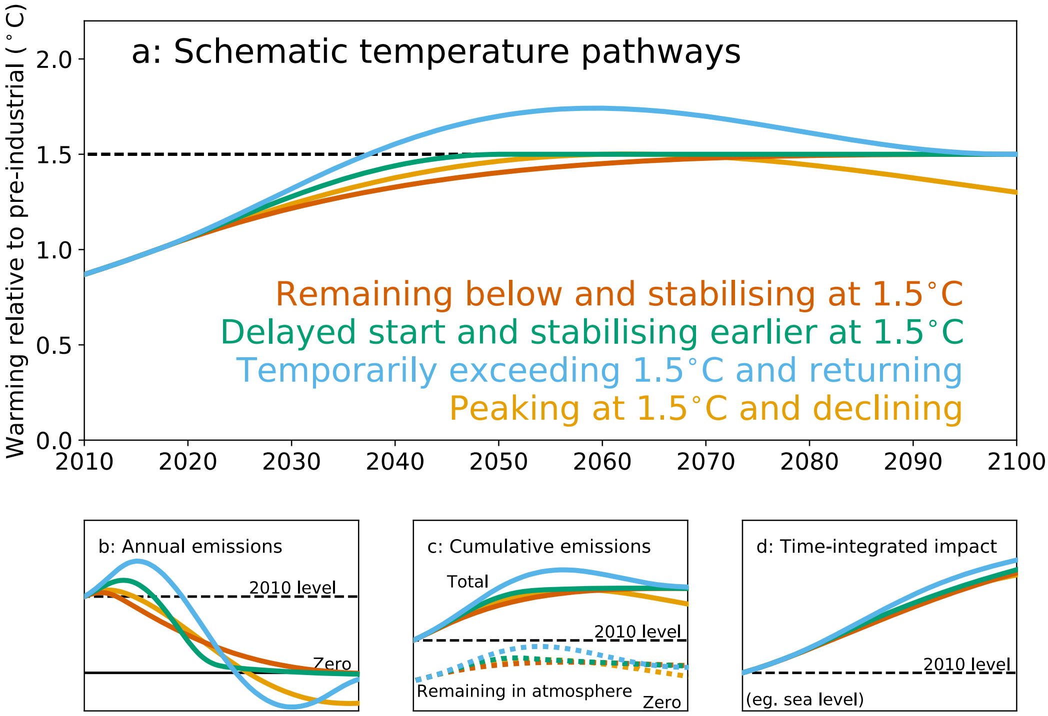


Figure 1.4: **Different 1.5°C-consistent pathways[1]:** Schematic illustration of the relationship between (a) global mean surface temperature (GMST) change; (b) annual rates of CO_2 emissions, assuming constant fractional contribution of non-CO_2 forcing to total human-induced warming; (c) total cumulative CO_2 emissions (solid lines) and the fraction thereof remaining in the atmosphere (dashed lines; these also indicates changes in atmospheric CO_2 concentrations); and (d) a time-integrated impact, such as sea-level rise, that continues to increase even after GMST has stabilized. Colours indicate different 1.5°C-consistent pathways. Brown: GMST remaining below and stabilizing at 1.5°C in 2100; Green: a delayed start but faster implementation pathway with GMST remaining below and reaching 1.5°C earlier; Blue: a pathway temporarily exceeding 1.5°C, with temperatures reduced to 1.5°C by net negative CO_2 emissions after temperatures peak; and Yellow: a pathway peaking at 1.5°C and subsequently declining. Temperatures are anchored to 0.87°C above pre–industrial in 2010; emissions–temperature relationships are computed using a simple climate model (Myhre et al., 2013; Millar et al., 2017a; Jenkins et al., 2018) with a lower value of the Transient Climate Response (TCR) than used in the quantitative pathway assessments in Chapter 2 to illustrate qualitative differences between pathways: this figure is not intended to provide quantitative information. The time-integrated impact is illustrated by the semi-empirical sea–level–rise model of Kopp et al. (2016).

[1] FOOTNOTE: An animated version of Figure 1.4 will be embedded in the web-based version of this Special Report

Cross-Chapter Box 1: Scenarios and Pathways

Contributing Authors: Mikiko Kainuma (Japan), Kristie L. Ebi (US), Sabine Fuss (Germany), Elmar Kriegler (Germany), Keywan Riahi (Austria), Joeri Rogelj (Austria/Belgium), Petra Tschakert (Australia/Austria) and Rachel Warren (UK)

Climate change scenarios have been used in IPCC assessments since the First Assessment Report (Leggett et al., 1992). The **SRES scenarios** (named after the IPCC Special Report on Emissions Scenarios; IPCC, 2000), published in 2000, consist of four scenarios that do not take into account any future measures to limit greenhouse gas (GHG) emissions. Subsequently, many policy scenarios have been developed based upon them (Morita et al., 2001). The SRES scenarios are superseded by a set of scenarios based on the Representative Concentration Pathways (RCPs) and Shared Socio–Economic Pathways (SSPs) (Riahi et al., 2017). The RCPs comprise a set of four GHG concentration trajectories that jointly span a large range of plausible human–caused climate forcing ranging from 2.6 W m^{-2} (RCP2.6) to 8.5 W m^{-2} (RCP8.5) by the end of the 21st century (van Vuuren et al., 2011). They were used to develop climate projections in the 5th Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012) and were assessed in the IPCC 5th Assessment Report (AR5). Based on the CMIP5 ensemble, RCP2.6, provides a better than two in three chance of staying below 2°C and a median warming of 1.6°C relative to 1850–1900 in 2100 (Collins et al., 2013).

The SSPs were developed to complement the RCPs with varying socio-economic challenges to adaptation and mitigation. SSP-based scenarios were developed for a range of climate forcing levels, including the end-of-century forcing levels of the RCPs (Riahi et al., 2017) and a level below RCP2.6 to explore pathways limiting warming to 1.5°C above pre–industrial levels (Rogelj et al., 2018). The SSP-based 1.5°C-consistent pathways are assessed in Chapter 2 of this report. These scenarios offer an integrated perspective on socio–economic, energy-system (Bauer et al., 2017), land use (Popp et al., 2017), air pollution (Rao et al., 2017) and GHG emissions developments (Riahi et al., 2017). Because of their harmonised assumptions, scenarios developed with the SSPs facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation.

Scenarios and Pathways in this Report

This report focuses on pathways that could limit the increase of global mean surface temperature (GMST) to 1.5°C above pre–industrial levels and pathways that align with the goals of sustainable development and poverty eradication. Pace and scale of mitigation and adaptation are assessed in the context of historical evidence to determine where unprecedented change is required (see Chapter 4). Other scenarios are also assessed, primarily as benchmarks for comparison of mitigation, impacts, and/or adaptation requirements. These include baseline scenarios that assume no climate policy; scenarios that assume some kind of continuation of current climate policy trends and plans, many of which are used to assess the implications of the nationally-determined contributions (NDCs); and scenarios holding warming below 2°C above pre–industrial levels. This report assesses the spectrum from global mitigation scenarios to local adaptation choices – complemented by a bottom-up assessment of individual mitigation and adaptation options and their implementation (policies, finance, institutions, governance, see Chapter 4). Regional, national, and local scenarios, as well as decision-making processes over values and difficult trade-offs are important for understanding the challenges of limiting GMST increase to 1.5°C and are thus indispensable when assessing implementation.

Different climate policies result in different temperature pathways, which result in different levels of climate risks and actual climate impacts with associated long-term implications. Temperature pathways are classified into continued warming pathways (in the cases of baseline and reference scenarios), pathways that keep the temperature below a specific limit (like 1.5°C or 2°C), and pathways that temporarily exceed and later fall to a specific limit (overshoot pathways). In the case of a temperature overshoot, net negative CO_2 emissions are required to remove excess CO_2 from the atmosphere.

In a 'prospective' mitigation pathway, emissions (or sometimes concentrations) are prescribed, giving a range of GMST outcomes because of uncertainty in the climate response. Prospective pathways are considered '1.5°C-consistent' in this report if, based current knowledge, the majority of available approaches assign an approximate probability of one-in-two to two-in-three to temperatures either remaining below 1.5°C or returning to 1.5°C either before or around 2100. Most pathways assessed in Chapter 2 are prospective pathways, and therefore even '1.5°C-consistent pathways' are also associated with risks of warming higher than 1.5°C, noting that many risks increase non-linearly with increasing GMST. In contrast, the 'risks of warming of 1.5°C'assessed in Chapter 3 refer to risks in a world in which GMST is either passing through (transient) or stabilized at 1.5°C, without considering probabilities of different GMST levels (unless otherwise qualified). To stay below any desired temperature limit, adjusting mitigation measures and strategies would be required as knowledge of the climate response is updated (Millar et al., 2017b; Emori et al., 2018). Such pathways can be called 'adaptive' mitigation pathways. Given there is always a possibility of a greater-than-expected climate response (Xu and Ramanathan, 2017), adaptive mitigation pathways are important to minimise climate risks, but need also to consider the risks and feasibility (see Cross-Chapter Box 3 in this Chapter) of faster-than-expected emission reductions. Aligning mitigation and adaptation pathways with sustainable development pathways and transformative visions for the future that would support avoiding negative impacts on the poorest and most disadvantaged populations and vulnerable sectors are assessed in Chapter 5.

Definitions of Scenarios and Pathways
Climate scenarios and pathways are terms that are sometimes used interchangeably, with a wide range of overlapping definitions (Rosenbloom, 2017).

A '**scenario'** is an internally consistent, plausible, and integrated description of a possible future of the human–environment system, including a narrative with qualitative trends and quantitative projections (IPCC, 2000). Climate change scenarios provide a framework for developing and integrating emissions, climate change and climate impact projections, including an assessment of their inherent uncertainties. The long-term and multi–faceted nature of climate change requires climate scenarios to describe how assumptions about inherently uncertain socio-economic trends in the 21st century could influence future energy and land use, resulting in emissions, and climate change as well as human vulnerability and exposure to climate change. Such driving forces include population, GDP, technological innovation, governance, and lifestyles. Climate change scenarios are used for analysing and contrasting climate policy choices.

The notion of a **'pathway'** can have multiple meanings in the climate literature. It is often used to describe the temporal evolution of a set of scenario features, such as GHG emissions and socioeconomic development. As such, it can describe individual scenario components or sometimes be used interchangeably with the word 'scenario'. For example, the RCPs describe GHG concentration trajectories (van Vuuren et al., 2011) and the SSPs are a set of narratives of societal futures augmented by quantitative projections of socio-economic determinants such as population, GDP, and urbanization (Kriegler et al., 2012; O'Neill et al., 2014). Socio-economic driving forces consistent with any of the SSPs can be combined with a set of climate policy assumptions (Kriegler et al., 2014) that together would lead to emissions and concentration outcomes consistent with the RCPs (Riahi et al., 2017). This is at the core of the scenario framework for climate change research that aims to facilitate creating scenarios integrating emissions and development pathways dimensions (Ebi et al., 2014; van Vuuren et al., 2014).

In other parts of the literature, 'pathway' implies a solution-oriented trajectory describing a pathway from today's world to achieving a set of future goals. **Sustainable Development Pathways** describe national and global pathways where climate policy becomes part of a larger sustainability transformation (Shukla and Chaturvedi, 2013; Fleurbaey et al., 2014; van Vuuren et al., 2015). The AR5 presented **climate-resilient pathways** as sustainable development pathways that combine the goals of adaptation and mitigation (Denton et al., 2014), more broadly defined as iterative processes for managing change within complex systems in order to reduce disruptions and enhance opportunities associated with climate change (IPCC, 2014b). The AR5 also introduced the notion of **climate-resilient development pathways,** with a more explicit focus on dynamic livelihoods, multidimensional poverty, structural inequalities, and equity among poor and non-poor people (Olsson et al., 2014). **Adaptation pathways**, understood as a series of adaptation choices involving trade-offs between short-term and long-term goals and values (Reisinger et al., 2014). They are decision-making processes sequenced over time with the purpose of deliberating and identifying socially-salient solutions in specific places (Barnett et al., 2014; Wise et al., 2014; Fazey et al., 2016). There is a range of possible pathways for transformational change, often negotiated through iterative and inclusive processes (Harris et al., 2017; Fazey et al., 2018; Tàbara et al., 2018).

1.2.4 Geophysical warming commitment

It is frequently asked whether limiting warming to 1.5°C is 'feasible' (Cross–Chapter Box 3 in this Chapter). There are many dimensions to this question, including the warming 'commitment' from past emissions of greenhouse gases and aerosol precursors. Quantifying commitment from past emissions is complicated by the very different behaviour of different climate forcers affected by human activity: emissions of long-lived greenhouse gases such as CO_2 and nitrous oxide (N_2O) have a very persistent impact on radiative forcing (Myhre et al., 2013), lasting from over a century (in the case of N_2O) to hundreds of thousands of years (for CO_2). Short-lived climate forcers (SLCFs) such as methane (CH_4) and aerosols, in contrast, persist for at most about a decade (in the case of methane) down to only a few days. These different behaviours must be taking into account in assessing the implications of any approach to calculating aggregate emissions (Cross-Chapter Box 2 in this Chapter).

Geophysical warming commitment is defined as the unavoidable future warming resulting from physical Earth system inertia. Different variants are discussed in the literature, including (i) the 'constant composition commitment' (CCC), defined by Meehl et al. (2007) as the further warming that would result if atmospheric concentrations of GHGs and other climate forcers were stabilised at the current level; and (ii) and the 'zero emissions commitment' (ZEC), defined as the further warming that would still occur if all future anthropogenic emissions of greenhouse gases and aerosol precursors were eliminated instantaneously (Meehl et al, 2007; Collins et al., 2013).

The CCC is primarily associated with thermal inertia of the ocean (Hansen et al., 2005), and has led to the misconception that substantial future warming is inevitable (Matthews and Solomon, 2013). The CCC takes into account the warming from past emissions, but also includes warming from future emissions (declining but still non-zero) that are required to maintain a constant atmospheric composition. It is therefore not relevant to the warming commitment from past emissions alone.

The ZEC, although based on equally idealised assumptions, allows for a clear separation of the response to past emissions from the effects of future emissions. The magnitude and sign of the ZEC depend on the mix of GHGs and aerosols considered. For CO_2, which has an effective atmospheric residence time of centuries to millennia (Eby et al., 2009), the multi-century warming commitment from emissions to date is estimated to range from slightly negative (i.e., a slight cooling relative to present-day) to slightly positive (Matthews and Caldeira, 2008; Lowe et al., 2009; Gillett et al., 2011; Collins et al., 2013). Some studies estimate a larger ZEC from CO_2, but for cumulative emissions much higher than those up to present day (Frölicher et al., 2014; Ehlert and Zickfeld, 2017). The ZEC from past CO_2 emissions is small because the continued warming effect from ocean thermal inertia is approximately balanced by declining radiative forcing due to CO_2 uptake by the ocean (Solomon et al., 2009; Williams et al., 2017). Thus, although present-day CO_2-induced warming is irreversible on millennial timescales (without human intervention such as active carbon dioxide removal or solar radiation modification (Section 1.4.1)), past CO_2 emissions do not commit to substantial further warming (Matthews and Solomon, 2013).

For warming SLCFs, meaning those associated with positive radiative forcing such as methane, the ZEC is negative. Eliminating emissions of these substances (also sometimes referred to as short-lived climate pollutants, see Section 4.3.6) results in an immediate cooling relative to the present (Figure 1.5, magenta line) (Frölicher and Joos, 2010; Matthews and Zickfeld, 2012; Mauritsen and Pincus, 2017). Cooling SLCFs (those associated with negative radiative forcing) such as sulphate aerosols create a positive ZEC, as elimination of these forcers results in rapid warming (Matthews and Zickfeld, 2012; Mauritsen and Pincus, 2017; Samset et al., 2018). Estimates of the warming commitment from eliminating aerosol emissions are affected by large uncertainties in net aerosol radiative forcing (Myhre et al., 2013, 2017). If present–day emissions of all GHGs (short- and long-lived) and aerosols (including sulphate, nitrate and carbonaceous aerosols) are eliminated (Figure 1.5, yellow line) GMST rises over the following decade. This initial warming is followed by a gradual cooling driven by the decline in radiative forcing of short-lived greenhouse gases (Matthews and Zickfeld, 2012; Collins et al., 2013). Peak warming following elimination of all emissions was assessed at a few tenths of a degree in AR5, and century-scale warming was assessed to change only slightly relative to the time emissions are reduced to zero (Collins et al., 2013). New evidence since AR5 suggests a larger methane forcing (Etminan et al., 2016) but no revision in the range of aerosol forcing (although this remains an active field of research, e.g., Myhre et al., 2017). This revised methane forcing estimate results in a smaller peak warming and a faster temperature decline than assessed in AR5 (Figure 1.5, yellow line).

Expert judgement based on the available evidence (including model simulations, radiative forcing and climate sensitivity) suggests that if all anthropogenic emissions were reduced to zero immediately, any further warming beyond the 1°C already experienced would *likely* be less than 0.5°C over the next two to three decades, and also *likely* less than 0.5°C on a century timescale.

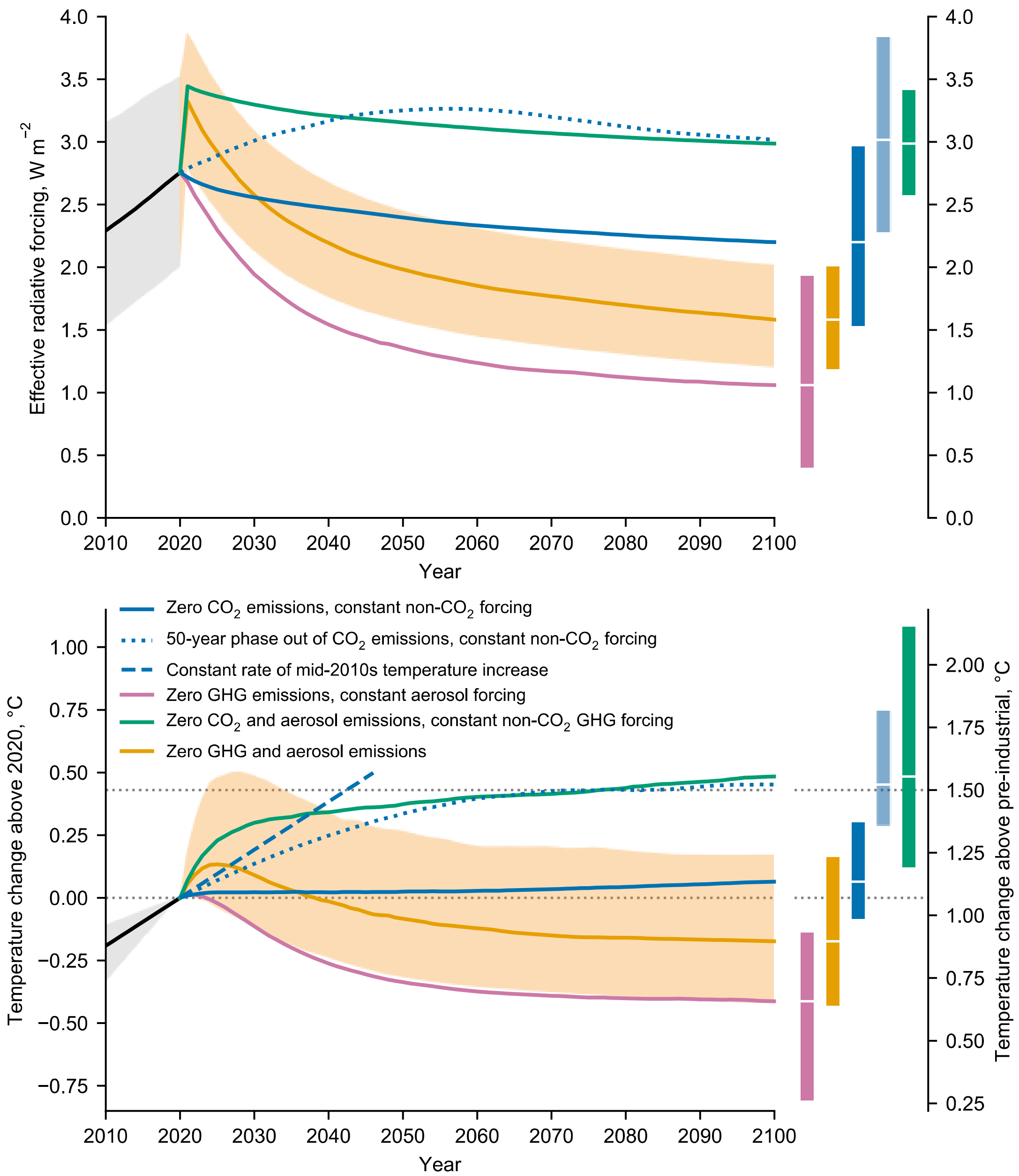


Figure 1.5: **Different interpretations of warming commitment from past emissions:** Radiative forcing (top) and global mean surface temperature change (bottom) for scenarios with different combinations of greenhouse gas and aerosol precursor emissions reduced to zero in 2020. Variables were calculated using a simple climate–carbon cycle model (Millar et al., 2017a) with a simple representation of atmospheric chemistry (Smith et al., 2018). The bars on the right–hand side indicate the median warming in 2100 and 5–95% uncertainty ranges (also indicated by the plume around the yellow line) taking into account one estimate of uncertainty in climate response, effective radiative forcing, and carbon cycle constraining simple model parameters with response ranges from AR5 combined with historical climate observations (Smith et al., 2018). Temperatures continue to increase slightly after elimination of CO_2 emissions (blue line) due to adjusting to the recent increase in non-CO_2 forcing. The dashed blue line extrapolates one estimate of the current rate of warming, while dotted blue lines show a case where CO_2 emissions are reduced linearly to zero assuming constant non-CO_2 forcing after 2020. Under these highly idealized assumptions, the time to stabilize temperatures at 1.5°C is approximately double the time remaining to reach 1.5°C at the current warming rate.

Since most sources of emissions cannot, in reality, be brought to zero instantaneously due to techno-economic inertia, the current rate of emissions also constitutes a conditional commitment to future emissions and consequent warming depending on achievable rates of emission reductions. The current level and rate of human-induced warming determines both the time left before a temperature threshold is exceeded if warming continues (dashed blue line in Figure 1.5) and the time over which the warming rate must be reduced to avoid exceeding that threshold (approximately indicated by the dotted blue line in Figure 1.5). Leach et al. (2018) use a central estimate of human-induced warming of 1.02°C in 2017 increasing at 0.215°C per decade (Haustein et al., 2017), to argue that it will take 13–32 years (one-standard-error range) to reach 1.5°C if the current warming rate continues, allowing 25–64 years to stabilise temperatures at 1.5°C if the warming rate is reduced at a constant rate of deceleration starting immediately. Since the rate of human-induced warming is proportional to the rate of CO_2 emissions (Matthews et al., 2009; Zickfeld et al., 2009) plus a term approximately proportional to the rate of increase in non–CO_2 radiative forcing (Gregory and Forster, 2008; Allen et al., 2018; Cross-Chapter Box 2 in this Chapter), these timescales also provide an indication of minimum emission reduction rates required if a warming greater than 1.5°C is to be avoided (see Technical Annex 1.A and FAQ 1.2).

Cross-Chapter Box 2: Measuring progress to net zero emissions combining long-lived and short-lived climate forcers

Contributing Authors: Piers Forster (UK), Myles Allen (UK), Elmar Kriegler (Germany), Joeri Rogelj (Austria/Belgium), Seth Schultz (US), Drew Shindell (US) and Kirsten Zickfeld (Canada/Germany)

Emissions of many different climate forcers will affect the rate and magnitude of climate change over the next few decades (Myhre et al., 2013). Since these decades will determine when 1.5°C is reached or whether a warming greater than 1.5°C is avoided, understanding the aggregate impact of different forcing agents is particularly important in the context of 1.5°C-consistent pathways. Paragraph 17 of Decision 1 of the 21st Conference of the Parties on the adoption of the Paris Agreement specifically states that this report is to identify aggregate greenhouse gas emission levels compatible with holding the increase in global average temperatures to 1.5°C above preindustrial levels (see Chapter 2). This request highlights the need to consider the implications of different methods of aggregating emissions of different gases, both for future temperatures and for other aspects of the climate system.

To date, reporting of GHG emissions under the UNFCCC has used Global Warming Potentials (GWPs) evaluated over a 100–year time horizon (GWP_{100}) to combine multiple climate forcers. IPCC Working Group 3 reports have also used GWP_{100} to represent multi-gas pathways (Clarke et al., 2014). For reasons of comparability and consistency with current practice, Chapter 2 in this Special Report continues to use this aggregation method. Numerous other methods of combining different climate forcers have been proposed, such as the Global Temperature-change Potential (GTP; Shine et al., 2005) and the Global Damage Potential (Tol et al., 2012; Deuber et al., 2013).

Climate forcers fall into two broad categories in terms of their impact on global temperature (Smith et al., 2012): long-lived GHGs, such as CO_2 and nitrous oxide (N_2O), whose warming impact depends primarily on the total cumulative amount emitted over the past century or the entire industrial epoch; and short-lived climate forcers (SLCFs), such as methane and black carbon, whose warming impact depends primarily on current and recent annual emission rates (Reisinger et al., 2012; Myhre et al., 2013; Smith et al., 2013; Strefler et al., 2014). These different dependencies affect the emissions reductions required of individual forcers to limit warming to 1.5°C or any other level.

Natural processes that remove CO_2 permanently from the climate system are so slow that reducing the rate of CO_2-induced warming to zero requires net zero global anthropogenic CO_2 emissions (Archer and Brovkin, 2008; Matthews and Caldeira, 2008; Solomon et al., 2009), meaning almost all remaining anthropogenic CO_2 emissions must be compensated for by an equal rate of anthropogenic carbon dioxide removal (CDR). Cumulative CO_2 emissions are therefore an accurate indicator of CO_2-induced warming, except in periods of high negative CO_2 emissions (Zickfeld et al., 2016), and potentially in century-long periods of near-stable temperatures (Bowerman et al., 2011; Wigley, 2018). In contrast, sustained constant emissions of a SLCF such as methane, would (after a few decades) be consistent with constant methane concentrations and hence very little additional methane-induced warming (Allen et al., 2018; Fuglestvedt et al., 2018). Both GWP and GTP would equate sustained SLCF emissions with sustained constant CO_2 emissions, which would continue to accumulate in the climate system, warming global temperatures indefinitely. Hence nominally 'equivalent' emissions of CO_2 and SLCFs, if equated conventionally using GWP or GTP, have very different temperature impacts, and these differences are particularly evident under ambitious mitigation characterising 1.5°C-consistent pathways.

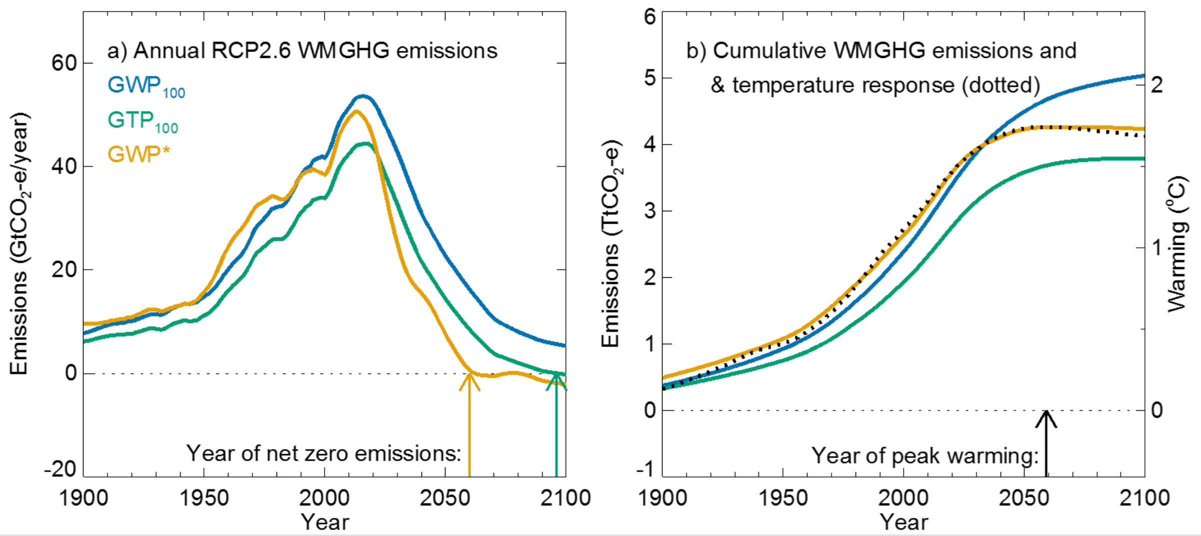
Since the AR5, a revised usage of GWP has been proposed (Lauder et al., 2013; Allen et al., 2016), denoted GWP* (Allen et al., 2018), that addresses this issue by equating a permanently sustained change in the emission *rate* of an SLCF or SLCF-precursor (in tonnes-per-year), or other non-CO_2 forcing (in Watts per square metre), with a one-off *pulse* emission (in tonnes) of a fixed amount of CO_2. Specifically, GWP* equates a 1 tonne-per-year increase in emission rate of an SLCF with a pulse emission of $\mathrm{GWP}_H \times H$ tonnes of CO_2, where GWP_H is the conventional GWP of that SLCF evaluated over time horizon H. While GWP_H for SLCFs decreases with increasing time horizon H, $\mathrm{GWP}_H \times H$ for SLCFs is less dependent on the choice of time horizon. Similarly, a permanent 1 W/m^2 increase in radiative forcing has a similar temperature impact as the cumulative emission of H/AGWP_H tonnes of CO_2, where AGWP_H is the Absolute Global Warming Potential of CO_2 (Shine et al., 2005; Myhre et al., 2013; Allen et al., 2018). This indicates approximately how future changes in non-CO_2 radiative forcing affect cumulative CO_2 emissions consistent with any given level of peak warming.

When combined using GWP*, cumulative aggregate GHG emissions are closely proportional to total GHG-induced warming, while the annual rate of GHG-induced warming is proportional to the annual rate of aggregate GHG emissions (see Cross-Chapter Box 2, Figure 1). This is not the case when emissions are aggregated using GWP or GTP, with discrepancies particularly pronounced when SLCF emissions are falling. Persistent net zero CO_2-equivalent emissions containing a residual positive forcing contribution from SLCFs and aggregated using GWP_{100} or GTP would result in a steady decline of GMST. Net zero global emissions aggregated using GWP* (which corresponds to zero net emissions of CO_2 and other long-lived GHGs like nitrous oxide, combined with constant SLCF forcing – see Figure 1.5) results in approximately stable GMST (Fuglestvedt et al., 2018; Allen et al., 2018 and Cross-Chapter Box 2, Figure 1, below).

Whatever method is used to relate emissions of different greenhouse gases, scenarios achieving stable GMST well below 2°C require both near–zero net emissions of long–lived greenhouse gases and deep reductions in warming SLCFs (Chapter 2), in part to compensate for the reductions in cooling SLCFs that are expected to accompany reductions in CO_2 emissions (Rogelj et al., 2016b; Hienola et al., 2018). Understanding the implications of different methods of combining emissions of different climate forcers is, however, helpful in tracking progress towards temperature stabilisation and 'balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases' as stated in Article 4 of the Paris Agreement. Fuglestvedt et al. (2018) and Tanaka and O'Neill (2018)show that when, and even whether, aggregate GHG emissions need to reach net zero before 2100 to limit warming to 1.5°C depends on the scenario, aggregation method and mix of long-lived and short-lived climate forcers.

The comparison of the impacts of different climate forcers can also consider more than their effects on GMST (Johansson, 2012; Tol et al., 2012; Deuber et al., 2013; Myhre et al., 2013). Climate impacts arise from both magnitude and rate of climate change, and from other variables such as precipitation (Shine et al., 2015). Even if GMST is stabilised, sea-level rise and associated impacts will continue to increase (Sterner et al., 2014), while impacts that depend on CO_2 concentrations such as ocean acidification may begin to reverse. From an economic perspective, comparison of different climate forcers ideally reflects the ratio of marginal economic damages if used to determine the exchange ratio of different GHGs under multi–gas regulation (Tol et al., 2012; Deuber et al., 2013; Kolstad et al., 2014).

Emission reductions can interact with other dimensions of sustainable development (see Chapter 5). In particular, early action on some SLCFs (including actions that may warm the climate such as reducing SO_2 emissions) may have considerable societal co-benefits such as reduced air pollution and improved public health with associated economic benefits (OECD, 2016; Shindell et al., 2016). Valuation of broadly defined social costs attempts to account for many of these additional non–climate factors along with climate-related impacts (Shindell, 2015; Sarofim et al., 2017; Shindell et al., 2017). See Chapter 4, Section 4.3.6, for a discussions of mitigation options, noting that mitigation priorities for different climate forcers depend on multiple economic and social criteria that vary between sectors, regions and countries.



Cross Chapter Box 2, Figure 1: Implications of different approaches to calculating aggregate greenhouse gas emissions on a pathway to net zero (a) Aggregate emissions of well–mixed greenhouse gases (WMGHGs) under the RCP2.6 mitigation scenario expressed as CO_2–equivalent using GWP_{100} (blue); GTP_{100} (green) and GWP* (yellow). Aggregate WMGHG emissions appear to fall more rapidly if calculated using GWP* than using either GWP or GTP, primarily because GWP* equates falling methane emissions with negative CO_2 emissions, as only active CO_2 removal would have the same impact on radiative forcing and GMST as a reduction in methane emission rates. (b) Cumulative emissions of WMGHGs combined as in panel (a) (blue, green & yellow lines & left hand axis) and warming response to combined emissions (black dotted line & right hand axis, Millar et al. (2017a). The temperature response under ambitious mitigation is closely correlated with cumulative WMGHG emissions aggregated using GWP*, but with neither emission rate nor cumulative emissions if aggregated using GWP or GTP.

1.3 Impacts at 1.5°C and beyond

1.3.1 Definitions

Consistent with the AR5 (IPCC, 2014e) , ‘impact’ in this report refers to the effects of climate change on human and natural systems. Impacts may include the effects of changing hazards, such as the frequency and intensity of heat waves. 'Risk' refers to potential negative impacts of climate change where something of value is at stake, recognizing the diversity of values. Risks depend on hazards, exposure, vulnerability (including sensitivity and capacity to respond) and likelihood. Climate change risks can be managed through efforts to mitigate climate change forcers, adaptation of impacted systems and remedial measures (Section 1.4.1).

In the context of this report, *regional* impacts of *global* warming at 1.5°C and 2°C are assessed in Chapter 3. The '*warming experience at 1.5°C*' is that of regional climate change (temperature, rainfall, and other changes) at the time when global average temperatures, as defined in Section 1.2.1, reach 1.5°C above pre-industrial (the same principle applies to impacts at any other global mean temperature). Over the decade 2006-2015, many regions have experienced higher than average levels of warming and some are already now 1.5°C warmer with respect to the pre-industrial period (Figure 1.3). At a global warming of 1.5°C, some seasons will be substantially warmer than 1.5°C above pre–industrial (Seneviratne et al., 2016). Therefore, most regional impacts of a global mean warming of 1.5°C will be different from those of a regional warming by 1.5°C.

The impacts of 1.5°C global warming will vary in both space and time (Ebi et al., 2016). For many regions, an increase in global mean temperature by 1.5°C or 2°C implies substantial increases in the occurrence and/or intensity of some extreme events (Fischer and Knutti, 2015; Karmalkar and Bradley, 2017; King et al., 2017), resulting in different impacts (see Chapter 3). By comparing impacts at 1.5°C *vs.* those at 2°C, this report discusses the 'avoided impacts' by maintaining global temperature increase at or below 1.5°C as compared to 2°C, noting that these also depend on the pathway taken to 1.5°C (see Section 1.2.3 and Cross-Chapter Box 8 in Chapter 3 on 1.5°C warmer worlds). Many impacts take time to observe, and because of the warming trend, impacts over the past 20 years were associated with a level of human-induced warming that was, on average, 0.1–0.23°C colder than its present level, based on the AR5 estimate of the warming trend over this period (Section 1.2.1 and Kirtman et al., 2013). Attribution studies (e.g., van Oldenborgh et al., 2017) can address this bias, but informal estimates of 'recent impact experience' in a rapidly warming world necessarily understate the temperature-related impacts of the current level of warming.

1.3.2 Drivers of Impacts

Impacts of climate change are due to multiple environmental drivers besides rising temperatures, such as rising atmospheric CO_2, shifting rainfall patterns, rising sea levels, increasing ocean acidification, and extreme events, such as floods, droughts, and heat waves (IPCC, 2014e). For example, changes in rainfall affect the hydrological cycle and water availability (Schewe et al., 2014). Several impacts depend on atmospheric composition, for example, increasing atmospheric carbon dioxide levels leading to changes in plant productivity (Forkel et al., 2016), but also to ocean acidification (Hoegh-Guldberg et al., 2007). Other impacts are driven by changes in ocean heat content, for example, the destabilization of coastal ice-sheets and sea-level rise (Bindoff et al., 2007; Chen et al., 2017), whereas impacts due to heat waves depend directly on ambient air or ocean temperature (Matthews et al., 2017). Impacts can be direct, for example, coral bleaching due to ocean warming, and indirect, for example, reduced tourism due to coral bleaching. Indirect impacts can also arise from mitigation efforts such as changed agricultural management (Section 3.6.2) or remedial measures such as solar radiation modification (Section 4.3.8, Cross-Chapter Box 10 in Chapter 4).

Impacts may also be triggered by combinations of factors, including 'impact cascades' (Cramer et al., 2014) through secondary consequences of changed systems. Changes in agricultural water availability caused by upstream changes in glacier volume are a typical example. Recent studies also identify compound events (e.g., droughts and heat waves), that is, when impacts are induced by the combination of several climate events (AghaKouchak et al., 2014; Leonard et al., 2014; Martius et al., 2016; Zscheischler and Seneviratne, 2017).

There are now techniques to attribute impacts formally to anthropogenic global warming and associated rainfall changes (Rosenzweig et al., 2008; Cramer et al., 2014; Hansen et al., 2016), taking into account other drivers such as land use change (Oliver and Morecroft, 2014) and pollution (e.g., tropospheric ozone; Sitch et al., 2007). There are multiple lines of evidence that climate change has observable and often severely negative effects on people, especially where climate-sensitive biophysical conditions and socioeconomic / political constraints on adaptive capacities combine to create high vulnerabilities (IPCC, 2012c; World Bank, 2013; IPCC, 2014e). The character and severity of impacts depend not only on the hazards (e.g. changed climate averages and extremes) but also on the vulnerability (including sensitivities and adaptive capacities) of different communities and their exposure to climate threats. These impacts also affect a range of natural and human systems such as terrestrial, coastal and marine ecosystems and their services, agricultural production, infrastructure, the built environment, human health and other socio–economic systems (Rosenzweig et al., 2017).

Sensitivity to changing drivers varies markedly across systems and regions. Impacts of climate change on natural and managed ecosystems can imply loss or increase in growth, biomass or diversity at the level of species populations, interspecific relationships such as pollination, landscapes or entire biomes. Impacts occur in addition to the natural variation in growth, ecosystem dynamics, disturbance, succession and other processes, rendering attribution of impacts at lower levels of warming difficult in certain situations. The same magnitude of warming can be lethal during one phase of the life of an organism and irrelevant during another. Many ecosystems (notably forests, coral reefs and others) undergo long-term successional processes characterised by varying levels of resilience to environmental change over time. Organisms and ecosystems may adapt to environmental change to a certain degree, for example, through changes in physiology, ecosystem structure, species composition or evolution. Large-scale shifts in ecosystems may cause important feedbacks, for example, in terms of changing water and carbon fluxes through impacted ecosystems – these can amplify or dampen atmospheric change at regional to continental scale. For example, of particular concern, is the response of most of the world's forests and seagrass ecosystems, which play key roles as carbon sinks (Settele et al., 2014; Marbà et al., 2015).

Some ambitious efforts to constrain atmospheric greenhouse gas concentrations may themselves impact ecosystems. In particular, changes in land use, potentially required for massively enhanced production of biofuels (either as simple replacement of fossil fuels, or as part of Bioenergy with Carbon Capture and Storage, BECCS) impact all other land ecosystems through competition for land (e.g., Creutzig, 2016) (see Cross-Chapter Box 7 in Chapter 3, Section 3.6.2.1).

Human adaptive capacity to a 1.5°C warmer world varies markedly for individual sectors and across sectors such as water supply, public health, infrastructure, ecosystems and food supply. For example, density and risk exposure, infrastructure vulnerability and resilience, governance and institutional capacity all drive different impacts across a range of human settlement types (Dasgupta et al., 2014; Revi et al., 2014; Rosenzweig et al., 2018). Additionally, the adaptive capacity of communities and human settlements in both rural and urban areas, especially in highly populated regions, raises equity, social justice and sustainable development issues. Vulnerabilities due to gender, age, level of education and culture act as compounding factors (Arora-Jonsson, 2011; Cardona et al., 2012; Resurrección, 2013; Olsson et al., 2014; Vincent et al., 2014).

1.3.3 Uncertainty and non-linearity of impacts

Uncertainties in projections of future climate change and impacts come from a variety of different sources, including the assumptions made regarding future emission pathways (Moss et al., 2010), the inherent limitations and assumptions of the climate models used for the projections, including limitations in simulating regional climate variability (James et al., 2017), downscaling and bias-correction methods (Ekström et al., 2015), and in impact models (e.g., Asseng et al., 2013). The evolution of climate change also affects uncertainty with respect to impacts. For example, the impacts of overshooting 1.5°C and stabilization at a later stage, compared to stabilization at 1.5°C without overshoot may differ in magnitude (Schleussner et al., 2016).

AR5 IPCC (2013b) and World Bank (2013) underscored the non-linearity of risks and impacts as temperature rises from 2°C to 4°C of warming, particularly in relation to water availability, heat extremes, bleaching of coral reefs, and more. Recent studies (Schleussner et al., 2016; James et al., 2017; King et al., 2018) assess the impacts of 1.5°C versus 2°C warming, with the same message of non-linearity. The resilience of ecosystems, meaning their ability either to resist change or to recover after a disturbance, may change, and often decline, in a non-linear way. An example are reef ecosystems, with some studies suggesting that reefs will change, rather than disappear entirely, and particular species showing greater tolerance to coral bleaching than others (Pörtner et al., 2014). A key issue is therefore whether ecosystems such as coral reefs survive an overshoot scenario, and to what extent would they be able to recover after stabilization at 1.5°C or higher levels of warming (see Box 3.4).

1.4 Strengthening the global response

This section frames the implementation options, enabling conditions (discussed further in Cross-Chapter Box 3 on feasibility in this Chapter), capacities and types of knowledge and their availability (Blicharska et al., 2017) that can allow institutions, communities and societies to respond to the 1.5°C challenge in the context of sustainable development and the Sustainable Development Goals (SDGs). It also addresses other relevant international agreements such as the Sendai Framework for Disaster Risk Reduction. Equity and ethics are recognised as issues of importance in reducing vulnerability and eradicating poverty.

The connection between the enabling conditions for limiting global warming to 1.5°C and the ambitions of the SDGs are complex across scale and multifaceted (Chapter 5). Climate mitigation-adaptation linkages, including synergies and trade-offs, are important when considering opportunities and threats for sustainable development. The IPCC AR5 acknowledged that ‘adaptation and mitigation have the potential to both contribute to and impede sustainable development, and sustainable development strategies and choices have the potential to both contribute to and impede climate change responses’ (Denton et al., 2014). Climate mitigation and adaptation measures and actions can reflect and enforce specific patterns of development and governance that differ amongst the world’s regions (Gouldson et al., 2015; Termeer et al., 2017). The role of limited adaptation and mitigation capacity, limits to adaptation and mitigation, and conditions of mal-adaptation and mal-mitigation are assessed in this report (Chapters 4 and 5).

1.4.1 Classifying Response Options

Key broad categories of responses to the climate change problem are framed here. **Mitigation** refers to efforts to reduce or prevent the emission of greenhouse gases, or to enhance the absorption of gases already emitted, thus limiting the magnitude of future warming (IPCC, 2014c). Mitigation requires the use of new technologies, clean energy sources, reduced deforestation, improved sustainable agricultural methods, and changes in individual and collective behaviour. Many of these may provide substantial co-benefits for air quality, biodiversity and sustainable development. Mal-mitigation includes changes that could reduce emissions in the short-term but could lock in technology choices or practices that include significant trade-offs for effectiveness of future adaptation and other forms of mitigation (Chapters 2 and 4).

Carbon dioxide removal (CDR) or 'negative emissions' activities are considered a distinct type of mitigation. While most types of mitigation focus on reducing the amount of carbon dioxide or greenhouse gases emitted, CDR aims to reduce concentrations already in the atmosphere. Technologies for CDR are mostly in their infancy despite their importance to ambitious climate change mitigation pathways (Minx et al., 2017). Although some CDR activities such as reforestation and ecosystem restoration are well understood, the feasibility of massive-scale deployment of many CDR technologies remains an open question (IPCC, 2014d; Leung et al., 2014) (Chapters 2 and 4). Technologies for the active removal of other greenhouse gases, such as methane, are even less developed, and are briefly discussed in Chapter 4.

Climate change **adaptation** refers to the actions taken to manage the impacts of climate change (IPCC, 2014e). The aim is to reduce vulnerability and exposure to the harmful effects of climate change (e.g. sea–level rise, more intense extreme weather events or food insecurity). It also includes exploring the potential beneficial opportunities associated with climate change (for example, longer growing seasons or increased yields in some regions). Different adaptation-pathways can be undertaken. Adaptation can be incremental, or transformational, meaning fundamental attributes of the system are changed (Chapter 3 and 4). There can be limits to ecosystem-based adaptation or the ability of humans to adapt (Chapter 4). If there is no possibility for adaptive actions that can be applied to avoid an intolerable risk, these are referred to as hard adaptation limits, while soft adaptation limits are identified when there are currently no options to avoid intolerable risks, but they are theoretically possible (Chapter 3 and 4). While climate change is a global issue, impacts are experienced locally. Cities and municipalities are at the frontline of adaptation (Rosenzweig et al., 2018), focusing on reducing and managing disaster risks due to extreme and slow-onset weather and climate events, installing flood and drought early warning systems, and improving water storage and use (Chapters 3 and 4 and Cross-Chapter Box 12 in Chapter 5). Agricultural and rural areas, including often highly vulnerable remote and indigenous communities, also need to address climate-related risks by strengthening and making more resilient agricultural and other natural resource extraction systems.

Remedial measures are distinct from mitigation or adaptation, as the aim is to temporarily reduce or offset warming (IPCC, 2012b). One such measure is Solar Radiation Modification (SRM), also referred to as Solar Radiation Management in the literature, which involves deliberate changes to the albedo of the Earth system, with the net effect of increasing the amount of solar radiation reflected from the Earth to reduce the peak temperature from climate change (The Royal Society, 2009; Smith and Rasch, 2013; Schäfer et al., 2015). It should be noted that while some radiation modification measures, such as cirrus cloud thinning (Kristjánsson et al., 2016), aim at enhancing outgoing long-wave radiation, SRM is used in this report to refer to all direct interventions on the planetary radiation budget. This report does not use the term 'geo-engineering' because of inconsistencies in the literature, which uses this term to cover SRM, CDR or both, whereas this report explicitly differentiates between CDR and SRM. Large-scale SRM could potentially be used to supplement mitigation in overshoot scenarios to keep the global mean temperature below 1.5°C and temporarily reduce the severity of near-term impacts (e.g., MacMartin et al., 2018). The impacts of SRM (both biophysical and societal), costs, technical feasibility, governance and ethical issues associated need to be carefully considered (Schäfer et al., 2015; Section 4.3.8 and Cross-Chapter Box 10 in Chapter 4).

1.4.2 Governance, implementation and policies

A challenge in meeting the enabling conditions of 1.5°C warmer world is the governance capacity of institutions to develop, implement and evaluate the changes needed within diverse and highly interlinked global social-ecological systems (Busby, 2016) (Chapter 4). Policy arenas, governance structures and robust institutions are key enabling conditions for transformative climate action

(Chapter 4). It is through governance that justice, ethics and equity within the adaptation-mitigation-sustainable development nexus can be addressed (Stechow et al., 2016) (Chapter 5).

Governance capacity includes a wide range of activities and efforts needed by different actors to develop coordinated climate mitigation and adaptation strategies in the context of sustainable development taking into account equity, justice and poverty eradication. Significant governance challenges include the ability to incorporate multiple stakeholder perspectives in the decision-making process to reach meaningful and equitable decisions, interactions and coordination between different levels of government, and the capacity to raise financing and support for both technological and human resource development. For example, Lövbrand et al. (2017), argue that the voluntary pledges submitted by states and non-state actors to meet the conditions of the Paris Agreement will need to be more firmly coordinated, evaluated and upscaled.

Barriers for transitioning from climate change mitigation and adaptation planning to practical policy implementation include finance, information, technology, public attitudes, social values and practices (Whitmarsh et al., 2011; Corner and Clarke, 2017) and human resource constraints. Institutional capacity to deploy available knowledge and resources is also needed (Mimura et al., 2014). Incorporating strong linkages across sectors, devolution of power and resources to sub-national and local governments with the support of national government and facilitating partnerships among public, civic, private sectors and higher education institutions (Leal Filho et al., 2018) can help in the implementation of identified response options (Chapter 4). Implementation challenges of 1.5ºC pathways are larger than for those that are consistent with limiting warming to well below 2ºC, particularly concerning scale and speed of the transition and the distributional impacts on ecosystems and socio-economic actors. Uncertainties in climate change at different scales and different capacities to respond combined with the complexities of coupled social and ecological systems point to a need for diverse and adaptive implementation options within and among different regions involving different actors. The large regional diversity between highly carbon-invested economies and emerging economies are important considerations for sustainable development and equity in pursuing efforts to limit warming to 1.5°C. Key sectors, including energy, food systems, health, and water supply, also are critical to understanding these connections.

Cross-Chapter Box 3: Framing feasibility: Key concepts and conditions for limiting global temperature increases to 1.5°C

Contributing Authors: William Solecki (US), Anton Cartwright (South Africa), Wolfgang Cramer (France/Germany), James Ford (UK/Canada), Kejun Jiang (Chine), Joana Portugal Pereira (Portugal/UK), Joeri Rogelj (Austria/Belgium), Linda Steg (Netherlands), Henri Waisman (France)

This Cross-Chapter Box describes the concept of feasibility in relation to efforts to limit global warming to 1.5°C in the context of sustainable development and efforts to eradicate poverty and draws from the understanding of feasibility emerging within the IPCC (IPCC, 2017). Feasibility can be assessed in different ways, and no single answer exists as to the question of whether it is feasible to limit warming to 1.5°C. This implies that an assessment of feasibility would go beyond a 'yes' or a 'no'. Rather, feasibility provides a frame to understand the different conditions and potential responses for implementing adaptation and mitigation pathways, and options compatible with a 1.5°C warmer world. This report assesses the overall feasibility of a 1.5°C world, and the feasibility of adaptation and mitigation options compatible with a 1.5°C warmer world in six dimensions:

Geophysical: What global emission pathways could be consistent with conditions of a 1.5°C warmer world? What are the physical potentials for adaptation?

Environmental-ecological: What are the ecosystem services and resources, including geological storage capacity and related rate of needed land use change, available to promote transformations, and to what extent are they compatible with enhanced resilience?
Technological: What technologies are available to support transformation?
Economic: What economic conditions could support transformation?
Socio-cultural: What conditions could support transformations in behaviour and lifestyles? To what extent are the transformations socially acceptable and consistent with equity?
Institutional: What institutional conditions are in place to support transformations, including multi-level governance, institutional capacity, and political support?

The report starts by assessing which mitigation pathways would lead to a 1.5°C world, which indicates that rapid and deep deviations from current emission pathways are necessary (Chapter 2). In the case of adaptation, an assessment of feasibility starts from an evaluation of the risks and impacts of climate change (Chapter 3). To mitigate and adapt to climate risks, system-wide technical, institutional and socio-economic transitions would be required, as well as the implementation of a range of specific mitigation and adaptation options. Chapter 4 applies various indicators categorised in these six dimensions to assess the feasibility of illustrative examples of relevant mitigation and adaptation options (Section 4.5.1). Such options and pathways have different effects on sustainable development, poverty eradication and adaptation capacity (Chapter 5).

The six feasibility dimensions interact in complex, and place-specific ways. Synergies and trade-offs may occur between the feasibility dimensions, and between specific mitigation and adaptation options (Section 4.5.4). The presence or absence of enabling conditions would affect the options that comprise feasibility pathways (Section 4.4), and can reduce trade-offs and amplify synergies between options.

Sustainable development, eradicating poverty and reducing inequalities are not only preconditions for feasible transformations, but the interplay between climate action (both mitigation and adaptation options) and the development patterns on which they apply may actually enhance the feasibility of particular options (see Chapter 5).

The connections between the feasibility dimensions can be specified across three types of effects (discussed below). Each of these dimensions presents challenges and opportunities in realizing conditions consistent with a 1.5°C warmer world.

Systemic effects: Conditions that have embedded within them system level functions that could include linear and non-linear connections and feedbacks. For example, the deployment of technology and large installations (e.g., renewable or low carbon energy mega–projects) depends upon economic conditions (costs, capacity to mobilize investments for R&D), social or cultural conditions (acceptability), and institutional conditions (political support; e.g., Sovacool et al., 2015). Case studies can demonstrate system level interactions and positive or negative feedback effects between the different conditions (Jacobson et al., 2015; Loftus et al., 2015). This suggests that each set of conditions and their interactions need to be considered to understand synergies, inequities and unintended consequences.

Dynamic effects: Conditions that are highly dynamic and vary over time, especially under potential conditions of overshoot or no overshoot. Some dimensions might be more time sensitive or sequential than others (i.e., if conditions are such that it is no longer geophysically feasible to avoid overshooting 1.5°C, the social and institutional feasibility of avoiding overshoot will be no longer relevant). Path dependencies, risks of legacy locks-ins related to existing infrastructures, and possibilities of acceleration permitted by cumulative effects like learning-by-doing driving dramatic costs decreases are all key features to be captured. The effects can play out over various time scales and thus require understanding the connections between near-term (meaning within the next several years to two decades) and their long-term implications (meaning over the next several decades) when assessing feasibility conditions.

Spatial effects: Conditions that are spatially variable and scale dependent, according to context-specific factors such as regional-scale environmental resource limits and endowment; economic wealth of local populations; social organisation, cultural beliefs, values and worldviews; spatial organisation, including conditions of urbanisation; and financial and institutional and governance capacity. This means that the conditions for achieving the global transformation required for a 1.5°C world will be heterogeneous and vary according to the specific context. On the other hand, the satisfaction of these conditions may depend upon global-scale drivers, such as international flows of finance, technologies or capacities. This points to the need for understanding feasibility to capture the interplay between the conditions at different scales.

With each effect, the interplay between different conditions influences the feasibility of both pathways (Chapter 2) and options (Chapter 4), which in turn affect the likelihood of limiting warming to 1.5°C. The complexity of these interplays triggers unavoidable uncertainties, requiring transformations that remain robust under a range of possible futures that limit warming to 1.5°C.

1.4.3 Transformation, transformation pathways, and transition: evaluating trade-offs and synergies between mitigation, adaptation and sustainable development goals

Embedded in the goal of limiting warming to 1.5°C is the opportunity for intentional societal transformation (see Box 1.1 on the Anthropocene). The form and process of transformation are varied and multifaceted (Pelling, 2011; O'Brien et al., 2012; O'Brien and Selboe, 2015; Pelling et al., 2015). Fundamental elements of 1.5°C-related transformation include a decoupling of economic growth from energy demand and CO_2 emissions, leap-frogging development to new and emerging low-carbon, zero-carbon and carbon-negative technologies, and synergistically linking climate mitigation and adaptation to global scale trends (e.g., global trade and urbanization) that will enhance the prospects for effective climate action, as well as enhanced poverty reduction and greater equity (Tschakert et al., 2013; Rogelj et al., 2015; Patterson et al., 2017) (Chapters 4 and 5). The connection between transformative climate action and sustainable development illustrates a complex coupling of systems that have important spatial and time scale lag effects and implications for process and procedural equity including intergenerational equity and for non-human species (Cross-Chapter Box 4 in this Chapter, Chapter 5). Adaptation and mitigation transition pathways highlight the importance of cultural norms and values, sector specific context, and proximate (i.e. occurrence of an extreme event) drivers that when acting together enhance the conditions for societal transformation (Solecki et al., 2017; Rosenzweig et al., 2018) (Chapters 4 and 5).

Diversity and flexibility in implementation choices exist for adaptation, mitigation (including carbon dioxide removal, CDR) and remedial measures (such as solar radiation modification, SRM), and a potential for trade-offs and synergies between these choices and sustainable development (IPCC, 2014f; Olsson et al., 2014). The responses chosen could act to synergistically enhance mitigation, adaptation and sustainable development or they may result in trade-offs which positively impact some aspects and negatively impact others. Climate change is expected to increase the likelihood of not achieving the Sustainable Development Goals (SDGs), while some strategies limiting warming towards 1.5°C are expected to significantly lower that risk and provide synergies for climate adaptation and mitigation (Chapter 5).

Dramatic transformations required to achieve the enabling conditions for a 1.5°C warmer world could impose trade-offs on dimensions of development (IPCC, 2014f; Olsson et al., 2014). Some choices of adaptation methods also could adversely impact development (Olsson et al., 2014).This report recognizes the potential for adverse impacts and focuses on finding the synergies between limiting warming, sustainable development, and eradicating poverty, thus highlighting pathways that do not constrain other goals, such as sustainable development and eradicating poverty.

The report is framed to address these multiple goals simultaneously and assesses the conditions to achieve a cost-effective and socially acceptable solution, rather than addressing these goals piecemeal (Stechow et al., 2016) (Section 4.5.4 and Chapter 5), although there may be different synergies and trade-offs between a 2°C (Stechow et al., 2016) and 1.5°C warmer world (Kainuma et al., 2017). Climate-resilient development pathways (see Cross-Chapter Box 12 in Chapter 5 and Glossary) are trajectories that strengthen sustainable development, including mitigating and adapting to climate change and efforts to eradicate poverty while promoting fair and cross-scalar resilience in a changing climate. They take into account dynamic livelihoods, the multiple dimensions of poverty, structural inequalities, and equity between and among poor and non-poor people (Olsson et al., 2014). Climate-resilient development pathways can be considered at different scales, including cities, rural areas, regions or at global level (Denton et al., 2014; Chapter 5).

Cross-Chapter Box 4: Sustainable Development and the Sustainable Development Goals

Contributing Authors: Diana Liverman (US), Mustafa Babiker (Sudan), Purnamita Dasgupta (India), Riyanti Djanlante (Indonesia), Stephen Humphreys (UK/Ireland), Natalie Mahowald (US), Yacob Mulugetta (UK/Ethiopia), Virginia Villariño (Argentina), Henri Waisman (France)

Sustainable development is most often defined as ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’ (WCED, 1987) and includes balancing social wellbeing, economic prosperity and environmental protection. The AR5 used this definition and linked it to climate change (Denton et al., 2014). The most significant step since AR5 is the adoption of the UN Sustainable Development Goals, and the emergence of literature that links them to climate (von Stechow et al., 2015; Wright et al., 2015; Epstein et al., 2017; Hammill and Price-Kelly, 2017; Kelman, 2017; Lofts et al., 2017; Maupin, 2017; Gomez-Echeverri, 2018).

In September 2015, the UN endorsed a universal agenda – ‘Transforming our World: the 2030 Agenda for Sustainable Development’ – which aims ‘to take the bold and transformative steps which are urgently needed to shift the world onto a sustainable and resilient path’. Based on a participatory process, the resolution in support of the 2030 agenda adopted 17 non-legally-binding Sustainable Development Goals (SDGs) and 169 targets to support people, prosperity, peace, partnerships and the planet (Kanie and Biermann, 2017).

The SDGs expanded efforts to reduce poverty and other deprivations under the UN Millennium Development Goals (MDGs). There were improvements under the MDGs between 1990 and 2015, including reducing overall poverty and hunger, reducing infant mortality, and improving access to drinking water (United Nations, 2015). However, greenhouse gas emissions increased by more than 50% from 1990 to 2015, and 1.6 billion people were still living in multidimensional poverty with persistent inequalities in 2015 (Alkire et al., 2015).

The SDGs raise the ambition for eliminating poverty, hunger, inequality and other societal problems while protecting the environment. They have been criticised: as too many and too complex, needing more realistic targets, overly focused on 2030 at the expense of longer term objectives, not embracing all aspects of sustainable development, and even contradicting each other (Horton, 2014; Death and Gabay, 2015; Biermann et al., 2017; Weber, 2017; Winkler and Satterthwaite, 2017).

Climate change is an integral influence on sustainable development, closely related to the economic, social and environmental dimensions of the SDGs. The IPCC has woven the concept of sustainable development into recent assessments, showing how climate change might undermine sustainable development, and the synergies between sustainable development and responses to climate change (Denton et al., 2014). Climate change is also explicit in the SDGs. SDG13 specifically requires 'urgent action to address climate change and its impacts'. The targets include strengthening resilience and adaptive capacity to climate-related hazards and natural disasters; integrating climate change measures into national policies, strategies and planning; and improving education, awareness-raising and human and institutional capacity.

Targets also include implementing the commitment undertaken by developed-country parties to the UNFCCC to the goal of mobilizing jointly $100 billion annually by 2020 and operationalizing the Green Climate Fund, as well as promoting mechanisms for raising capacity for effective climate change-related planning and management in least developed countries and Small Island Developing States, including focusing on women, youth and local and marginalised communities. SDG13 also acknowledges that the United Nations Framework Convention on Climate Change (UNFCCC) is the primary international, intergovernmental forum for negotiating the global response to climate change.

Climate change is also mentioned in SDGs beyond SDG13, for example in goal targets 1.5, 2.4, 11.B, 12.8.1 related to poverty, hunger, cities and education respectively. The UNFCCC addresses other SDGs in commitments to 'control, reduce or prevent anthropogenic emissions of greenhouse gases […] in all relevant sectors, including the energy, transport, industry, agriculture, forestry and waste management sectors' (Art4, 1(c)) and to work towards 'the conservation and enhancement, as appropriate, of […] biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems' (Art4, 1(d)). This corresponds to SDGs that seek clean energy for all (Goal 7), sustainable industry (Goal 9) and cities (Goal 11) and the protection of life on land and below water (14 and 15).

The SDGs and UNFCCC also differ in their time horizons. The SDGs focus primarily on 2030 whereas the Paris Agreement sets out that 'Parties aim […] to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century'.

The IPCC decision to prepare this report of the impacts of 1.5°C and associated emission pathways explicitly asked for the assessment to be in the context of sustainable development and efforts to eradicate poverty. Chapter 1 frames the interaction between sustainable development, poverty eradication and ethics and equity. Chapter 2 assesses how risks and synergies of individual mitigation measures interact with1.5°C pathways within the context of the SDGs, and how these vary according to the mix of measures in alternative mitigation portfolios (Section 2.5). Chapter 3 examines the impacts of 1.5°C global warming on natural and human systems with comparison to 2°C and provides the basis for considering the interactions of climate change with sustainable development in Chapter 5. Chapter 4 analyses strategies for strengthening the response to climate change, many of which interact with sustainable development. Chapter 5 takes sustainable development, eradicating poverty and reducing inequalities as its focal point for the analysis of pathways to 1.5°C, and discusses explicitly the linkages between achieving SDGs while eradicating poverty and reducing inequality.

Cross-Chapter Box 4, Figure 1: Climate action is number 13 of the UN Sustainable Development Goals.

1.5 Assessment frameworks and emerging methodologies that integrate climate change mitigation and adaptation with sustainable development

This report employs information and data that are global in scope and include region-scale analysis. It also includes syntheses of municipal, sub-national, and national case studies. Global level statistics including physical and social science data are used, as well as detailed and illustrative case study material of particular conditions and contexts. The assessment provides the state of knowledge, including an assessment of confidence and uncertainty. The main timescale of the assessment is the 21st century and the time is separated into the near-, medium-, and long-term. Spatial and temporal contexts are illustrated throughout including: assessment tools that include dynamic projections of emission trajectories and the underlying energy and land transformation (Chapter 2); methods for assessing observed impacts and projected risks in natural and managed ecosystems and at 1.5°C and higher levels of warming in natural and managed ecosystems and human systems (Chapter 3); assess the feasibility of mitigation and adaptation options (Chapter 4); and linkages of the Shared Socioeconomic Pathways (SSPs) and Sustainable Development Goals (SDGs) (Cross-Chapter Boxes 1 and 4 in this Chapter, Chapter 2 and Chapter 5).

1.5.1 Knowledge sources and evidence used in the report

This report is based on a comprehensive assessment of documented evidence of the enabling conditions to pursuing efforts to limit the global average temperature to 1.5°C and adapt to this level of warming in the overarching context of the Anthropocene (Delanty and Mota, 2017). Two sources of evidence are used; peer-reviewed scientific literature and 'grey' literature in accordance with procedure on the use of literature in IPCC reports (IPCC, 2013a, Annex 2 to Appendix A), with the former being the dominant source. Grey literature is largely used on key issues not covered in peer-reviewed literature.

The peer-reviewed literature includes the following sources: 1) knowledge regarding the physical climate system and human-induced changes, associated impacts, vulnerabilities and adaptation options, established from work based on empirical evidence, simulations, modelling and scenarios, with emphasis on new information since the publication of the IPCC AR5 to the cut-off date for this report (15th of May 2018); 2) Humanities and social science theory and knowledge from actual human experiences of climate change risks and vulnerability in the context of the social-ecological systems, development, equity, justice, and the role of governance, and from indigenous knowledge systems; and 3) Mitigation pathways based on climate projections into the future.

The grey literature category extends to empirical observations, interviews, and reports from government, industry, research institutes, conference proceedings and international or other organisations. Incorporating knowledge from different sources, settings and information channels while building awareness at various levels will advance decision making and motivate implementation of context specific responses to 1.5°C warming (Somanathan et al., 2014). The assessment does not assess non–written evidence and does not use oral evidence, media reports, or newspaper publications. With important exceptions, such as China, published knowledge from the most vulnerable parts of the world to climate change is limited (Czerniewicz et al., 2017).

1.5.2 Assessment frameworks and methodologies

Climate models and associated simulations

The multiple sources of climate model information used in this assessment are provided in Chapter 2 (Section 2.2) and Chapter 3 (Section 3.2). Results from global simulations, which have also been assessed in previous IPCC reports and that are conducted as part of the World Climate Research Programme (WCRP) Coupled Models Inter-comparison Project (CMIP) are used. The IPCC AR4 and Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) reports were mostly based on simulations from the CMIP3 experiment, while the AR5 was mostly based on simulations from the CMIP5 experiment. The simulations of the CMIP3 and CMIP5 experiments were found to be very similar (e.g.; Knutti and Sedláček, 2012; Mueller and Seneviratne, 2014). In addition to the CMIP3 and CMIP5 experiments, results from coordinated regional climate model experiments (e.g.; the Coordinated Regional Climate Downscaling Experiment, CORDEX) have been assessed, which are available for different regions (Giorgi and Gutowski, 2015). For instance, assessments based on publications from an extension of the IMPACT2C project (Vautard et al., 2014; Jacob and Solman, 2017) are newly available for 1.5°C projections. Recently, simulations from the ‘Half a degree Additional warming, Prognosis and Projected Impacts’ (HAPPI) multi-model experiment have been performed to specifically assess climate changes at 1.5°C vs 2°C global warming (Mitchell et al., 2016). The HAPPI protocol consists of coupled land-atmosphere initial condition ensemble simulations with prescribed sea surface temperatures (SSTs), sea-ice, GHG and aerosol concentrations, solar and volcanic activity that coincide with three forced climate states: present-day (2006–2015) (see section 1.2.1), and future (2091–2100) either with 1.5°C or 2°C global warming (prescribed by modified SSTs).

Detection and attribution of change in climate and impacted systems

Formalized scientific methods are available to detect and attribute impacts of greenhouse gas forcing on observed changes in climate (e.g. Hegerl et al., 2007; Seneviratne et al., 2012; Bindoff et al., 2013) and impacts of climate change on natural and human systems (e.g. Stone et al., 2013; Hansen and Cramer, 2015; Hansen et al., 2016). The reader is referred to these sources, as well as to the AR5 for more background on these methods.

Global climate warming has already reached approximately 1°C (see Section 1.2.1) relative to pre–industrial conditions, and thus ‘climate at 1.5°C global warming’ corresponds to approximately the addition of only half a degree of warming compared to the present day, comparable to the warming that has occurred since the 1970s (Bindoff et al., 2013). Methods used in the attribution of observed changes associate with this recent warming are therefore also applicable to assessments of future changes in climate at 1.5°C warming, especially in cases where no climate model simulations or analyses are available.

Impacts of 1.5°C global warming can be assessed in part from regional and global climate changes that have already been detected and attributed to human influence (e.g., Schleussner et al., 2017) and are components of the climate system that are most responsive to current and projected future forcing. For this reason, when specific projections are missing for 1.5°C global warming, some of the assessments of climate change provided in Chapter 3 (Section 3.3) build upon joint assessments of a) changes that were observed and attributed to human influence up to the present, i.e. for 1°C global warming and b) projections for higher levels of warming (e.g., 2°C, 3°C or 4°C) to assess the changes at 1.5°C. Such assessments are for transient changes only (see Chapter 3, Section 3.3).

Besides quantitative detection and attribution methods, assessments can also be based on indigenous and local knowledge (see Chapter 4, Box 4.3). While climate observations may not be available to assess impacts from a scientific perspective, local community knowledge can also indicate actual impacts (Brinkman et al., 2016; Kabir et al., 2016). The challenge is that a community’s perception of loss due to the impacts of climate change is an area that requires further research (Tschakert et al., 2017).

Costs and benefits analysis

Cost-benefit analyses are common tools used for decision-making, whereby the costs of impacts are compared to the benefits from different response actions (IPCC, 2014d, e). However, for the case of climate change, recognising the complex inter-linkages of the Anthropocene, cost-benefit analyses tools can be difficult to use because of disparate impacts versus costs and complex interconnectivity within the global social-ecological system (see Box 1.1 and Cross-Chapter Box 5 in Chapter 2). Some costs are relatively easily quantifiable in monetary terms but not all. Climate change impacts humans' lives and livelihoods, culture and values and whole ecosystem. It has unpredictable feedback loops and impacts on other regions, (IPCC, 2014e) giving rise to indirect, secondary, tertiary and opportunity costs that are typically extremely difficult to quantify. Monetary quantification is further complicated by the fact that costs and benefits can occur in different regions at very different times, possibly spanning centuries, while it is extremely difficult if not impossible to meaningfully estimate discount rates for future costs and benefits. Thus standard cost–benefit analyses become difficult to justify (IPCC, 2014e; Dietz et al., 2016) and are not used as an assessment tool in this report.

1.6 Confidence, uncertainty and risk

This report relies on the IPCC’s uncertainty guidance provided in Mastrandrea et al. (2011), and sources given therein. Two metrics for qualifying key findings are used:

Confidence: Five qualifiers are used to express levels of confidence in key findings, ranging from *very low*, through *low*, *medium*, *high*, to *very high*. The assessment of confidence involves at least two dimensions, one being the type, quality, amount or internal consistency of individual lines of evidence, and the second being the level of agreement between different lines of evidence. Very high confidence findings must either be supported by a high level of agreement across multiple lines of mutually independent and individually robust lines of evidence or, if only a single line of evidence is available, by a very high level of understanding underlying that evidence. Findings of low or very low confidence are presented only if they address a topic of major concern.

Likelihood: A calibrated language scale is used to communicate assessed probabilities of outcomes, ranging from *exceptionally unlikely* (<1%), *extremely unlikely* (<5%), *very unlikely* (<10%), *unlikely* (<33%), *about as likely as not* (33–66%), *likely* (>66%), *very likely* (>90%), *extremely likely* (>95%)

to *virtually certain* (>99%). These terms are normally only applied to findings associated with high or very high confidence. Frequency of occurrence within a model ensemble does not correspond to actual assessed probability of outcome unless the ensemble is judged to capture and represent the full range of relevant uncertainties.

Three specific challenges arise in the treatment of uncertainty and risk in this report. First, the current state of the scientific literature on 1.5°C means that findings based on multiple lines of robust evidence for which quantitative probabilistic results can be expressed may be few, and not the most policy-relevant. Hence many key findings are expressed using confidence qualifiers alone.

Second, many of the most important findings of this report are conditional because they refer to ambitious mitigation scenarios. Conditional probabilities often depend strongly on how conditions are specified, such as whether temperature goals are met through early emission reductions, reliance on negative emissions, or through a low climate response. Whether a certain risk is deemed likely at 1.5°C may therefore depend strongly on how 1.5°C is specified, whereas a statement that a certain risk may be substantially higher at 2°C relative to 1.5°C may be much more robust.

Third, achieving ambitious mitigation goals will require active, goal-directed efforts aiming explicitly for specific outcomes and incorporating new information as it becomes available (Otto et al., 2015). This shifts the focus of uncertainty from the climate outcome itself to the level of mitigation effort that may be required to achieve it. Probabilistic statements about human decisions are always problematic, but in the context of robust decision-making, many near-term policies that are needed to keep open the option of achieving 1.5°C may be the same, regardless of the actual probability that the goal will be met (Knutti et al., 2015).

1.7 Storyline of the report

The storyline of this report (Figure 1.6) includes a set of interconnected components. The report consists of five chapters, a Technical Summary and a Summary for Policymakers. It also includes a set of boxes to elucidate specific or cross-cutting themes, as well as Frequently Asked Questions for each chapter and a Glossary.

At a time of unequivocal and rapid global warming, this report emerges from the long-term temperature goal of the Paris Agreement; strengthening the global response to the threat of climate change by pursuing efforts to limit warming to 1.5°C through reducing emissions to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases. The assessment focuses first, in Chapter 1, on how 1.5°C is defined and understood, what is the current level of warming to date, and the present trajectory of change. The framing presented in Chapter 1 provides the basis through which to understand the enabling conditions of a 1.5°C warmer world and connections to the SDGs, poverty eradication, and equity and ethics.

In Chapter 2, scenarios of a 1.5°C warmer world and the associated pathways are assessed. The pathways assessment builds upon the AR5 with a greater emphasis on sustainable development in mitigation pathways. All pathways begin now, and involve rapid and unprecedented societal transformation. An important framing device for this report is the recognition that choices that determine emissions pathways, whether ambitious mitigation or ‘no policy’ scenarios, do not occur independently of these other changes and are, in fact, highly interdependent.

Projected impacts that emerge in a 1.5°C warmer world and beyond are dominant narrative threads of the report and are assessed in Chapter 3. The chapter focuses on observed and attributable global and regional climate changes and impacts and vulnerabilities. The projected impacts have diverse and uneven spatial, temporal, and human, economic, and ecological system-level manifestations. Central to the assessment is the reporting of impacts at 1.5°C and 2°C, potential impacts avoided through limiting warming to 1.5°C, and, where possible, adaptation potential and limits to adaptive capacity.

Response options and associated enabling conditions emerge next, in Chapter 4. Attention is directed to exploring questions of adaptation and mitigation implementation and integration and transformation in a highly interdependent world, with consideration of synergies and trade-offs. Emission pathways, in particular, are broken down into policy options and instruments. The role of technological choices, institutional capacity and large-scale global scale trends like urbanization and changes in ecosystems are assessed.

Chapter 5 covers linkages between achieving the SDGs and a 1.5°C warmer world and turns toward identifying opportunities and challenges of transformation. This is assessed within a transition to climate-resilient development pathways, and connection between the evolution towards 1.5°C, associated impacts, and emission pathways. Positive and negative effects of adaptation and mitigation response measures and pathways for a 1.5°C warmer world are examined. Progress along these pathways involves inclusive processes, institutional integration, adequate finance and technology, and attention to issues of power, values, and inequalities to maximize the benefits of pursuing climate stabilisation at 1.5°C and the goals of sustainable development at multiple scales of human and natural systems from global, regional, national to local and community levels.

Figure 1.6: Schematic of report storyline.

Frequently Asked Questions

FAQ 1.1: Why are we talking about 1.5°C?

Summary: Climate change represents an urgent and potentially irreversible threat to human societies and the planet. In recognition of this, the overwhelming majority of countries around the world adopted the Paris Agreement in December 2015, the central aim of which includes pursuing efforts to limit global temperature rise to 1.5°C. In doing so, these countries, through the United Nations Framework Convention on Climate Change (UNFCCC) also invited the IPCC to provide a Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emissions pathways.

At the 21st Conference of the Parties (COP21) in December 2015, 195 nations adopted the Paris Agreement[2]. The first instrument of its kind, the landmark agreement includes the aim to strengthen the global response to the threat of climate change by 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels'.

The first UNFCCC document to mention a limit to global warming of 1.5°C was the Cancun Agreement, adopted at the sixteenth COP (COP16) in 2010. The Cancun Agreement established a process to periodically review the 'adequacy of the long-term global goal (LTGG) in the light of the ultimate objective of the Convention and the overall progress made towards achieving the LTGG, including a consideration of the implementation of the commitments under the Convention'. The definition of LTGG in the Cancun Agreement was 'to hold the increase in global average temperature below 2°C above pre-industrial levels'. The agreement also recognised the need to consider 'strengthening the long term global goal on the basis of the best available scientific knowledge… to a global average temperature rise of 1.5°C'.

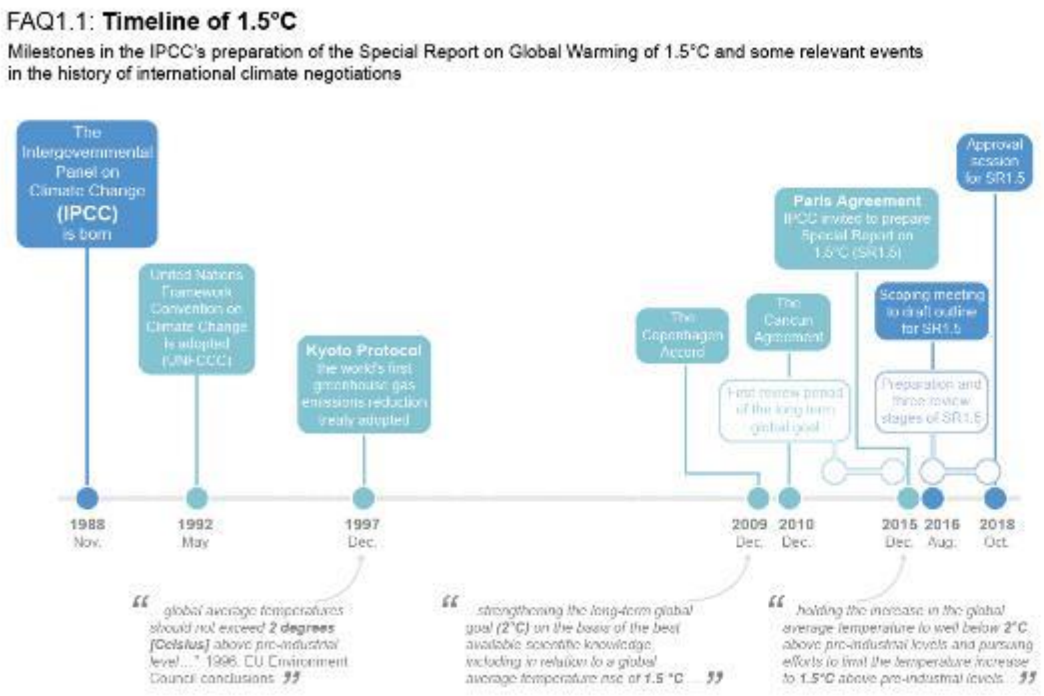
Beginning in 2013 and ending at the COP21 in Paris in 2015, the first review period of the long term global goal largely consisted of the Structured Expert Dialogue (SED). This was a fact-finding, face-to-face exchange of views between invited experts and UNFCCC delegates. The final report of the SED[3] concluded that 'in some regions and vulnerable ecosystems, high risks are projected even for warming above 1.5°C'. The SED report also suggested that Parties would profit from restating the temperature limit of the long-term global goal as a 'defence line' or 'buffer zone', instead of a 'guardrail' up to which all would be safe, adding that this new understanding would 'probably also favour emission pathways that will limit warming to a range of temperatures below 2°C'. Specifically on strengthening the temperature limit of 2°C, the SED's key message was: 'While science on the 1.5°C warming limit is less robust, efforts should be made to push the defence line as low as possible'. The findings of the SED, in turn, fed into the draft decision adopted at COP21.

With the adoption of the Paris Agreement, the UNFCCC invited the IPCC to provide a Special Report in 2018 on 'the impacts of global warming of 1.5°C above pre–industrial levels and related global greenhouse gas emissions pathways'. The request was that the report, known as SR1.5, should not only assess what a 1.5°C warmer world would look like but also the different pathways by which global temperature rise could be limited to 1.5°C. In 2016, the IPCC accepted the invitation, adding that the Special Report would also look at these issues in the context of strengthening the global response to the threat of climate change, sustainable development and efforts to eradicate poverty.

---

[2] FOOTNOTE: Paris Agreement FCCC/CP/2015/10/Add.1 https://unfccc.int/documents/9097
[3] FOOTNOTE: Structured Expert Dialogue (SED) final report FCCC/SB/2015/INF.1 https://unfccc.int/documents/8707

The combination of rising exposure to climate change and the fact that there is a limited capacity to adapt to its impacts amplifies the risks posed by warming of 1.5°C and 2°C. This is particularly true for developing and island countries in the tropics and other vulnerable countries and areas. The risks posed by global warming of 1.5°C are greater than for present day conditions but lower than at 2°C.



FAQ1.1, Figure 1: A timeline of notable dates in preparing the IPCC Special Report on Global Warming of 1.5°C (blue) embedded within processes and milestones of the United Nations Framework Convention on Climate Change (UNFCCC; grey), including events that may be relevant for discussion of temperature limits.

FAQ 1.2: How close are we to 1.5°C?

Summary: *Human-induced warming has already reached about 1°C above pre-industrial levels at the time of writing of this Special Report. By the decade 2006–2015, human activity had warmed the world by 0.87°C (±0.12°C) compared pre-industrial times (1850–1900). If the current warming rate continues, the world would reach human–induced global warming of 1.5°C around 2040.*

Under the 2015 Paris Agreement, countries agreed to cut greenhouse gas emissions with a view to 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels'. While the overall intention of strengthening the global response to climate change is clear, the Paris Agreement does not specify precisely what is meant by 'global average temperature', or what period in history should be considered 'pre-industrial'. To answer the question of how close are we to 1.5°C of warming, we need to first be clear about how both terms are defined in this Special Report.

The choice of pre-industrial reference period, along with the method used to calculate global average temperature, can alter scientists' estimates of historical warming by a couple of tenths of a degree Celsius. Such differences become important in the context of a global temperature limit just half a degree above where we are now. But provided consistent definitions are used, they do not affect our understanding of how human activity is influencing the climate.

In principle, 'pre-industrial levels' could refer to any period of time before the start of the industrial revolution. But the number of direct temperature measurements decreases as we go back in time. Defining a 'pre-industrial' reference period is, therefore, a compromise between the reliability of the temperature information and how representative it is of truly pre-industrial conditions. Some pre-industrial periods are cooler than others for purely natural reasons. This could be because of spontaneous climate variability or the response of the climate to natural perturbations, such as volcanic eruptions and variations in the sun's activity. This IPCC Special Report on Global Warming of 1.5°C uses the reference period 1850 to 1900 to represent pre-industrial conditions. This is the earliest period with near-global observations and is the reference period used as an approximation of pre-industrial temperatures in the IPCC Fifth Assessment Report.

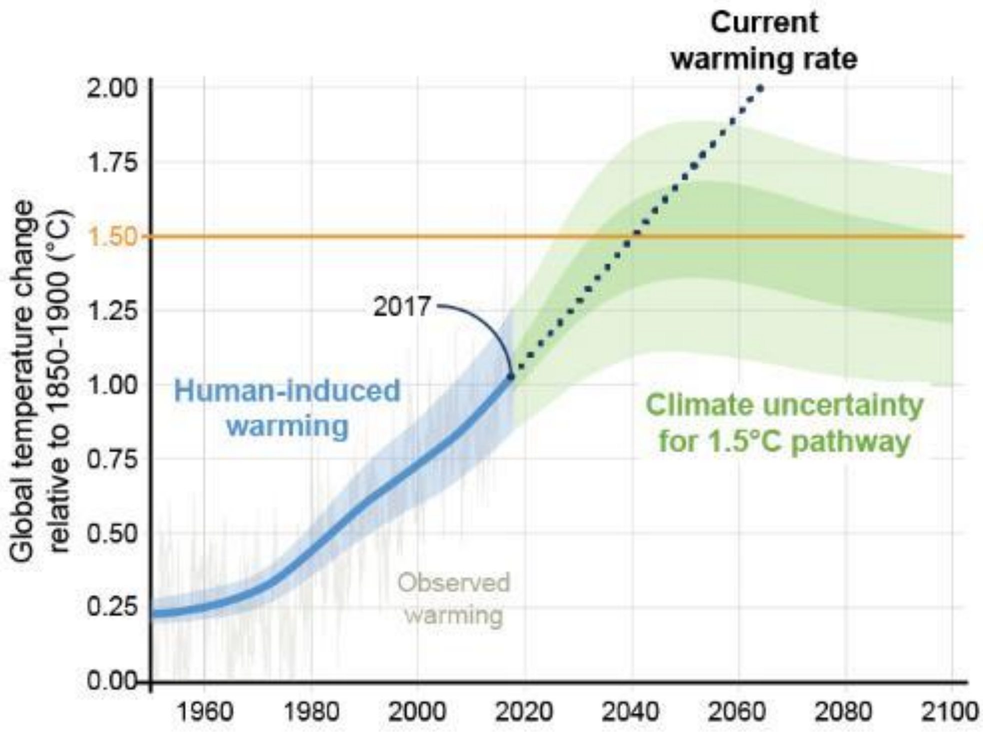
Once scientists have defined 'pre-industrial', the next step is to calculate the amount of warming at any given time relative to that reference period. In this report, warming is defined as the increase in the 30-year global average of combined temperature over land and at the ocean surface. The 30-year timespan accounts for the effect of natural variability, which can cause global temperatures to fluctuate from one year to the next. For example, 2015 and 2016 were both affected by a strong El Niño event, which amplified the underlying human-caused warming.

In the decade 2006–2015, warming reached 0.87°C (±0.12°C) relative to 1850–1900, predominantly due to human activity increasing the amount of greenhouse gases in the atmosphere. Given that global temperature is currently rising by 0.2°C (±0.1°C) per decade, human–induced warming reached 1°C above pre-industrial levels around 2017 and, if this pace of warming continues, would reach 1.5°C around 2040.

While the change in global average temperature tells researchers about how the planet as a whole is changing, looking more closely at specific regions, countries and seasons reveals important details. Since the 1970s, most land regions have been warming faster than the global average, for example. This means that warming in many regions has already exceeded 1.5°C above pre-industrial levels. Over a fifth of the global population live in regions that have already experienced warming in at least one season that is greater than 1.5°C above pre-industrial levels.

FAQ1.2: How close are we to 1.5°C?

Human-induced warming reached approximately 1°C above pre-industrial levels in 2017



FAQ1.2, Figure 1: Human-induced warming reached approximately 1°C above pre-industrial levels in 2017. At the present rate, global temperatures would reach 1.5°C around 2040.

References

Aaheim, A., T. Wei, and B. Romstad, 2017: Conflicts of economic interests by limiting global warming to +3 °C. *Mitigation and Adaptation Strategies for Global Change*, **22(8)**, 1131-1148, doi:10.1007/s11027-016-9718-8.

Adger, W.N. et al., 2014: Human Security. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 755-791.

AghaKouchak, A., L. Cheng, O. Mazdiyasni, and A. Farahmand, 2014: Global warming and changes in risk of concurrent climate extremes: Insights from the 2014 California drought. *Geophysical Research Letters*, **41(24)**, 8847-8852, doi:10.1002/2014GL062308.

Ajibade, I., 2016: Distributive justice and human rights in climate policy: the long road to Paris. *Journal of Sustainable Development Law and Policy (The)*, **7(2)**, 65, doi:10.4314/jsdlp.v7i2.4.

Albert, S. et al., 2017: Heading for the hills: climate-driven community relocations in the Solomon Islands and Alaska provide insight for a 1.5 °C future. *Regional Environmental Change*, 1-12, doi:10.1007/s10113-017-1256-8.

Alkire, S., C. Jindra, G. Robles Aguilar, S. Seth, and A. Vaz, 2015: Multidimensional poverty index. *OPHI Briefing 42*.

Allen, M.R. and T.F. Stocker, 2013: Impact of delay in reducing carbon dioxide emissions. *Nature Climate Change*, **4(1)**, 23-26, doi:10.1038/nclimate2077.

Allen, M.R. et al., 2016: New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nature Climate Change*, **6(May)**, 1-5, doi:10.1038/nclimate2998.

Allen, M.R. et al., 2018: A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *npj Climate and Atmospheric Science* (in press).

Archer, D. and V. Brovkin, 2008: The millennial atmospheric lifetime of anthropogenic CO_2. *Climatic Change*, **90(3)**, 283-297, doi:10.1007/s10584-008-9413-1.

Arora-Jonsson, S., 2011: Virtue and vulnerability: Discourses on women, gender and climate change. *Global Environmental Change*, **21(2)**, 744-751, doi:10.1016/j.gloenvcha.2011.01.005.

Asseng, S. et al., 2013: Uncertainty in simulating wheat yields under climate change. *Nature Climate Change*, **3(9)**, 827-832, doi:10.1038/nclimate1916.

Bäckstrand, K., J.W. Kuyper, B.O. Linnér, and E. Lövbrand, 2017: Non-state actors in global climate governance: from Copenhagen to Paris and beyond. *Environmental Politics*, **26(4)**, 561-579, doi:10.1080/09644016.2017.1327485.

Baker, H.S. et al., 2018: Higher CO_2 concentrations increase extreme event risk in a 1.5°C world. *Nature Climate Change* (in press).

Barnett, J. et al., 2014: A local coastal adaptation pathway. *Nature Climate Change*, **4(12)**, 1103-1108, doi:10.1038/nclimate2383.

Bauer, N. et al., 2017: Shared Socio-Economic Pathways of the Energy Sector - Quantifying the Narratives. *Global Environmental Change*, **42**, 316-330, doi:10.1016/j.gloenvcha.2016.07.006.

Bereiter, B. et al., 2015: Revision of the EPICA Dome C CO_2 record from 800 to 600-kyr before present. *Geophysical Research Letters*, **42(2)**, 542-549, doi:10.1002/2014GL061957.

Bethke, I. et al., 2017: Potential volcanic impacts on future climate variability. *Nature Climate Change*, **7(11)**, 799-805, doi:10.1038/nclimate3394.

Biermann, F., N. Kanie, and R.E. Kim, 2017: Global governance by goal-setting: the novel approach of the UN Sustainable Development Goals. *Current Opinion in Environmental Sustainability*, **26-27**, 26-31, doi:10.1016/j.cosust.2017.01.010.

Biermann, F. et al., 2016: Down to Earth: Contextualizing the Anthropocene. *Global Environmental Change*, **39**, 341-350, doi:10.1016/j.gloenvcha.2015.11.004.

Bindoff, N.L. et al., 2007: Observations: Oceanic Climate Change and Sea Level. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*.

Bindoff, N.L. et al., 2013: Detection and Attribution of Climate Change: from Global to Regional. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge

University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 426-488.
Birkmann, J., T. Welle, W. Solecki, S. Lwasa, and M. Garschagen, 2016: Boost resilience of small and mid-sized cities. *Nature*, **537(7622)**, 605-608, doi:10.1038/537605a.
Blicharska, M. et al., 2017: Steps to overcome the North-South divide in research relevant to climate change policy and practice. *Nature Climate Change*, **7(1)**, 21-27, doi:10.1038/nclimate3163.
Bodansky, D., J. Brunnée, and L. Rajamani, 2017: *International Climate Change Law*. Oxford University Press, 416 pp.
Bowerman, N.H.A., D.J. Frame, C. Huntingford, J.A. Lowe, and M.R. Allen, 2011: Cumulative carbon emissions, emissions floors and short-term rates of warming: implications for policy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **369(1934)**, 45-66, doi:10.1098/rsta.2010.0288.
Bowerman, N.H.A. et al., 2013: The role of short-lived climate pollutants in meeting temperature goals. *Nature Climate Change*, **3(12)**, 1021-1024, doi:10.1038/nclimate2034.
Brinkman, T.J. et al., 2016: Arctic communities perceive climate impacts on access as a critical challenge to availability of subsistence resources. *Climatic Change*, **139(3-4)**, 413-427, doi:10.1007/s10584-016-1819-6.
Brondizio, E.S. et al., 2016: Re-conceptualizing the Anthropocene: A call for collaboration. *Global Environmental Change*, **39**, 318-327, doi:10.1016/j.gloenvcha.2016.02.006.
Busby, J., 2016: After Paris: Good enough climate governance. *Current History*, **15(777)**, 3-9.
Caney, S., 2005: Cosmopolitan Justice, Responsibility, and Global Climate Change. *Leiden Journal of International Law*, **18(04)**, 747-75, doi:10.1017/S0922156505002992.
Caney, S., 2010: Climate change and the duties of the advantaged. *Critical Review of International Social and Political Philosophy*, **13(1)**, 203-228, doi:10.1080/13698230903326331.
Cardona, O.D. et al., 2012: Determinants of Risk: Exposure and Vulnerablity. In: *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 (IPCC)* [Field, C.B., V.R. 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, United Kingdom and New York, NY, USA, pp. 65-108.
Chen, X. et al., 2017: The increasing rate of global mean sea-level rise during 1993-2014. *Nature Climate Change*, **7(7)**, 492-495, doi:10.1038/nclimate3325.
Christensen, J.H. et al., 2013: Climate Phenomena and their Relevance for Future Regional Climate Change Supplementary Material. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 62.
Clarke, L.E. et al., 2014: Assessing transformation pathways. 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, United Kingdom and New York, NY, USA, pp. 413-510.
Collins, M. et al., 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. pp. 1029-1136.
Corner, A. and J. Clarke, 2017: *Talking Climate - From Research to Practice in Public Engagement*. Palgrave Macmillan, Oxford, UK, 146 pp.
Cowtan, K. and R.G. Way, 2014: Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. *Quarterly Journal of the Royal Meteorological Society*, **140(683)**, 1935-1944, doi:10.1002/qj.2297.
Cowtan, K. et al., 2015: Robust comparison of climate models with observations using blended land air and ocean sea surface temperatures. *Geophysical Research Letters*, **42(15)**, 6526-6534, doi:10.1002/2015GL064888.
Cramer, W. et al., 2014: Detection and attribution of observed impacts. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada,

R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, pp. 979-1037.

Creutzig, F., 2016: Economic and ecological views on climate change mitigation with bioenergy and negative emissions. *GCB Bioenergy*, **8(1)**, 4-10, doi:10.1111/gcbb.12235.

Crutzen, P.J., 2002: Geology of mankind. *Nature*, **415(6867)**, 23, doi:10.1038/415023a.

Crutzen, P.J. and E.F. Stoermer, 2000: The Anthropocene. *Global Change Newsletter*, **41**, 17-18.

Czerniewicz, L., S. Goodier, and R. Morrell, 2017: Southern knowledge online? Climate change research discoverability and communication practices.. *Information, Communication & Society*, **20(3)**, 386-405, doi:10.1080/1369118X.2016.1168473.

Dasgupta, P. et al., 2014: Rural areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 613-657.

Death, C. and C. Gabay, 2015: Doing biopolitics differently? Radical potential in the post-2015 MDG and SDG debates. *Globalizations*, **12(4)**, 597-612, doi:10.1080/14747731.2015.1033172.

Delanty, G. and A. Mota, 2017: Governing the Anthropocene. *European Journal of Social Theory*, **20(1)**, 9-38, doi:10.1177/1368431016668535.

Denton, F. et al., 2014: Climate-Resilient Pathways: Adaptation, Mitigation, and Sustainable Development. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1101-1131.

Deser, C., R. Knutti, S. Solomon, and A.S. Phillips, 2012: Communication of the Role of Natural Variability in Future North American Climate. *Nature Climate Change*, **2(11)**, 775-779, doi:10.1038/nclimate1562.

Deuber, O., G. Luderer, and O. Edenhofer, 2013: Physico-economic evaluation of climate metrics: A conceptual framework. *Environmental Science & Policy*, **29**, 37-45, doi:10.1016/j.envsci.2013.01.018.

Dietz, S., B. Groom, and W.A. Pizer, 2016: Weighing the Costs and Benefits of Climate Change to Our Children. *The Future of Children*, **26(1)**, 133-155.

Dinah, S., 2008: Equity. In: *The Oxford Handbook of International Environmental Law* [Bodansky, D., J. Brunnée, and E. Hey (eds.)]. Oxford University Press, Oxford, UK.

Dooley, K., J. Gupta, and A. Patwardhan, 2018: INEA editorial: Achieving 1.5 °C and climate justice. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 1-9, doi:10.1007/s10784-018-9389-x.

Dryzek, J.S., 2016: Institutions for the Anthropocene: Governance in a Changing Earth System. *British Journal of Political Science*, **46(04)**, 937-956, doi:10.1017/S0007123414000453.

Duyck, S., S. Jodoin, and A. Johl (eds.), 2018: *Routledge Handbook of Human Rights and Climate Governance*. Routledge, Abingdon, Oxon, 430 pp.

Ebi, K.L., L.H. Ziska, and G.W. Yohe, 2016: The shape of impacts to come: lessons and opportunities for adaptation from uneven increases in global and regional temperatures. *Climatic Change*, **139(3)**, 341-349, doi:10.1007/s10584-016-1816-9.

Ebi, K.L. et al., 2014: A new scenario framework for climate change research: Background, process, and future directions. *Climatic Change*, **122(3)**, 363-372, doi:10.1007/s10584-013-0912-3.

Eby, M. et al., 2009: Lifetime of anthropogenic climate change: Millennial time scales of potential CO_2 and surface temperature perturbations. *Journal of Climate*, **22(10)**, 2501-2511, doi:10.1175/2008JCLI2554.1.

Ehlert, D. and K. Zickfeld, 2017: What determines the warming commitment after take back cessation of CO_2 emissions? *Environmental Research Letters*, **12(1)**, doi:10.1088/1748-9326/aa564a.

Ekström, M., M.R. Grose, and P.H. Whetton, 2015: An appraisal of downscaling methods used in climate change research. *Wiley Interdisciplinary Reviews: Climate Change*, **6(3)**, 301-319, doi:10.1002/wcc.339.

Emori, S. et al., 2018: Risk implications of long-term global climate goals: overall conclusions of the ICA-RUS project. *Sustainability Science*, **13(2)**, 279-289.

England, M.H. et al., 2014: Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nature Climate Change*, **4(3)**, 222-227, doi:10.1038/nclimate2106.

Epstein, A.H., and S.L.H. Theuer, 2017: *Sustainable development and climate action: thoughts on an integrated*

approach to SDG and climate policy implementation, 50 pp.
Etminan, M., G. Myhre, E.J. Highwood, and K.P. Shine, 2016: Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters*, **43(24)**, 12,614-12,623, doi:10.1002/2016GL071930.
Fazey, I. et al., 2016: Past and future adaptation pathways. *Climate and Development*, **8(1)**, 26-44, doi:10.1080/17565529.2014.989192.
Fazey, I. et al., 2018: Community resilience for a 1.5°C world. *Current Opinion in Environmental Sustainability*, **31**, 30-40, doi:10.1016/j.cosust.2017.12.006.
Field, C.B. et al., 2014: Technical Summary. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 35-94.
Fischer, E.M. and R. Knutti, 2015: Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nature Climate Change*, **5(6)**, 560-564, doi:10.1038/nclimate2617.
Fleurbaey, M. et al., 2014: Sustainable Development and Equity. 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., Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, P.E. K. Seyboth, A. Adler, I. Baum, S. Brunner, and T.Z.J.C.M. B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow (eds.)]. Cambridge University Press, Cambridge, Cambridge, United Kingdom and New York, NY, USA, pp. 283-350.
Forkel, M. et al., 2016: Enhanced seasonal CO_2 exchange caused by amplified plant productivity in northern ecosystems. *Science*, **351(6274)**, 696 LP - 699.
Foster, G. and S. Rahmstorf, 2011: Global temperature evolution 1979-2010. *Environmental Research Letters*, **6(4)**, 044022, doi:10.1088/1748-9326/6/4/044022.
Frölicher, T.L. and F. Joos, 2010: Reversible and irreversible impacts of greenhouse gas emissions in multi-century projections with the NCAR global coupled carbon cycle-climate model. *Climate Dynamics*, **35(7)**, 1439-1459, doi:10.1007/s00382-009-0727-0.
Frölicher, T.L., M. Winton, and J.L. Sarmiento, 2014: Continued global warming after CO_2 emissions stoppage. *Nature Climate Change*, **4(1)**, 40-44, doi:10.1038/nclimate2060.
Fuglestvedt, J. et al., 2018: Implications of possible interpretations of 'greenhouse gas balance' in the Paris Agreement. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, doi:10.1098/rsta.2016.0445.
Gillett, N.P., V.K. Arora, D. Matthews, and M.R. Allen, 2013: Constraining the ratio of global warming to cumulative CO_2 emissions using CMIP5 simulations. *Journal of Climate*, **26(18)**, 6844-6858, doi:10.1175/JCLI-D-12-00476.1.
Gillett, N.P., V.K. Arora, K. Zickfeld, S.J. Marshall, and W.J. Merryfield, 2011: Ongoing climate change following a complete cessation of carbon dioxide emissions. *Nature Geoscience*, **4**, 83-87, doi:10.1038/ngeo1047.
Giorgi, F. and W.J. Gutowski, 2015: Regional Dynamical Downscaling and the CORDEX Initiative. *Annual Review of Environment and Resources*, **40(1)**, 467-490, doi:10.1146/annurev-environ-102014-021217.
Gomez-Echeverri, L., 2018: Climate and development: enhancing impact through stronger linkages in the implementation of the Paris Agreement and the Sustainable Development Goals (SDGs).. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, **376(2119)**, 20160444, doi:10.1098/rsta.2016.0444.
Goodwin, P. et al., 2018: Pathways to 1.5 °c and 2 °c warming based on observational and geological constraints. *Nature Geoscience*, **11(2)**, 102-107, doi:10.1038/s41561-017-0054-8.
Gouldson, A. et al., 2015: Exploring the economic case for climate action in cities. *Global Environmental Change*, **35**, 93-105, doi:10.1016/j.gloenvcha.2015.07.009.
Gradstein, F.M., J.G. Ogg, M.D. Schmitz, and G.M. Ogg (eds.), 2012: *The Geologic Time Scale*. Elsevier BV, Boston, MA, USA, 1144 pp.
Gregory, J.M. and P.M. Forster, 2008: Transient climate response estimated from radiative forcing and observed temperature change. *Journal of Geophysical Research Atmospheres*, **113(23)**, doi:10.1029/2008JD010405.
Hall, J., G. Fu, and J. Lawry, 2007: Imprecise probabilities of climate change: Aggregation of fuzzy scenarios and model uncertainties. *Climatic Change*, **81(3-4)**, 265-281, doi:10.1007/s10584-006-9175-6.
Hammill, B.A. and H. Price-Kelly, 2017: *Using NDCs , NAPs and the SDGs to Advance Climate-Resilient Development*. Cambridge University Press, Cambridge, United Kingdom, 1-10 pp.

Hansen, G. and W. Cramer, 2015: Global distribution of observed climate change impacts. *Nature Climate Change*, **5(3)**, 182-185, doi:10.1038/nclimate2529.

Hansen, G., D. Stone, M. Auffhammer, C. Huggel, and W. Cramer, 2016: Linking local impacts to changes in climate: a guide to attribution. *Regional Environmental Change*, **16(2)**, 527-541, doi:10.1007/s10113-015-0760-y.

Hansen, J., R. Ruedy, M. Sato, and K. Lo, 2010: Global surface temperature change. *Reviews of Geophysics*, **48(4)**, RG4004, doi:10.1029/2010RG000345.

Hansen, J. et al., 2005: Earth's energy imbalance: confirmation and implications.. *Science*, **308(November)**, 1431-1435, doi:10.1126/science.1110252.

Harlan, S.L. et al., 2015: Climate Justice and Inequality: Insights from Sociology. In: *Climate Change and Society: Sociological Perspectives* [Dunlap, R.E. and R.J. Brulle (eds.)]. Oxford University Press, New York, NY, USA, pp. 127-163.

Harrington, C., 2016: The Ends of the World: International Relations and the Anthropocene. *Millennium: Journal of International Studies*, **44(3)**, 478-498, doi:10.1177/0305829816638745.

Harris, L.M., E.K. Chu, and G. Ziervogel, 2017: Negotiated resilience. *Resilience*, **3293**, 1-19, doi:10.1080/21693293.2017.1353196.

Hartmann, D.J. et al., 2013: Observations: Atmosphere and Surface. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 159-254.

Haustein, K. et al., 2017: A real-time Global Warming Index. *Scientific Reports*, **7(1)**, 15417, doi:10.1038/s41598-017-14828-5.

Hawkins, E. et al., 2017: Estimating changes in global temperature since the pre-industrial period. *Bulletin of the American Meteorological Society*, BAMS-D-16-0007.1, doi:10.1175/BAMS-D-16-0007.1.

Hegerl, G.C. et al., 2007: Understanding and Attributing Climate Change. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 663-745.

Hienola, A. et al., 2018: The impact of aerosol emissions on the 1.5 °C pathways. *Environmental Research Letters*, **13(4)**, 44011.

Hoegh-Guldberg, O. et al., 2007: Coral Reefs Under Rapid Climate Change and Ocean Acidification. *Science*, **318(5857)**, 1737 LP - 1742, doi:10.1126/science.1152509.

Holz, C., S. Kartha, and T. Athanasiou, 2017: Fairly sharing 1.5: national fair shares of a 1.5 °C-compliant global mitigation effort. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 1-18, doi:10.1007/s10784-017-9371-z.

Horton, R., 2014: Why the sustainable development goals will fail. *The Lancet*, **383(9936)**, 2196, doi:10.1016/S0140-6736(14)61046-1.

Humphreys, S., 2017: Climate, Technology, Justice. In: *Protecting the Environment for Future Generations: Principles and Actors in International Environmental Law*. Erich Schmidt Verlag, Berlin.

IBA, 2014: *Achieving Justice and Human Rights in an Era of Climate Disruption*. 240 pp.

IPCC, 2000: Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. [Nakićenović, N. and R. Swart (eds.)]. 570 pp.

IPCC, 2012a: 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 (IPCC). [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, United Kingdom and New York, NY, USA, 582 pp.

IPCC, 2012b: Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Geoengineering. [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, C. Field, V. Barros, T.F. Stocker, Q. Dahe, J. Minx, K. Mach, G.K. Plattner, S. Schlömer, G. Hansen, and M. Mastrandrea (eds.)]. IPCC Working Group III Technical Support Unit, Potsdam Institute for Climate Impact Research, Potsdam, Germany, 99 pp.

IPCC, 2012c: Summary for Policymakers. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [Field, C.B., V.R. 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, United Kingdom and New York, NY, USA, pp. 3-21.

IPCC, 2013a: *Principles Governing IPCC Work*. Intergovernmental Panel on Climate Change (IPCC), Geneva,

Switzerland, 2 pp.
IPCC, 2013b: Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33.
IPCC, 2014a: Climate Change 2014 Synthesis Report. [Core Writing Team, R.K. Pachauri, and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 1-112 pp.
IPCC, 2014b: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. , 1132.
IPCC, 2014c: 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 Univeristy Press, Cambridge, United Kingdom and New York, NY, USA, 1454 pp.
IPCC, 2014d: Summary for Policymakers. 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, United Kingdom and New York, NY, USA, pp. 1-30.
IPCC, 2014e: Summary for Policymakers. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.
IPCC, 2014f: Summary for Policymakers. In: *Climate Change 2014 Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri, and L.A. Meyer (eds.)]. pp. 2-34.
IPCC, 2017: Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Mitigation, Sustainability and Climate Stabilization Scenarios. [Shukla, P.R., J. Skea, R. Diemen, E. Huntley, M. Pathak, J. Portugal-Pereira, J. Scull, and R. Slade (eds.)]. IPCC Working Group III Technical Support Unit, Imperial College London, London, UK, 44 pp.
Jacob, D. and S. Solman, 2017: IMPACT2C - An introduction. *Climate Services*, **7**, 1-2, doi:10.1016/j.cliser.2017.07.006.
Jacobson, M.Z. et al., 2015: 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. *Energy Environ. Sci.*, **8(7)**, 2093-2117, doi:10.1039/C5EE01283J.
James, R., R. Washington, C.F. Schleussner, J. Rogelj, and D. Conway, 2017: Characterizing half-a-degree difference: a review of methods for identifying regional climate responses to global warming targets. *Wiley Interdisciplinary Reviews: Climate Change*, **8(2)**, e457--n/a, doi:10.1002/wcc.457.
Jarvis, A.J., D.T. Leedal, and C.N. Hewitt, 2012: Climate-society feedbacks and the avoidance of dangerous climate change. *Nature Climate Change*, **2(9)**, 668-671, doi:10.1038/nclimate1586.
Jenkins, S., R.J. Millar, N. Leach, and M.R. Allen, 2018: Framing Climate Goals in Terms of Cumulative CO_2-Forcing-Equivalent Emissions. *Geophysical Research Letters*, **45(6)**, 2795-2804, doi:10.1002/2017GL076173.
Johansson, D.J.A., 2012: Economics- and physical-based metrics for comparing greenhouse gases. *Climatic Change*, **110(1-2)**, 123-141, doi:10.1007/s10584-011-0072-2.
Jones, G.S., P.A. Stott, and N. Christidis, 2013: Attribution of observed historical near-surface temperature variations to anthropogenic and natural causes using CMIP5 simulations. *Journal of Geophysical Research: Atmospheres*, **118(10)**, 4001-4024, doi:10.1002/jgrd.50239.
Jones, G.S., P.A. Stott, and J.F.B. Mitchell, 2016: Uncertainties in the attribution of greenhouse gas warming and implications for climate prediction. *Journal of Geophysical Research: Atmospheres*, **121(12)**, 6969-6992, doi:10.1002/2015JD024337.
Jones, P., 2016: The reliability of global and hemispheric surface temperature records. *Advances in Atmospheric Sciences*, **33(3)**, 269-282, doi:10.1007/s00376-015-5194-4.
Kabir, M.I. et al., 2016: Knowledge and perception about climate change and human health: findings from a baseline survey among vulnerable communities in Bangladesh. *BMC Public Health*, **16(1)**, 266, doi:10.1186/s12889-016-2930-3.

Kainuma, M., R. Pandey, T. Masui, and S. Nishioka, 2017: Methodologies for leapfrogging to low carbon and sustainable development in Asia. *Journal of Renewable and Sustainable Energy*, **9(2)**, doi:10.1063/1.4978469.
Kanie, N. and F. Biermann, 2017: Governing through goals: Sustainable development goals as governance innovation.
Karl, T.R. et al., 2015: Possible artifacts of data biases in the recent global surface warming hiatus. *Science*, **348(6242)**, 1469-1472, doi:10.1126/science.aaa5632.
Karmalkar, A. and R.S. Bradley, 2017: Consequences of Global Warming of 1.5°C and 2°C for Regional Temperature and Precipitation Changes in the Contiguous United States. *PLOS ONE*, **12(1)**, e0168697, doi:10.1371/journal.pone.0168697.
Kelman, I., 2017: Linking disaster risk reduction, climate change, and the sustainable development goals. *Disaster Prevention and Management: An International Journal*, **26(3)**, 254-258, doi:10.1108/DPM-02-2017-0043.
King, A.D., D.J. Karoly, and B.J. Henley, 2017: Australian climate extremes at 1.5°C and 2°C of global warming. *Nature Climate Change*, **7(6)**, 412-416, doi:10.1038/nclimate3296.
King, A.D. et al., 2018: Reduced Heat Exposure by Limiting Global Warming to 1.5°C. *Nature Climate Change* (in press).
Kirtman, B., A. Adedoyin, and N. Bindoff, 2013: Near-term Climate Change: Projections and Predictability. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 953-1028.
Klein, R.J.T. et al., 2014: Adaptation opportunities, constraints, and limits. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 899-943.
Klinsky, S. and H. Winkler, 2018: Building equity in: strategies for integrating equity into modelling for a 1.5°C world. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, doi:10.1098/rsta.2016.0461.
Knox, J.H., 2015: Human Rights Principles and Climate Change. In: *Oxford Handbook of International Climate Change Law* [Carlarne, C., K.R. Gray, and R. Tarasofsky (eds.)]. Oxford University Press, Oxford.
Knutti, R. and J. Sedláček, 2012: Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Climate Change*, **3(4)**, 369-373, doi:10.1038/nclimate1716.
Knutti, R., J. Rogelj, J. Sedláček, and E.M. Fischer, 2015: A scientific critique of the two-degree climate change target. *Nature Geoscience*, **9(1)**, 13-18, doi:10.1038/ngeo2595.
Kolstad, C. et al., 2014: Social, Economic, and Ethical Concepts and Methods. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Inter- governmental Panel on Climate Changegovernmental 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, United Kingdom and New York, NY, USA, pp. 207-282.
Kopp, R.E. et al., 2016: Temperature-driven global sea-level variability in the Common Era. *Proceedings of the National Academy of Sciences*, **113(11)**, 1-8, doi:10.1073/pnas.1517056113.
Kosaka, Y. and S.P. Xie, 2013: Recent global-warming hiatus tied to equatorial Pacific surface cooling. *Nature*, **501(7467)**, 403-407, doi:10.1038/nature12534.
Kriegler, E., J.W. Hall, H. Held, R. Dawson, and H.J. Schellnhuber, 2009: Imprecise probability assessment of tipping points in the climate system. *Proceedings of the National Academy of Sciences*, **106(13)**, 5041-5046, doi:10.1073/pnas.0809117106.
Kriegler, E. et al., 2012: The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. *Global Environmental Change*, **22(4)**, 807-822, doi:10.1016/j.gloenvcha.2012.05.005.
Kriegler, E. et al., 2014: A new scenario framework for climate change research: The concept of shared climate policy assumptions. *Climatic Change*, **122(3)**, 401-414, doi:10.1007/s10584-013-0971-5.
Kristjánsson, J.E., M. Helene, and S. Hauke, 2016: The hydrological cycle response to cirrus cloud thinning. *Geophysical Research Letters*, **42(24)**, 10,807-810,815, doi:10.1002/2015GL066795.

Lauder, A.R. et al., 2013: Offsetting methane emissions - An alternative to emission equivalence metrics. *International Journal of Greenhouse Gas Control*, **12**, 419-429, doi:10.1016/j.ijggc.2012.11.028.
Leach, N.J. et al., 2018: Current level and rate of warming determine emissions budgets under ambitious mitigation. *Nature Geoscience* (in press).
Leal Filho, W. et al., 2018: Implementing climate change research at universities: Barriers, potential and actions. *Journal of Cleaner Production*, **170**, 269-277, doi:10.1016/j.jclepro.2017.09.105.
Leggett, J. et al., 1992: Emissions scenarios for the IPCC: an update. In: *Climate change 1992: The Supplementary Report to the IPCC Scientific Assessment* [Houghton, J.T., B.A. Callander, and S.K. Varney (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 69-95.
Leichenko, R. and J.A. Silva, 2014: Climate change and poverty: Vulnerability, impacts, and alleviation strategies. *Wiley Interdisciplinary Reviews: Climate Change*, **5(4)**, 539-556, doi:10.1002/wcc.287.
Leonard, M. et al., 2014: A compound event framework for understanding extreme impacts. *Wiley Interdisciplinary Reviews: Climate Change*, **5(1)**, 113-128, doi:10.1002/wcc.252.
Leung, D.Y.C., G. Caramanna, and M.M. Maroto-Valer, 2014: An overview of current status of carbon dioxide capture and storage technologies. *Renewable and Sustainable Energy Reviews*, **39**, 426-443, doi:10.1016/j.rser.2014.07.093.
Lofts, K., S. Shamin, T.S. Zaman, and R. Kibugi, 2017: Brief on Sustainable Development Goal 13 on Taking Action on Climate Change and Its Impacts: Contributions of International Law, Policy and Governance,. *McGill Journal of Sustainable Development Law*, **11(1)**, 183-192, doi:10.3868/s050-004-015-0003-8.
Loftus, P.J., A.M. Cohen, J.C.S. Long, and J.D. Jenkins, 2015: A critical review of global decarbonization scenarios: What do they tell us about feasibility? *Wiley Interdisciplinary Reviews: Climate Change*, **6(1)**, 93-112, doi:10.1002/wcc.324.
Lövbrand, E., M. Hjerpe, and B.O. Linnér, 2017: Making climate governance global: how UN climate summitry comes to matter in a complex climate regime. *Environmental Politics*, **26(4)**, 580-599, doi:10.1080/09644016.2017.1319019.
Lowe, J.A. et al., 2009: How difficult is it to recover from dangerous levels of global warming? *Environmental Research Letters*, **4(1)**, 014012, doi:10.1088/1748-9326/4/1/014012.
Lüthi, D. et al., 2008: High-resolution carbon dioxide concentration record 650,000-800,000 years before present. *Nature*, **453(7193)**, 379-382, doi:10.1038/nature06949.
MacMartin, D.G., K.L. Ricke, and D.W. Keith, 2018: Solar geoengineering as part of an overall strategy for meeting the 1.5C Paris target. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, doi:10.1098/rsta.2016.0454.
Marbà, N. et al., 2015: Impact of seagrass loss and subsequent revegetation on carbon sequestration and stocks. *Journal of Ecology*, **103(2)**, 296-302, doi:10.1111/1365-2745.12370.
Marcott, S.A., J.D. Shakun, P.U. Clark, and A.C. Mix, 2013: A reconstruction of regional and global temperature for the past 11,300 years. *Science*, **339(6124)**, 1198-201, doi:10.1126/science.1228026.
Marsicek, J., B.N. Shuman, P.J. Bartlein, S.L. Shafer, and S. Brewer, 2018: Reconciling divergent trends and millennial variations in Holocene temperatures. *Nature*, **554**, 92.
Martius, O., S. Pfahl, and C. Chevalier, 2016: A global quantification of compound precipitation and wind extremes. *Geophysical Research Letters*, **43(14)**, 7709-7717, doi:10.1002/2016GL070017.
Masson-Delmotte, V. et al., 2013: Information from Paleoclimate Archives. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge Univeristy Press, Cambridge, UK and New York, NY , USA.
Mastrandrea, M.D. et al., 2011: The IPCC AR5 guidance note on consistent treatment of uncertainties: a common approach across the working groups. *Climatic Change*, **108(4)**, 675-691, doi:10.1007/s10584-011-0178-6.
Mathesius, S., M. Hofmann, K. Caldeira, and H.J. Schellnhuber, 2015: Long-term response of oceans to CO_2 removal from the atmosphere. *Nature Climate Change*, **5(12)**, 1107-1113, doi:10.1038/nclimate2729.
Matthews, H.D. and K. Caldeira, 2008: Stabilizing climate requires near-zero emissions. *Geophys. Res. Lett.*, **35(4)**, L04705, doi:10.1029/2007GL032388.
Matthews, H.D. and K. Zickfeld, 2012: Climate response to zeroed emissions of greenhouse gases and aerosols. *Nature Climate Change*, **2(5)**, 338-341, doi:10.1038/nclimate1424.
Matthews, H.D. and S. Solomon, 2013: Irreversible Does Not Mean Unavoidable. *Science*, **340(6131)**, 438-439, doi:10.1126/science.1236372.
Matthews, H.D., N.P. Gillett, P. Stott, and K. Zickfeld, 2009: The proportionality of global warming to

cumulative carbon emissions. *Nature*, **459(7248)**, 829-32, doi:10.1038/nature08047.
Matthews, T.K.R., R.L. Wilby, and C. Murphy, 2017: Communicating the deadly consequences of global warming for human heat stress. *Proceedings of the National Academy of Sciences*, **114(15)**, 3861-3866, doi:10.1073/pnas.1617526114.
Maupin, A., 2017: The SDG13 to combat climate change: an opportunity for Africa to become a trailblazer? *African Geographical Review*, **36(2)**, 131-145, doi:10.1080/19376812.2016.1171156.
Mauritsen, T. and R. Pincus, 2017: Committed warming inferred from observations. *Nature Climate Change*, **2(July)**, 1-5, doi:10.1038/nclimate3357.
Medhaug, I., M.B. Stolpe, E.M. Fischer, and R. Knutti, 2017: Reconciling controversies about the 'global warming hiatus'. *Nature*, **545(7652)**, 41-47, doi:10.1038/nature22315.
Meehl, G.A. et al., 2007: Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 747-845.
Millar, R.J., Z.R. Nicholls, P. Friedlingstein, and M.R. Allen, 2017a: A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions. *Atmospheric Chemistry and Physics*, **17(11)**, 7213-7228, doi:10.5194/acp-17-7213-2017.
Millar, R.J. et al., 2017b: Emission budgets and pathways consistent with limiting warming to 1.5°C. *Nature Geoscience*, **10(10)**, 741-747, doi:10.1038/NGEO3031.
Mimura, N. et al., 2014: Adaptation planning and implementation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 869-898.
Minx, J.C., W.F. Lamb, M.W. Callaghan, L. Bornmann, and S. Fuss, 2017: Fast growing research on negative emissions. *Environmental Research Letters*, **12(3)**, doi:10.1088/1748-9326/aa5ee5.
Mitchell, D. et al., 2016: Realizing the impacts of a 1.5°C warmer world. *Nature Climate Change*, **6(8)**, 735-737, doi:10.1038/nclimate3055.
Mitchell, D. et al., 2017: Half a degree Additional warming, Projections, Prognosis and Impacts (HAPPI): Background and Experimental Design. *Geoscientific Model Development*, **10**, 571-583, doi:10.5194/gmd-10-571-2017.
Miyan, M.A., 2015: Droughts in Asian Least Developed Countries: Vulnerability and sustainability. *Weather and Climate Extremes*, **7**, 8-23, doi:10.1016/J.WACE.2014.06.003.
Morice, C.P., J.J. Kennedy, N.A. Rayner, and P.D. Jones, 2012: Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set. *Journal of Geophysical Research Atmospheres*, **117(8)**, doi:10.1029/2011JD017187.
Morita, T. et al., 2001: Greenhouse Gas Emission Mitigation Scenarios and Implications. In: *Climate Change 2001: Mitigation. Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Metz, B., O. Davidson, R. Swart, and J. Pan (eds.)]. Cambridge University Press, Cambridge, pp. 115-164.
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.
Mueller, B. and S.I. Seneviratne, 2014: Systematic land climate and evapotranspiration biases in CMIP5 simulations. *Geophysical Research Letters*, **41(1)**, 128-134, doi:10.1002/2013GL058055.
Myhre, G. et al., 2013: Anthropogenic and natural radiative forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 658-740.
Myhre, G. et al., 2017: Multi-model simulations of aerosol and ozone radiative forcing due to anthropogenic emission changes during the period 1990-2015. *Atmospheric Chemistry and Physics*, **17(4)**, 2709-2720, doi:10.5194/acp-17-2709-2017.
Mysiak, J., S. Surminski, A. Thieken, R. Mechler, and J. Aerts, 2016: Brief communication: Sendai framework for disaster risk reduction - Success or warning sign for Paris? *Natural Hazards and Earth System Sciences*, **16(10)**, 2189-2193, doi:10.5194/nhess-16-2189-2016.
O'Brien, K. and E. Selboe, 2015: Social transformation. In: *The Adaptive Challenge of Climate Change*

[OBrien, K. and E. Selboe (eds.)]. Cambridge University Press, Cambridge, UK, pp. 311-324.

O'Brien, K. et al., 2012: Toward a sustainable and resilient future. In: *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 (IPCC)* [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, United Kingdom and New York, NY, USA, pp. 437-486.

OECD, 2016: *The OECD supporting action on climate change*. Organisation for Economic Co-operation and Development (OECD), Paris, France, 18 pp.

OHCHR, 2009: *Report of the Office of the United Nations High Commissioner for Human Rights on the relationship between climate change and human rights*. A/HRC/10/61, 32 pp.

OHCHR, 2015: *Understanding Human Rights and Climate Change*. Office of the United Nations High Commissioner for Human Rights (OHCHR), 28 pp.

OHCHR, 2017: *Analytical study on the relationship between climate change and the full and effective enjoyment of the rights of the child*. UN Doc. A/HRC/35/13, 18 pp.

Okereke, C., 2010: Climate justice and the international regime. *Wiley Interdisciplinary Reviews: Climate Change***, 1(3)**, 462-474, doi:10.1002/wcc.52.

Oliver, T.H. and M.D. Morecroft, 2014: Interactions between climate change and land use change on biodiversity: attribution problems, risks, and opportunities. *Wiley Interdisciplinary Reviews: Climate Change***, 5(3)**, 317-335, doi:10.1002/wcc.271.

Olsson, L. et al., 2014: Livelihoods and poverty. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 798-832.

O'Neill, B.C. et al., 2014: A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change***, 122(3)**, 387-400, doi:10.1007/s10584-013-0905-2.

Otto, F.E.L., D.J. Frame, A. Otto, and M.R. Allen, 2015: Embracing uncertainty in climate change policy. *Nature Climate Change***, 5(August)**, 1-5, doi:10.1038/nclimate2716.

Otto, F.E.L., R.B. Skeie, J.S. Fuglestvedt, T. Berntsen, and M.R. Allen, 2017: Assigning historic responsibility for extreme weather events. *Nature Climate Change***, 7(11)**, 757-759, doi:10.1038/nclimate3419.

Pattberg, P. and F. Zelli (eds.), 2016: *Environmental politics and governance in the anthropocene: Institutions and legitimacy in a complex world*. Routledge, 268 pp.

Patterson, J. et al., 2017: Exploring the governance and politics of transformations towards sustainability. *Environmental Innovation and Societal Transitions***, 24**, 1-16, doi:10.1016/j.eist.2016.09.001.

Pelling, M., 2011: *Adaptation to Climate Change: From Resilience to Transformation*. Routledge, Abingdon, Oxon, UK and New York, NY, USA, 274 pp.

Pelling, M., K. O'Brien, and D. Matyas, 2015: Adaptation and transformation. *Climatic Change***, 133(1)**, 113-127, doi:10.1007/s10584-014-1303-0.

Pendergrass, A.G., F. Lehner, B.M. Sanderson, and Y. Xu, 2015: Does extreme precipitation intensity depend on the emissions scenario? *Geophysical Research Letters***, 42(20)**, 8767-8774, doi:10.1002/2015GL065854.

Pfleiderer, P., C.F. Schleussner, M. Mengel, and J. Rogelj, 2018: Global mean temperature indicators linked to warming levels avoiding climate risk. *Environmental Research Letters*.

Popp, A. et al., 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change***, 42**, 331-345, doi:10.1016/j.gloenvcha.2016.10.002.

Porter, J.R. et al., 2014: Food security and food production systems. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485-533.

Pörtner, H.O. et al., 2014: Ocean systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University

Press, Cambridge, United Kingdom and New York, NY, USA, pp. 411-484.
Rao, S. et al., 2017: Future Air Pollution in the Shared Socio-Economic Pathways. *Global Environmental Change*, **42(January)**, 346-358, doi:10.1016/j.gloenvcha.2016.05.012.
Reckien, D. et al., 2017: Climate change, equity and the Sustainable Development Goals: an urban perspective. *Environment & Urbanization*, **29(1)**, 159-182, doi:10.1177/0956247816677778.
Reisinger, A. et al., 2012: Implications of alternative metrics for global mitigation costs and greenhouse gas emissions from agriculture. *Climatic Change*, 1-14, doi:10.1007/s10584-012-0593-3.
Reisinger, A. et al., 2014: Australasia. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1371-1438.
Resurrección, B.P., 2013: Persistent women and environment linkages in climate change and sustainable development agendas. *Women's Studies International Forum*, **40(Supplement C)**, 33-43, doi:10.1016/j.wsif.2013.03.011.
Revi, A. et al., 2014: Urban areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 535-612.
Riahi, K. et al., 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, **42**, 153-168, doi:10.1016/j.gloenvcha.2016.05.009.
Ribes, A. and L. Terray, 2013: Application of regularised optimal fingerprinting to attribution. Part II: application to global near-surface temperature. *Climate Dynamics*, **41(11)**, 2837-2853, doi:10.1007/s00382-013-1736-6.
Ribes, A., F.W. Zwiers, J.M. Azaïs, and P. Naveau, 2017: A new statistical approach to climate change detection and attribution. *Climate Dynamics*, **48(1)**, 367-386, doi:10.1007/s00382-016-3079-6.
Richardson, M., K. Cowtan, and R.J. Millar, 2018: Global temperature definition affects achievement of long-term climate goals. *Environmental Research Letters*, **13(5)**, 054004.
Richardson, M., K. Cowtan, E. Hawkins, and M.B. Stolpe, 2016: Reconciled climate response estimates from climate models and the energy budget of Earth. *Nature Climate Change*, **6**, 931-935.
Robinson, M. and T. Shine, 2018: Achieving a climate justice pathway to 1.5°C. *Nature Clim. Change* (in press).
Rogelj, J., C.F. Schleussner, and W. Hare, 2017: Getting It Right Matters: Temperature Goal Interpretations in Geoscience Research. *Geophysical Research Letters*, **44(20)**, 10,662-10,665, doi:10.1002/2017GL075612.
Rogelj, J. et al., 2015: Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nature Climate Change*, **5(6)**, 519-527, doi:10.1038/nclimate2572.
Rogelj, J. et al., 2016a: Paris Agreement climate proposals need boost to keep warming well below 2°C. *Nature Climate Change*, **534(June)**, 631-639, doi:10.1038/nature18307.
Rogelj, J. et al., 2016b: Differences between carbon budget estimates unravelled. *Nature Climate Change*, **6(3)**, 245-252, doi:10.1038/nclimate2868.
Rogelj, J. et al., 2018: Transition pathways towards limiting climate change below 1.5°C. *Nature Climate Change*, **8(4)**, 325-332.
Rohde, R. et al., 2013: Berkeley Earth Temperature Averaging Process. *Geoinformatics & Geostatistics: An Overview*, **1(2)**, 1-13, doi:10.4172/2327-4581.1000103.
Rosenbloom, D., 2017: Pathways: An emerging concept for the theory and governance of low-carbon transitions. *Global Environmental Change*, **43**, 37-50, doi:10.1016/j.gloenvcha.2016.12.011.
Rosenzweig, C. et al., 2008: Attributing physical and biological impacts to anthropogenic climate change. *Nature*, **453(7193)**, 353-357, doi:10.1038/nature06937.
Rosenzweig, C. et al., 2017: Assessing inter-sectoral climate change risks: the role of ISIMIP. *Environmental Research Letters*, **12(1)**, 10301.
Rosenzweig, C., W. Solecki, P. Romeo-Lankao, M. Shagun, S. Dhakal, and S. Ali Ibrahim (eds.), 2018: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Samset, B.H. et al., 2018: Climate Impacts From a Removal of Anthropogenic Aerosol Emissions. *Geophysical*

Research Letters, **45(2)**, 1020-1029, doi:10.1002/2017GL076079.
Sarofim, M.C., S.T. Waldhoff, and S.C. Anenberg, 2017: Valuing the Ozone-Related Health Benefits of Methane Emission Controls. *Environmental and Resource Economics*, **66(1)**, 45-63, doi:10.1007/s10640-015-9937-6.
Savaresi, A., 2016: The Paris Agreement: a new beginning? *Journal of Energy & Natural Resources Law*, **34(1)**, 16-26, doi:10.1080/02646811.2016.1133983.
Schäfer, S., M. Lawrence, H. Stelzer, W. Born, and S. Low (eds.), 2015: *The European Transdisciplinary Assessment of Climate Engineering (EuTRACE): Removing Greenhouse Gases from the Atmosphere and Reflecting Sunlight away from Earth*. 170 pp.
Schewe, J. et al., 2014: Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences*, **111(9)**, 3245-3250.
Schleussner, C.F., P. Pfleiderer, and E.M. Fischer, 2017: In the observational record half a degree matters. *Nature Climate Change*, **7(7)**, 460-462, doi:10.1038/nclimate3320.
Schleussner, C.F. et al., 2016: Differential climate impacts for policy relevant limits to global warming: the case of 1.5°C and 2°C. *Earth System Dynamics*, **7(2)**, 327-351, doi:10.5194/esd-7-327-2016.
Schroeder, H., M.T. Boykoff, and L. Spiers, 2012: Equity and state representations in climate negotiations. *Nature Climate Change*, **2**, 834-836, doi:10.1038/nclimate1742.
Schurer, A.P., M.E. Mann, E. Hawkins, S.F.B. Tett, and G.C. Hegerl, 2017: Importance of the pre-industrial baseline for likelihood of exceeding Paris goals. *Nature Climate Change*, doi:10.1038/nclimate3345.
Seneviratne, S.I., M.G. Donat, A.J. Pitman, R. Knutti, and R.L. Wilby, 2016: Allowable CO_2 emissions based on regional and impact-related climate targets. *Nature*, **529(7587)**, 477-483, doi:10.1038/nature16542.
Seneviratne, S.I. et al., 2012: Changes in climate extremes and their impacts on the natural physical environment. In: *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 (IPCC)* [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, United Kingdom and New York, NY, USA, pp. 109-230.
Settele, J. et al., 2014: Terrestrial and inland water systems. In: *Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 271-359.
Shiferaw, B. et al., 2014: Managing vulnerability to drought and enhancing livelihood resilience in sub-Saharan Africa: Technological, institutional and policy options. *Weather and Climate Extremes*, **3**, 67-79, doi:10.1016/J.WACE.2014.04.004.
Shindell, D.T., 2015: The social cost of atmospheric release. *Climatic Change*, **130(2)**, 313-326, doi:10.1007/s10584-015-1343-0.
Shindell, D.T., Y. Lee, and G. Faluvegi, 2016: Climate and health impacts of US emissions reductions consistent with 2C. *Nature Climate Change*, **6**, 503-509.
Shindell, D.T., J.S. Fuglestvedt, and W.J. Collins, 2017: The social cost of methane: theory and applications. *Faraday Discussions*, **6**, 773, doi:10.1039/C7FD00009J.
Shine, K.P., J.S. Fuglestvedt, K. Hailemariam, and N. Stuber, 2005: Alternatives to the Global Warming Potential for comparing climate impacts of emissions of greenhouse gases. *Climatic Change*, **68(3)**, 281-302, doi:10.1007/s10584-005-1146-9.
Shine, K.P., R.P. Allan, W.J. Collins, and J.S. Fuglestvedt, 2015: Metrics for linking emissions of gases and aerosols to global precipitation changes. *Earth System Dynamics*, **6(2)**, 525-540, doi:10.5194/esd-6-525-2015.
Shue, H., 2013: Climate Hope: Implementing the Exit Strategy. *Chicago Journal of International Law*, **13(2)**, 381.
Shue, H., 2014: *Climate Justice: Vulnerability and Protection*. Oxford University Press, Oxford, UK, 366 pp.
Shue, H., 2018: Mitigation gambles: uncertainty, urgency and the last gamble possible. *Philosophical Transactions of the Royal Society*, doi:10.1098/rsta.2017.0105.
Shukla, P.R. and V. Chaturvedi, 2013: Sustainable energy transformations in India under climate policy. *Sustainable Development*, **21(1)**, 48-59, doi:10.1002/sd.516.
Simmons, A.J. et al., 2017: A reassessment of temperature variations and trends from global reanalyses and monthly surface climatological datasets. *Quarterly Journal of the Royal Meteorological Society*, **143(702)**, 101-119, doi:10.1002/qj.2949.
Simpson, M. et al., 2016: Decision Analysis for Management of Natural Hazards. *Annual Review of*

Environment and Resources, **41(1)**, 489-516, doi:10.1146/annurev-environ-110615-090011.
Sitch, S., P.M. Cox, W.J. Collins, and C. Huntingford, 2007: Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. *Nature*, **448**, 791.
Skeie, R.B. et al., 2017: Perspective has a strong effect on the calculation of historical contributions to global warming. *Environmental Research Letters*, **12(2)**, doi:10.1088/1748-9326/aa5b0a.
Smith, C.J. et al., 2018: FAIR v1.3: A simple emissions-based impulse response and carbon cycle model. *Geoscientific Model Development* (in press), doi:10.5194/gmd-2017-266.
Smith, S.J. and P.J. Rasch, 2013: The long-term policy context for solar radiation management. *Climatic Change*, **121(3)**, 487-497, doi:10.1007/s10584-012-0577-3.
Smith, S.J., J. Karas, J. Edmonds, J. Eom, and A. Mizrahi, 2013: Sensitivity of multi-gas climate policy to emission metrics. *Climatic Change*, **117(4)**, 663-675, doi:10.1007/s10584-012-0565-7.
Smith, S.M. et al., 2012: Equivalence of greenhouse-gas emissions for peak temperature limits. *Nature Climate Change*, **2(7)**, 535-538, doi:10.1038/nclimate1496.
Solecki, W., M. Pelling, and M. Garschagen, 2017: Transitions between risk management regimes in cities. *Ecology and Society*, **22(2)**, art38, doi:10.5751/ES-09102-220238.
Solomon, S., G.K.G. Plattner, R. Knutti, and P. Friedlingstein, 2009: Irreversible climate change due to carbon dioxide emissions.. *Proceedings of the National Academy of Sciences of the United States of America*, **106(6)**, 1704-9, doi:10.1073/pnas.0812721106.
Somanathan, E. et al., 2014: National and Sub-national Policies and Institutions. 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, United Kingdom and New York, NY, USA.
Sovacool, B.K., B.O. Linnér, and M.E. Goodsite, 2015: The political economy of climate adaptation. *Nature Climate Change*, **5(7)**, 616-618, doi:10.1038/nclimate2665.
Stavins, R. et al., 2014: International Cooperation: Agreements and Instruments. 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, United Kingdom and New York, NY, USA, pp. 1001-1082.
Stechow, C. et al., 2016: 2°C and the SDGs: United they stand, divided they fall? *Environmental Research Letters*, **11(3)**, 34022, doi:10.1088/1748-9326/11/3/034022.
Steffen, W. et al., 2016: Stratigraphic and Earth System approaches to defining the Anthropocene. *Earth's Future*, **4(8)**, 324-345, doi:10.1002/2016EF000379.
Sterner, E., D.J.A. Johansson, and C. Azar, 2014: Emission metrics and sea level rise. *Climatic Change*, **127(2)**, 335-351, doi:10.1007/s10584-014-1258-1.
Stocker, T.F. et al., 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33-115.
Stone, D. et al., 2013: The challenge to detect and attribute effects of climate change on human and natural systems. *Climatic Change*, **121(2)**, 381-395, doi:10.1007/s10584-013-0873-6.
Strefler, J., G. Luderer, T. Aboumahboub, and E. Kriegler, 2014: Economic impacts of alternative greenhouse gas emission metrics: a model-based assessment. *Climatic Change*, **125(3-4)**, 319-331, doi:10.1007/s10584-014-1188-y.
Tàbara, J.D. et al., 2018: Positive tipping points in a rapidly warming world. *Current Opinion in Environmental Sustainability*, **31**, 120-129, doi:10.1016/j.cosust.2018.01.012.
Tanaka, K. and B.C. O'Neill, 2018: The Paris Agreement zero-emissions goal is not always consistent with the 1.5°C and 2°C temperature targets. *Nature Climate Change*, **8(4)**, 319-324, doi:10.1038/s41558-018-0097-x.
Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, **93(4)**, 485-498, doi:10.1175/BAMS-D-11-00094.1.
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. *Journal of Environmental Planning and Management*, **60(4)**, 558-576, doi:10.1080/09640568.2016.1168288.
The Royal Society, 2009: *Geoengineering the climate: science, governance and uncertainty*. 1-5 pp.

Tokarska, K.B. and K. Zickfeld, 2015: The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change. *Env. Res. Lett.*, **10**, 94013, doi:doi:10.1088/1748-9326/10/9/094013.

Tokarska, K.B. and N.P. Gillett, 2018: Cumulative carbon emissions budgets consistent with 1.5 °C global warming. *Nature Climate Change*, **8(4)**, 296-299, doi:10.1038/s41558-018-0118-9.

Tol, R.S.J., T.K. Berntsen, B.C. O'Neill, Fuglestvedt, and P.S. Keith, 2012: A unifying framework for metrics for aggregating the climate effect of different emissions. *Environmental Research Letters*, **7(4)**, 44006.

Tschakert, P., B. van Oort, A.L. St. Clair, and A. LaMadrid, 2013: Inequality and transformation analyses: a complementary lens for addressing vulnerability to climate change. *Climate and Development*, **5(4)**, 340-350, doi:10.1080/17565529.2013.828583.

Tschakert, P. et al., 2017: Climate change and loss, as if people mattered: values, places, and experiences. *Wiley Interdisciplinary Reviews: Climate Change*, **8(5)**, e476--n/a, doi:10.1002/wcc.476.

UNDP, 2016: *Human Development Report 2016: Human Development for Everyone*. 286 pp.

UNFCCC, 2016: *Aggregate effect of the intended nationally determined contributions: an update*. FCCC/CP/2016/2, United Nations Framework Convention on Climate Change (UNFCCC), 75 pp.

UNGA, 2015: *Transforming our world: The 2030 agenda for sustainable development*. A/RES/70/1, United Nations General Assembly (UNGA), 35 pp.

United Nations, 2015: *The Millennium Development Goals Report 2015*. 75 pp.

van Oldenborgh, G.J. et al., 2017: Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters*, **12(12)**, 124009.

van Vuuren, D.P. et al., 2011: The representative concentration pathways: An overview. *Climatic Change*, **109(1)**, 5-31, doi:10.1007/s10584-011-0148-z.

van Vuuren, D.P. et al., 2014: A new scenario framework for Climate Change Research: Scenario matrix architecture. *Climatic Change*, **122(3)**, 373-386, doi:10.1007/s10584-013-0906-1.

van Vuuren, D.P. et al., 2015: Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **98**, 303-323, doi:10.1016/j.techfore.2015.03.005.

Vautard, R. et al., 2014: The European climate under a 2°C global warming. *Environmental Research Letters*, **9(3)**, doi:10.1088/1748-9326/9/3/034006.

Vincent, K.E., P. Tschakert, J. Barnett, M.G. Rivera-Ferre, and A. Woodward, 2014: Cross-chapter box on gender and climate change. In: *Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 105-107.

von Stechow, C. et al., 2015: Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. *Annual Review of Environment and Resources*, **40(1)**, 363-394, doi:10.1146/annurev-environ-021113-095626.

Vose, R.S. et al., 2012: NOAA's merged land-ocean surface temperature analysis. *Bulletin of the American Meteorological Society*, **93(11)**, 1677-1685, doi:10.1175/BAMS-D-11-00241.1.

Waters, C.N. et al., 2016: The Anthropocene is functionally and stratigraphically distinct from the Holocene. *Science*, **351(6269)**, aad2622-aad2622, doi:10.1126/science.aad2622.

WCED, 1987: *Our Common Future*. World Commission on Environment and Development (WCED), Geneva, Switzerland, 383 pp.

Weber, H., 2017: Politices of 'Leaving no one behind': contesting the 2030 Sustainable development goals. *Globalizations*, **14(3)**, 399-414.

Whitmarsh, L., S. O'Neill, and I. Lorenzoni (eds.), 2011: *Engaging the Public with Climate Change: Behaviour Change and Communication*. Earthscan, London, UK and Washington, DC, USA, 289 pp.

Wigley, T.M.L., 2018: The Paris warming targets: emissions requirements and sea level consequences. *Climatic Change*, **147(1-2)**, 31-45, doi:10.1007/s10584-017-2119-5.

Williams, R.G., V. Roussenov, T.L. Frölicher, and P. Goodwin, 2017: Drivers of Continued Surface Warming After Cessation of Carbon Emissions. *Geophysical Research Letters*, **44(20)**, 10,633-10,642, doi:10.1002/2017GL075080.

Winkler, I.T. and M.L. Satterthwaite, 2017: Leaving no one behind? Persistent inequalities in the SDGs. *The International Journal of Human Rights*, **21(8)**, 1073-1097, doi:10.1080/13642987.2017.1348702.

Wise, R.M. et al., 2014: Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change*, **28**, 325-336, doi:10.1016/j.gloenvcha.2013.12.002.

World Bank, 2013: *Turn Down the Heat: Climate Extremes, Regional Impacts, and the Case for Resilience*. 254 pp.

Wright, H., S. Huq, and J. Reeves, 2015: Impact of climate change on least developed countries: are the SDGs possible? IIED Briefing May 2015, 4 pp.
Xu, Y. and V. Ramanathan, 2017: Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes. *Proc. Natl. Acad. Sci.* 1-9, doi:10.1073/pnas.1618481114.
Zalasiewicz, J. et al., 2017: Making the case for a formal Anthropocene Epoch: an analysis of ongoing critiques. *Newsletters on Stratigraphy*, **50(2)**, 205-226, doi:10.1127/nos/2017/0385.
Zickfeld, K., A.H. MacDougall, and H. Damon Matthews, 2016: On the proportionality between global temperature change and cumulative CO_2 emissions during periods of net negative CO_2 emissions. *Environmental Research Letters*, **11(5)**, doi:10.1088/1748-9326/11/5/055006.
Zickfeld, K., M. Eby, H.D. Matthews, and A.J. Weaver, 2009: Setting cumulative emissions targets to reduce the risk of dangerous climate change.. *Proceedings of the National Academy of Sciences of the United States of America*, **106(38)**, 16129-16134, doi:10.1073/pnas.0805800106.
Zscheischler, J. and S.I. Seneviratne, 2017: Dependence of drivers affects risks associated with compound events. *Science Advances*, **3(6)**, doi:10.1126/sciadv.1700263.

Chapter 1: Framing and Context

Technical Annex 1.A

This Annex provides technical details of the calculations behind the figures in the chapter, as well as some supporting figures provided for sensitivity analysis or to provide support to the main assessment.

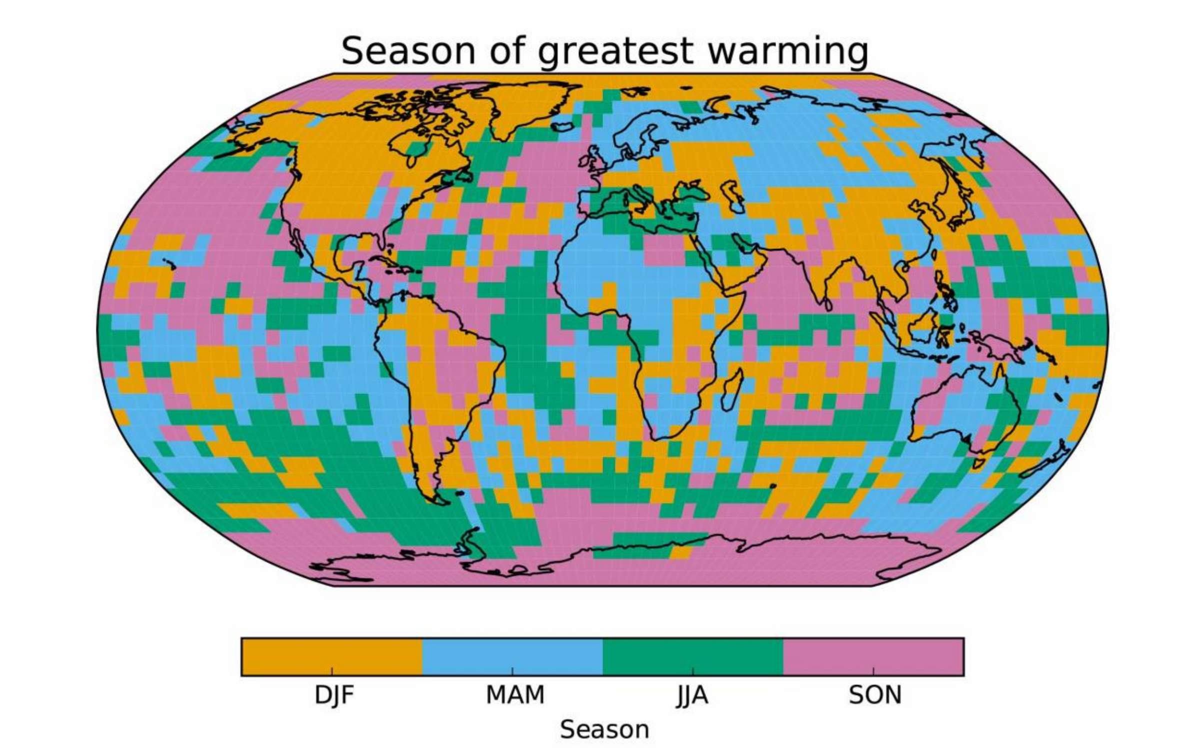
Table of Content

Annex 1.A.1: supporting material for for Figure 1.1 2
Annex 1.A.2: supporting material for Figure 1.2 5
Annex 1.A.3: supporting material for Figure 1.3 8
Annex 1.A.4: supporting material for Figure 1.4 11
Annex 1.A.5: supporting material for Figure 1.5 12
Annex 1.A.6: supporting material for FAQ 1.2 Figure 1 and Figure SPM1 13
Annex 1.A.7: Recent trends in emissions and radiative forcing 18
References 21

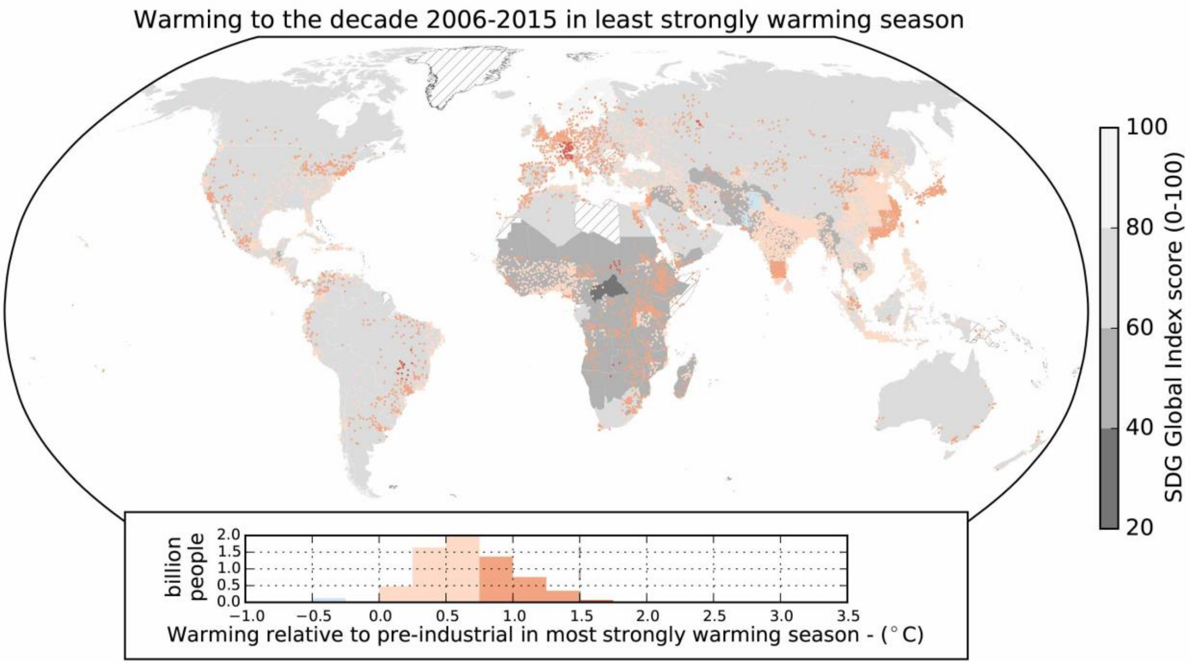
Annex 1.A.1: supporting material for for Figure 1.1

Externally-forced warming is calculated for the Cowtan & Way (Cowtan and Way, 2014) dataset at every location and for each season as in Figure 1.3. The season with the greatest externally-forced warming at every location (averaged over the 2006-2015 period) is selected to give the colour of the dots at that grid box.

Technical Annex 1.A Figure 1 shows the season of maximum warming in each grid-box used in Figure 1.1, while Technical Annex 1.A Figure 2 shows the warming to 2006-2015 in the season that has warmed the least.



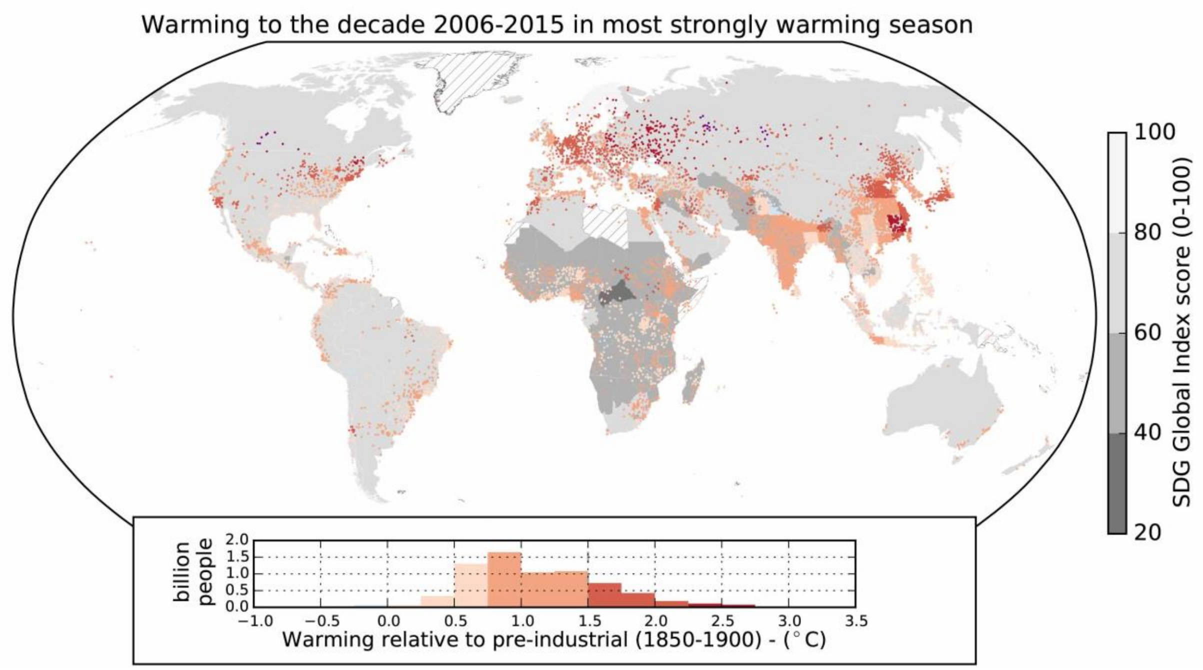
Technical Annex 1.A, Figure 1: Season of greatest human-induced warming over 2006-2015 relative to 1850-1900 for the data shown in Figure 1.1.



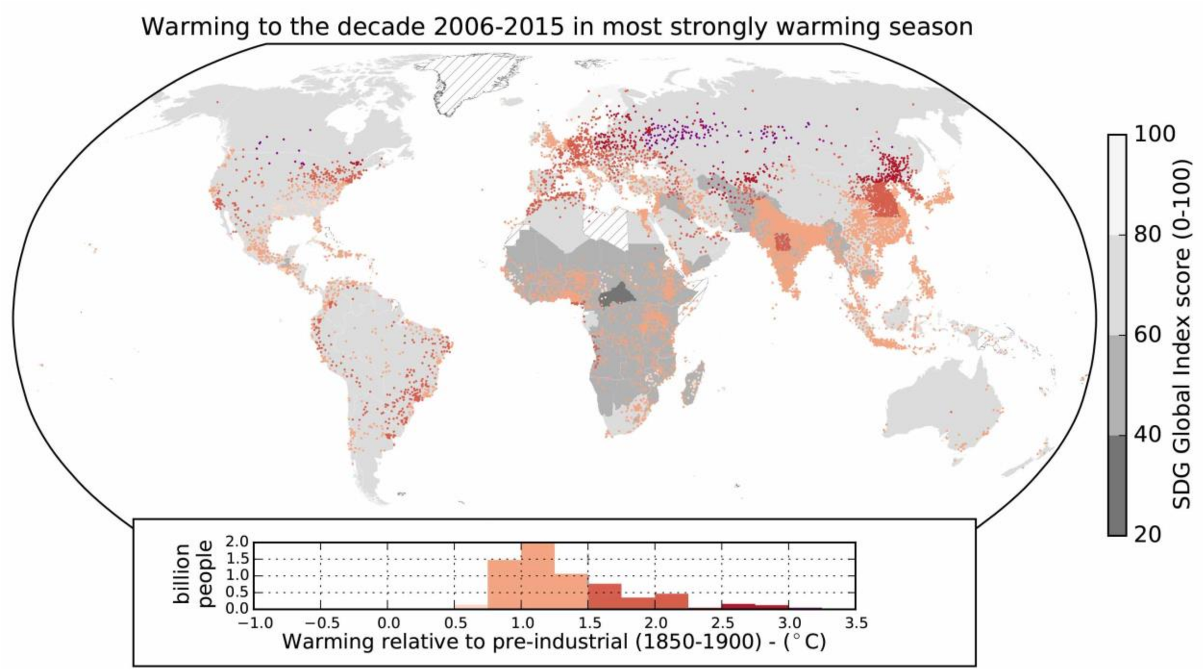
Technical Annex 1.A, Figure 2: As for Figure 1.1 but with scatter points coloured by warming in the season with least warming over the 2006-2015 period.

Population data is taken from Doxsey-Whitfield et al. (2015) for 2010. The number of scatter points shown in each 1°x1° grid box is directly proportional to the population count in the grid-box, with a maximum number of scatter points in a single grid-box associated with the maximum population count in the dataset. For grid-boxes with (non-zero) population counts that are below the population threshold consistent with just a single scatter point (approximately 650,000), the probability that a single scatter point is plotted reduces from unity towards zero with decreasing population in the grid-box to give an accurate visual impression of population distribution.

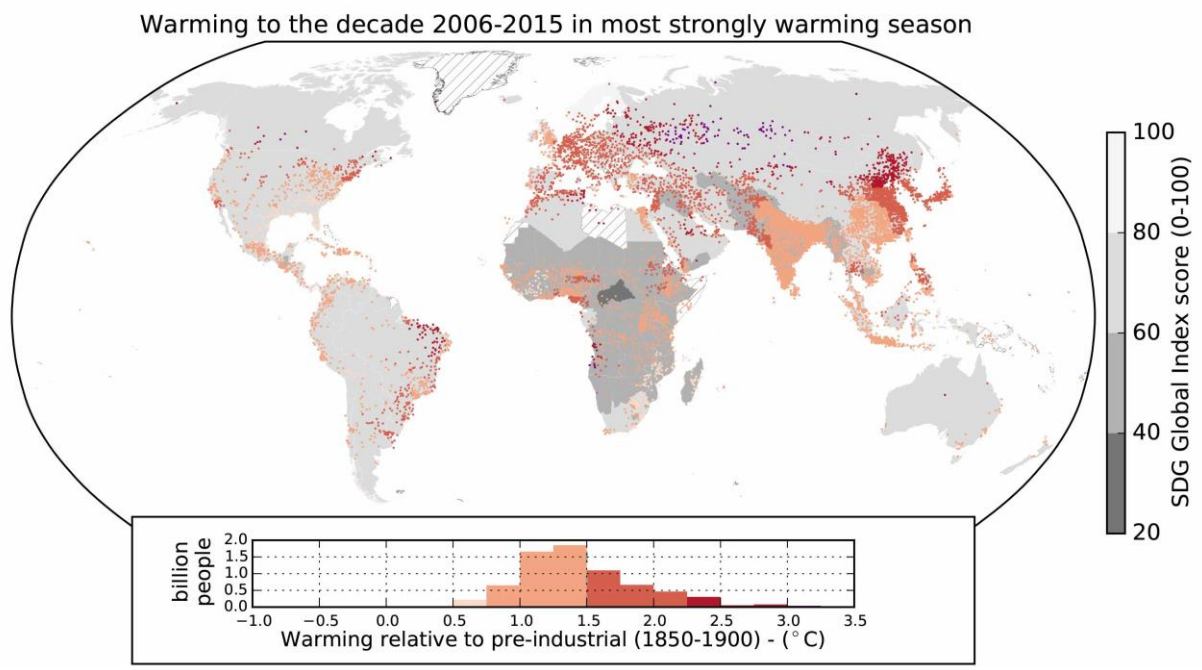
The SDG Global Index Score is a quantitative measure of progress towards the 17 sustainable development goals (Sachs et al., 2017). The goals cross-cut the three dimensions of sustainable development – environmental sustainability, economic growth, and social inclusion. It has a range of 0-100, 100 corresponding to all SDGs being met. Versions of Figure 1.1 using the HadCRUT4, NOAA and GISTEMP temperature datasets are shown in Technical Annex 1.A Figure 3-5 respectively.



Technical Annex 1.A, Figure 3: As for Figure 1.1 but using the HadCRUT4 temperature dataset.



Technical Annex 1.A, Figure 4: As for Figure 1.1 but using the NOAA temperature dataset.



Technical Annex 1.A, Figure 5: As for Figure 1.1 but using the GISTEMP temperature dataset.

Annex 1.A.2: supporting material for Figure 1.2

Observational data used in Chapter figure 1.2 are taken from the Met Office Hadley Centre (http://www.metoffice.gov.uk/hadobs/hadcrut4/), National Oceanic and Atmospheric Administration (NOAA) (https://www.ncdc.noaa.gov/data-access/marineocean-data/noaa-global-surface-temperature-noaaglobaltemp), NASA's Goddard Institute for Space Studies (https://data.giss.nasa.gov/gistemp/) and the Cowtan & Way dataset (http://www-users.york.ac.uk/~kdc3/papers/coverage2013/series.html). The GISTEMP and NOAA observational products (which begin in 1880) are expressed relative to 1850-1900 by assigning these datasets the same anomaly as HadCRUT4 for the mean of the 1880-2017 period. All available data is used, through to the end of 2017, for all datasets. The grey "Observational range" shades between the minimum and maximum monthly-mean anomaly across these four temperature datasets for the month in question.

CMIP5 multi-model means, light blue dashed (full field surface air temperature) and solid (masked and blended as in Cowtan et al. (2015)) are expressed relative to a 1861-1880 base period and then expressed relative to the 1850-1900 reference period using the anomaly between the periods in the HadCRUT4 product (0.02°C). Model data are taken from Richardson et al. (2018). Only RCP8.5 r1i1p1 ensemble members are used with only one ensemble member per model for calculating the mean lines in this figure.

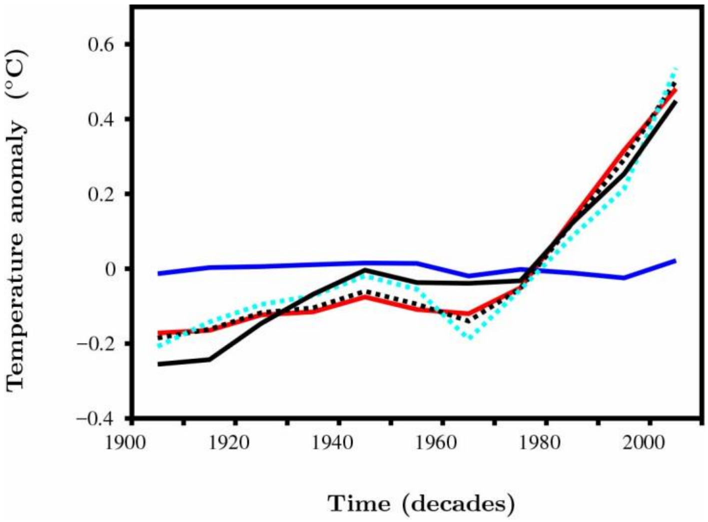
The pink "Holocene" shading is derived from the "Standard5x5Grid" reconstruction of Marcott et al. (2013) (expressed relative to 1850-1900 using the HadCRUT4 anomaly between this reference period and the 1961-90 base period of the data). The vertical extent of the solid shading is determined by the maximum and minimum temperature anomalies in the dataset in the period before 1850. Marcott et al. (2013) report data with a periodicity of 20 years, so the variability shown by the solid pink shading is not directly comparable to the higher frequency variability seen in the observational products which are reported every month), but this Holocene range can be compared to the emerging signal of human-induced warming. Above and below the maximum and minimum temperature anomalies from Marcott et al. (2013) the pink shading fades out to after a magnitude of warming that is equal to the standard deviation of monthly temperature anomalies in the HadCRUT4 dataset over the pre-industrial reference period of 1850-1900, and as such this faded shading does not bound all monthly anomalies in the pre-industrial reference period.

Near term predictions from IPCC-AR5 (Kirtman et al., 2013), for the period 2016-2035 were estimated to be *likely* (>66% probability) between 0.3°C and 0.7°C above the 1986-2005 average, assuming no climatically significant future volcanic eruptions. These are expressed relative to pre-industrial using the updated 0.63°C warming to the 1986-2005 period (Section 1.2.1).

Human-induced temperature change (thick yellow line) and total (human+natural) externally-forced temperature change (thick orange line) are estimated using the method of Haustein et al. (2017) applied to the 4-dataset mean. Best-estimate historical radiative forcings, extended until the end of 2016, are taken from Myhre et al. (2013), incorporating the significant revision to the methane forcing proposed by Etminan et al. (2016). The 2-box thermal impulse-response model used in Myhre et al. (2013), with modified thermal response time-scales to match the multi-model mean from Geoffroy et al. (2013), is used to derive the shape to the global mean temperature response timeseries to total anthropogenic and natural (combined volcanic and solar) forcing. Both of these timeseries are expressed as anomalies relative to their simulated 1850-1900 averages and then used as independent regressors in a multi-variate linear regression to derive scaling factors on the two timeseries that minimise the residual between the combined forced response and the multi-dataset observational mean. The transparent shading around the thick yellow line indicates the *likely* range in attributed human-induced warming conservatively assessed at ±20%. Note that the corresponding *likely* range of ±0.1°C uncertainty in the 0.7°C best-estimate anthropogenic warming trend over the 1951-2010 period assessed in Bindoff et al. (2013) corresponds to a smaller fractional uncertainty (±14%): the broader range reflects greater uncertainty in early-century warming.

The vertical extent of the 1986-2005 cross denotes the 5-95% observational uncertainty range of ±0.06°C (see Table 1.1) while that of the 2006-2015 cross denotes the assessed *likely* uncertainty range of ±0.12°C (Section 1.2.1).

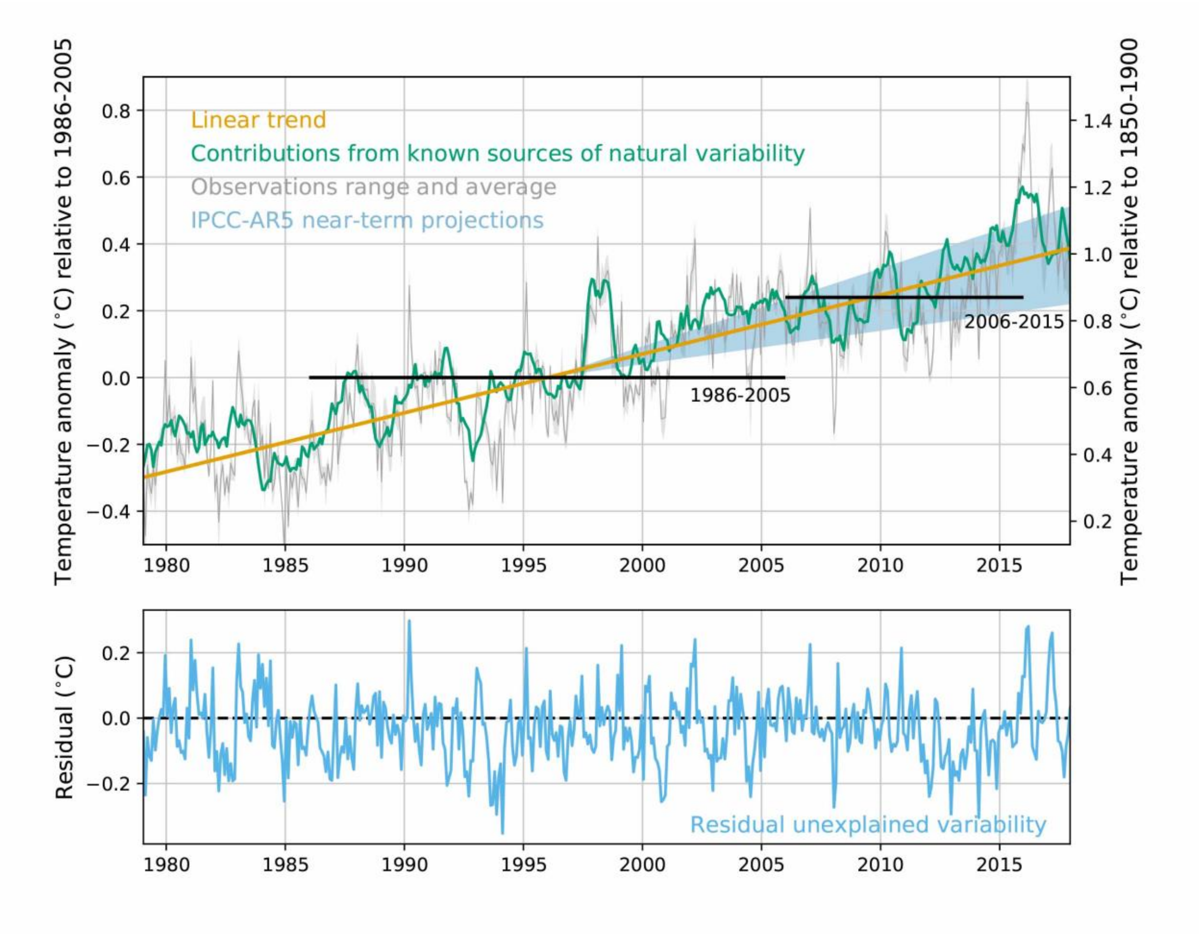
To provide a methodologically independent check on the attribution of human-induced warming since the 19^{th} century (quantitative attribution results quoted in AR5 being primarily focussed on the period 1951-2010), Technical Annex 1.A Figure 6 shows a recalculation of the results of Ribes and Terray (2013), figure 1, applied to the CMIP5 multi-model mean response. Details of the calculation are provided in the original paper. In order to quantify the level of human-induced warming since the late 19^{th} century, observations of GMST are regressed onto the model responses to either natural-only (NAT) or anthropogenic-only (ANT) forcings, consistent with many attribution studies assessed in AR5. Prior to this analysis, model outputs are pre-processed in order to ensure consistency with observations: spatial resolution is lowered to 5°, the spatio-temporal observational mask is applied, and all missing data are set to 0. Global and decadal averages of near-surface temperature are calculated over the 1901-2010 period (11 decades), and translated into anomalies by subtracting the mean over the entire period (1901-2010). Multi-model mean response patterns are calculated over a subset of 7 CMIP5 models providing at least 4 historical simulations and 3 historical NAT-only simulations, all covering the 1901-2010 period. The regression analysis indicates how these multi-model mean responses have to be rescaled in order to best fit observations, accounting for internal variability in both observations and model responses, but neglecting observational uncertainty. Almost no rescaling is needed for ANT (regression coefficient: 1.05 ±0.18), while the NAT simulated response is revised downward (regression coefficient: 0.28±0.49). The resulting estimate of the total externally forced response is very close to observations (Figure 6). The ANT regression coefficient can then be used to assess the human-induced warming over a longer period. Estimated in this way, the human-induced linear warming trend 1880-2012 is found to be 0.86°C±0.14°C.



Technical Annex 1.A, Figure 6: Contributions of natural (NAT) and anthropogenic (ANT) forcings to changes in GMST over the period 1901-2010. Decadal time-series of GMST in HadCRUT4 observations (solid black), from multi-model mean response without any rescaling (dotted cyan), and as reconstructed by the linear regression (dotted black). The estimated contributions of NAT forcings only (solid blue) and anthropogenic forcing only (solid red) correspond to the CMIP5 multi-model mean response to these forcings, after rescaling. All temperatures are anomalies with respect to the 1901-2010 average, after pre-processing (missing data treated as 0). Vertices are plotted at the mid-point of the corresponding decade.

To quantify the potential impact of natural (externally-forced or internally-generated) variability on decadal-mean temperatures in 2006-2015, Technical Annex1.A Figure 7 shows an estimate of the observed warming rate, corrected for the effects of natural variability according to the method of Foster and Rahmstorf, (2011) applied to the average of the four observational datasets used in this report, updated to the end of 2017. The grey line shows the raw monthly GMST observations (with shading showing inter-dataset range), while the green shows the sum of the linear trend plus estimated known sources of variability, such as El Niño events or volcanic eruptions, estimated using an empirical regression model. The orange line shows the linear trend, after correcting for the impact of these known sources of variability, of 0.18°C per decade, while the two black lines show the recent reference periods used in this report. For comparison, the AR5 near-term predicted warming rate of 0.3-0.7°C over 30 years (Kirtman et al, 2013) is shown as the pale blue plume.

The blue line in the lower panel shows residual fluctuations that cannot be attributed to known sources or modes of variability, reflecting internally-generated chaotic weather variability (the difference between grey and green lines in the top panel). The green line is not persistently below the yellow line, nor is the blue line persistently negative, over the period 2006-2015. There is a downward excursion in the residual “unexplained” variability around 2012-13, and a strong ENSO cool phase event in 2011, but even together these depress the decadal average by only a couple of hundredths of a degree.

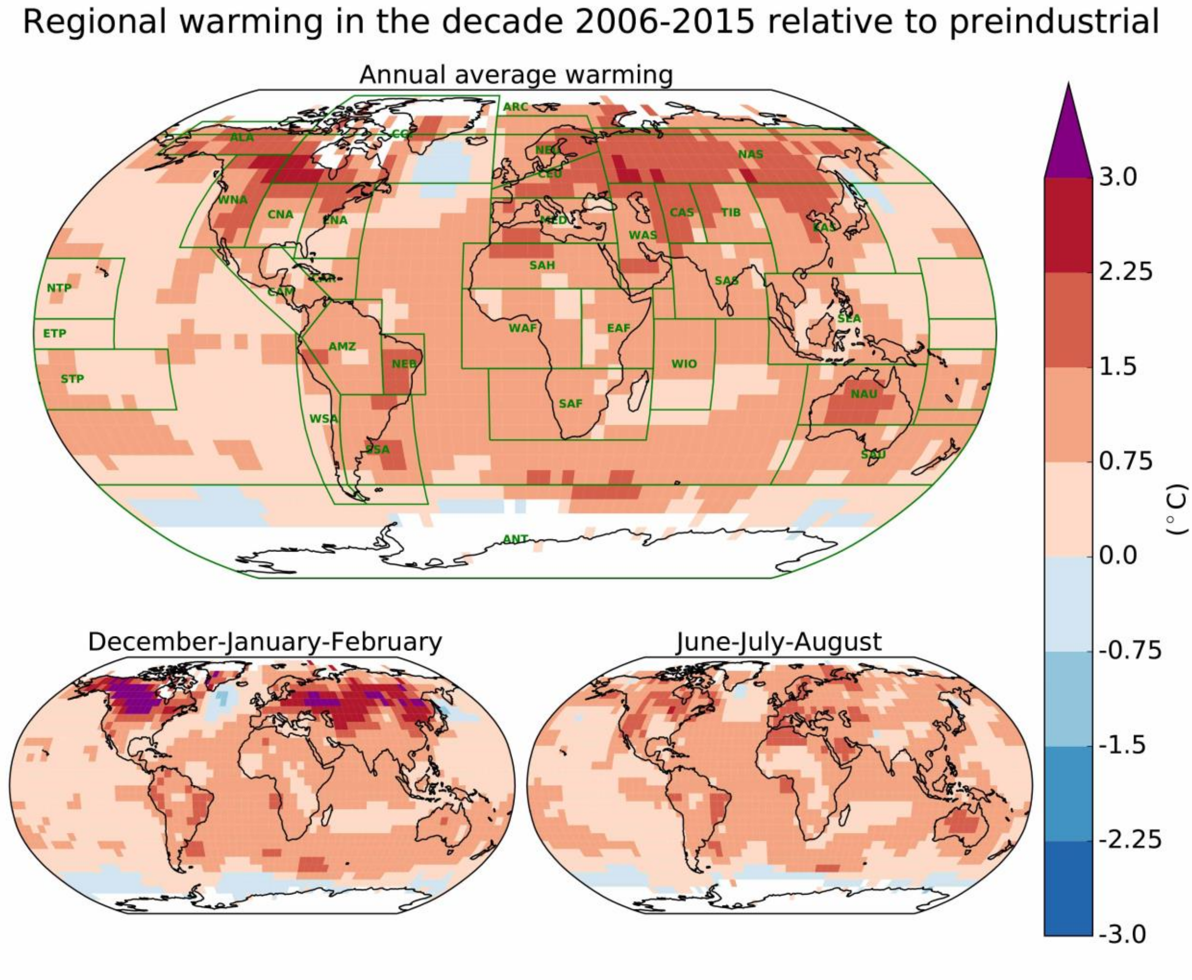


Technical Annex 1.A, Figure 7: Warming and warming rate 1979-2017. The solid grey line shows the average of the four observational datasets used in this assessment report with the observational range shown by grey shading. The yellow line shows the linear trend through the observational data, corrected for the effects of known sources of natural variability (green line). The blue shading indicates that warming rates compatible with the IPCC-AR5 near-term projections. The lower panel shows the residual unexplained variability (difference between grey and green lines in upper panel) after accounting for known sources, including ENSO, solar variability and volcanic activity.

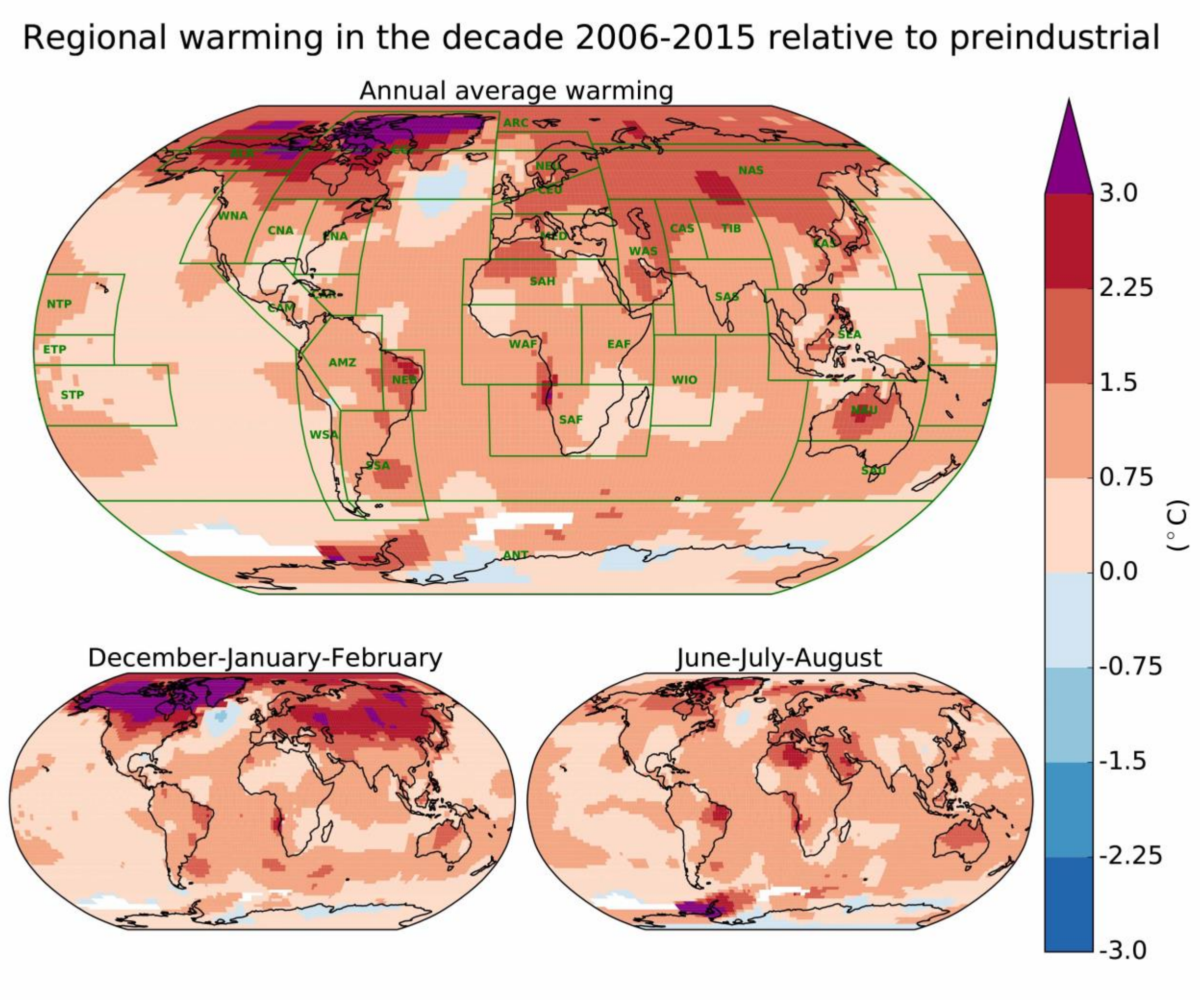
Annex 1.A.3: supporting material for Figure 1.3

Regional warming shown in Figure 1.3 is derived using a similar method to the calculation of externally-forced warming in Figure 1.2. At every grid box location in the native Cowtan & Way resolution, the timeseries of local temperature anomalies in the Cowtan & Way dataset are regressed onto the associated externally-forced warming timeseries, calculated as in Figure 1.1 using all available historical monthly-mean anomalies. The best-fit relationship between these two quantities is then used to estimate the forced warming relative to 1850-1900 at this location. The maps in Figure 1.3 show the average of these estimated local forced warming timeseries over the 2006-2015 period. Trends are only plotted only where over 50% of the entire observational record at this location is available.

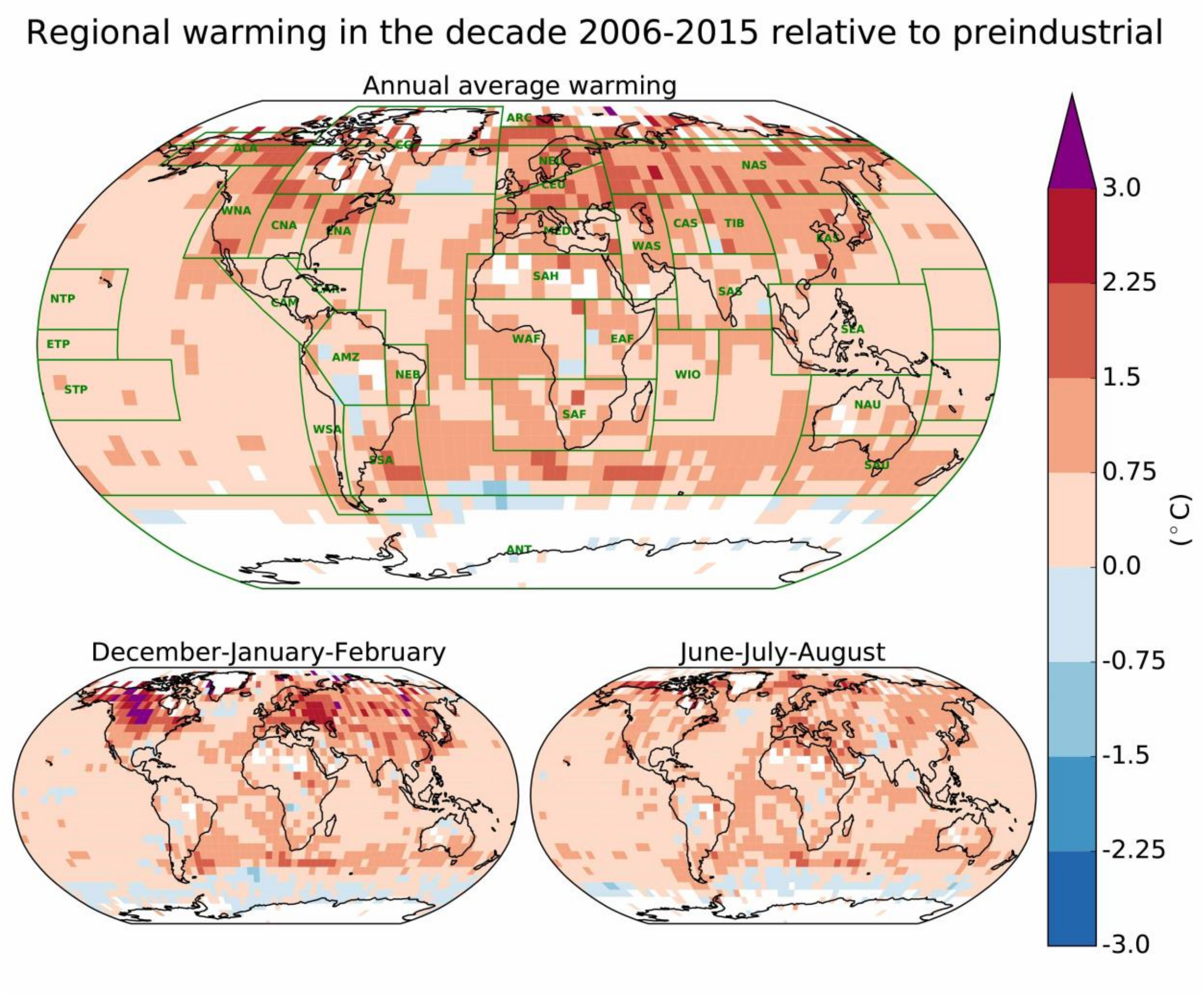
Supplementary maps are included below for the NOAA, GISTEMP and HadCRUT4 observational data. The regression of local temperature anomalies onto the global mean externally-forced warming, allows warming to be expressed relative to 1850-1900 despite many local series in these datasets beginning after 1900, but clearly these inferred century-time-scale warming levels are subject to a lower confidence level than the corresponding global values.



Technical Annex 1.A Figure 8: Externally-forced warming for the average of 2006-2015 relative to 1850-1900 calculated for the NOAA observational dataset as for Figure 1.3.



Technical Annex 1.A, Figure 9: Externally-forced warming for the average of 2006-2015 relative to 1850-1900 calculated for the GISTEMP observational dataset as for Figure 1.3.



Technical Annex 1.A, Figure 10: Externally-forced warming for the average of 2006-2015 relative to 1850-1900 calculated for the HadCRUT4 observational dataset as for Figure 1.3.

Annex 1.A.4: supporting material for Figure 1.4

Idealised temperature pathways computed by specifying the level of human-induced warming in 2017, $T_{2017} = 1°\mathrm{C}$, with temperatures from 1850 to 2017 approximated by an exponential rise, with the exponential rate constant, γ, set to give a rate of human-induced warming in 2017 of 0.2°C/decade. Temperatures from 2018-2100 are determined by fitting a smooth 4th-order polynomial through specified warming at particular times after 2017.

Radiative forcing F that would give the temperature profiles is computed using a 2-time-constant climate response function (Myhre et al., 2013b), with Equilibrium Climate Sensitivity (ECS) of 2.7°C and Transient Climate Response (TCR) of 1.6°C and other parameters as given in Millar et al. (2017). Equivalent CO_2 concentrations given by $C = 278 \times \exp(F/5.4)$ ppm.

Cumulative CO_2-forcing-equivalent emissions (Jenkins et al, 2018), or the CO_2 emission pathways that would give the CO_2 concentration pathways compatible with the temperature scenario is computed using an invertible simple carbon cycle model (Myhre et al., 2013b), modified to account for changing CO_2 airborne fraction over the historical period (Millar et al., 2017). These are proportional to CO_2 emissions under the assumption of a constant fractional contribution of non-CO_2

forcers to warming. Indicative cumulative impact variable (e.g. sea level rise) is computed from temperature pathways shown in using semi-empirical model of Kopp et al. (2016).

Annex 1.A.5: supporting material for Figure 1.5

All scenarios in Figure 1.5 start with a 1000 member ensemble of the FAIR model (Smith et al., 2018) driven with emissions from the RCP historical dataset from 1765 to 2000 (Meinshausen et al., 2011), SSP2 from 2005 to 2020 (Fricko et al., 2017), and a linear interpolation between the two inventories for 2000 to 2005. Equilibrium climate sensitivity (ECS) and transient climate response (TCR) parameters are drawn from a joint lognormal distribution informed by CMIP5 models. Uncertainties in present-day non-CO_2 ERF are drawn from the distributions in Myhre et al. (2013) and uncertainties in the carbon cycle response are given a 5 to 95% range of 13% around the best estimate (Millar et al., 2017). All uncertainties except TCR and ECS are assumed to be uncorrelated with each other.

FAIR derives an effective radiative forcing (ERF) time series from emissions, from which temperature change calculated. Greenhouse gas concentrations are first calculated, from which the radiative forcing relationships from Myhre et al. (1998) are used to determine ERF. An increase of ERF of 25% for methane forcing is applied which approximates the updated relationship from Etminan et al. (2016). The Myhre et al. (1998) relationships with a scaling for methane rather than the newer Etminan et al. (2016) relationships are used because the former does not assume any band overlap between CO_2 and N_2O, and isolating CO_2 forcing from N_2O forcing is problematic for certain commitments where CO_2 emissions are set to zero and N_2O forcing is held constant.

Aerosol forcing is based on the Aerocom radiative efficiencies (Myhre et al., 2013a) for ERFari (ERF from aerosol-radiation interactions) and a logarithmic dependence on emissions of black carbon, organic carbon and sulfate for ERFaci (ERF from aerosol-cloud interactions) based on the model of Ghan et al., (2013). Tropospheric ozone forcing is based on Stevenson et al., (2013). Other minor categories of anthropogenic forcing are derived from simple relationships that approximate the evolution of ERF in Annex II of Working Group I of AR5 (Prather et al., 2013) as described in Smith et al., (2018). For forcing categories other than methane (for which a significant revision to be best estimate ERF has occurred since AR5), a time-varying scaling factor is implemented over the historical period, so that for a best estimate forcing, the AR5 ERF time series is replicated. This historical scaling decays linearly between 2000 and 2011 so that in 2011 onwards the FAIR ERF estimate is used for projections. For the 2000-2011 period the impact of the historical scaling is small, because FAIR emissions-forcing relationships are mostly derived from IPCC AR5 best estimates in 2005 or 2011 (Smith et al., 2018).

Two ensembles are produced: a historical (1765 to 2014) ensemble containing all (anthropogenic plus natural) forcing, and a historical+future (1765 to 2100) ensemble containing only anthropogenic forcing for each commitment scenario. In the ensemble where natural forcing is included, solar forcing for the historical period is calculated by using total solar irradiance from the SOLARIS HEPPA v3.2 dataset (Matthes et al., 2017) for 1850-2014 and from Myhre et al. (2013) for 1765-1850: the 1850-1873 mean is subtracted from the time series which is then multiplied by 0.25 (annual illumination factor) times 0.7 (planetary co-albedo) to generate the effective radiative forcing (ERF) timeseries. Volcanic forcing is taken by using stratospheric aerosol optical depths from the CMIP6 historical Easy Volcanic Aerosol dataset (Toohey et al., 2016) prepared for the HadGEM3 CMIP6 historical integrations for 1850-2014. The integrated stratospheric aerosol optical depth at 550 nm (tau) is calculated and converted to ERF by the relationship ERF = -18*tau, based on time slice experiments in the HadGEM3 general circulation model, which agrees well with earlier HadGEM2 and HadCM3 versions of the UK Met Office Hadley Centre model (Gregory et al., 2016). The 1850-2014 mean volcanic ERF of -0.107 is subtracted as an offset to define the mean historical volcanic

ERF as zero. Owing to rapid adjustments to stratospheric aerosol forcing, which are included in the definition of ERF, this less negative value of -18*tau is adopted for volcanic ERF than the RF = -25*tau used in AR5.

The historical all-forcing scenario is then used to constrain parameter sets that satisfy the historical observed temperature trend of 0.90 ± 0.19°C (mean and 5 to 95% range) over the 1880 to 2014 period, using the mean of the HadCRUT4, GISTEMP and NOAA datasets. The trend was derived using an inflation factor for autocorrelation of residuals, and is the same method used to derive linear temperature trends in AR5 (Hartmann et al., 2013). The uncertainty bounds used here are wider than, but consistent with, the 1-sigma range of ±0.12°C assessed for the temperature change in 2006-2015 relative to 1850-1900. The parameter sets that satisfy the historical temperature constraint in the historical ensemble (323 out of 1000) are then selected for the anthropogenic-only ensembles that include commitments.

Each commitment scenario is driven with the following assumptions:

1. Zero CO_2 emissions, constant non-CO2 forcing (blue): FAIR spun up with anthropogenic forcing to 2020. Total non-CO_2 forcing in 2020 is used as the input to the 2021-2100 period with all CO_2 fossil and land use emissions abruptly set to zero.

2. Phase out of CO_2 emissions with 1.5°C commitment (blue dotted): FAIR spun up with anthropogenic forcing to 2020. Total non-CO_2 forcing in 2020 is used as the input to the 2021-2100 periof. Fossil and land-use CO_2 emissions are ramped down to zero at a linear rate over 50 years from 2021 to 2070, consistent with a 1.5°C temperature rise since pre-industrial at the point of zero CO_2 emissions in 2070.

3. Linear continuation of 2010-2020 temperature trend (blue dashed, in bottom panel only).

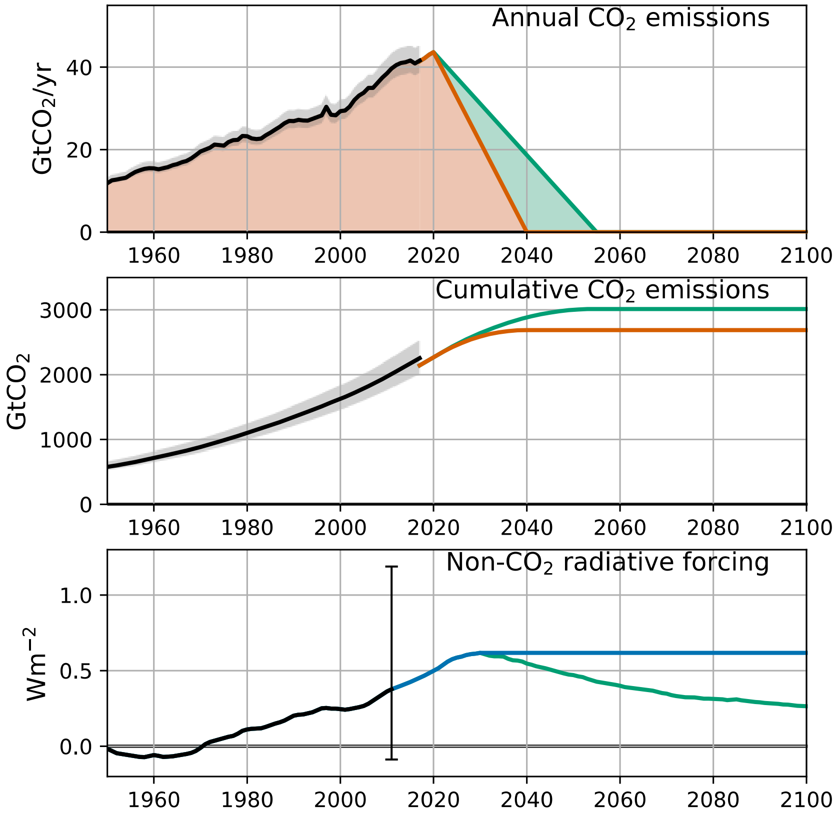
4. Zero GHG emissions, constant aerosol forcing (pink): FAIR spun up with anthropogenic forcing to 2020. All GHG emissions set abruptly to zero in 2021, with aerosol emissions held fixed at their 2020 levels.

5. Zero CO_2 and aerosol emissions, constant non-CO_2 GHG forcing (teal): FAIR spun up with anthropogenic forcing to 2020. Total non-CO_2 GHG forcing, which also includes the proportion of tropospheric ozone forcing attributable to methane emissions, in 2020 is used as the input to the 2021-2100 period. Fossil and land-use CO_2 and aerosol emissions abruptly set to zero in 2021.

6. Zero emissions (yellow): FAIR spun up with anthropogenic forcing to 2020. All emissions set abruptly to zero in 2021.

Annex 1.A.6: supporting material for FAQ 1.2 Figure 1 and Figure SPM1

This section provides supporting material for the figure in FAQ 1.2 and the figure SPM1 in the Summary for Policymakers. Figure 11, top panel, shows time-series of annual CO_2 emissions from the Global Carbon Project (Le Quéré et al, 2018) (black line and grey band, with the width of the band indicating the *likely* range, or one-standard-error, uncertainty in annual emissions), extrapolated to 2020 and then declining in a straight line to reach net zero in either 2055 (green line) or 2040 (brown line).



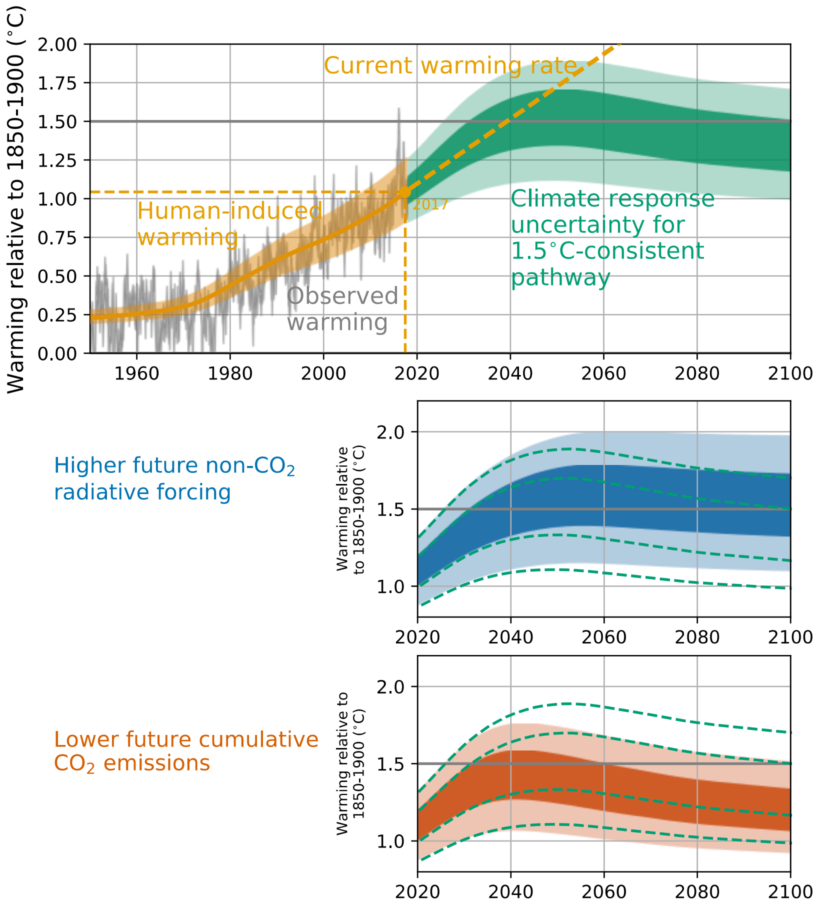
Technical Annex 1.A, Figure 11: Time-series of (top) annual CO_2 emissions, (middle) cumulative CO_2 emissions, and (bottom) non-CO_2 radiative forcing corresponding to observation-based estimates over the historical period and idealised 1.5°C-consistent pathways.

The middle panel in figure 11 shows cumulative (time-integrated) CO_2 emissions, or the areas highlighted as brown+green or brown, respectively, in the top panel. Brown and green lines show cumulative emissions diagnosed from a simple climate-carbon-cycle model (Millar et al, 2017), with historical airborne fraction scaled to reproduce median estimated annual emissions in 2017. Note this does not precisely reproduce median estimated cumulative emissions in 2017, but is well within the range of uncertainty.

The bottom panel in figure 11 shows median non-CO2 effective radiative forcing (ERF) estimates used to drive the model over the historical period, extending forcing components using the RCP8.5 scenario (http://www.pik-potsdam.de/~mmalte/rcps/) between 2011 and 2020, with scaling applied to each full forcing component time-series to match the corresponding AR5 ERF component in 2011. The vertical bar in 2011 shows a simple indication of the *likely* range of non-CO_2 forcing in 2011 obtained simply by subtracting the best-estimate CO_2 forcing from the total anthropogenic forcing uncertainty, assuming the latter is normally distributed: AR5 did not give a full assessment of the distribution of non-CO_2 radiative forcing. It demonstrates there is considerable uncertainty in this quantity, which translates into uncertainty in climate system properties inferred from these data, but has a much smaller impact on estimates of human-induced warming to date, because this is also constrained by temperature observations. The green line shows non-CO_2 forcing in an indicative 1.5°C-consistent pathway consistent with those assessed by Chapter 2, while the blue line shows an idealised case in which non-CO_2 forcing remains constant after 2030.

For all percentiles of the climate response distribution, non-CO_2 forcing timeseries for these idealised scenarios are scaled to allow the corresponding percentiles of the assessed *likely* range of human-induced warming in 2017 to be achieved, assuming the latter is normally distributed. All non-CO_2 forcing components other than aerosols are scaled following their corresponding ranges of uncertainty of values in 2011 given in AR5, with low values of 2011 ERF corresponding to high values of TCR and *vice versa*. This accounts for the anti-correlation between estimated values of the TCR and estimates of current anthropogenic forcing. Then aerosol ERF (the most uncertain component) is scaled to reproduce the correct percentile of human-induced warming in 2011. Values of TCR, ECS and 2011 forcing components are given in Technical Annex 1.A Table 1.

Figure 12 shows timeseries of observed and human-induced warming to 2017 and responses to these idealised future emissions scenarios. Observed and human-induced warming estimates are reproduced exactly as in Figure 1.2, with the orange shaded band showing the assessed uncertainty range of ±20%. The dashed line shows a simple linear extrapolation of the current rate of warming, as calculated over the past 5 years. Responses to idealized future CO_2 emissions and non-CO_2 forcing trajectories are simulated with the FAIR simple climate-carbon-cycle model (Millar et al, 2017b). The four values of the Transient Climate Response (TCR) shown (giving the borders of the green, blue and orange shaded regions) correspond to the 17^{th}, 33^{rd}, 67^{th} and 83^{rd} percentiles of a normal distribution compatible with the *likely* range of TCR as assessed by AR5, combined with the same percentiles of a log-normal distribution for the Equilibrium Climate Sensitivity (ECS) similarly anchored to the AR5 *likely* range for this quantity. Other thermal climate response parameters (short and long adjustment time-scales) are set to match those given in Myhre et al (2013) as used in Millar et al (2017a).



Technical Annex 1.A, Figure 12: Time-series of observed and human-induced warming to 2017 and responses to idealised 1.5°C-consistent pathways of CO_2 and non-CO_2 forcing shown in figure 11.

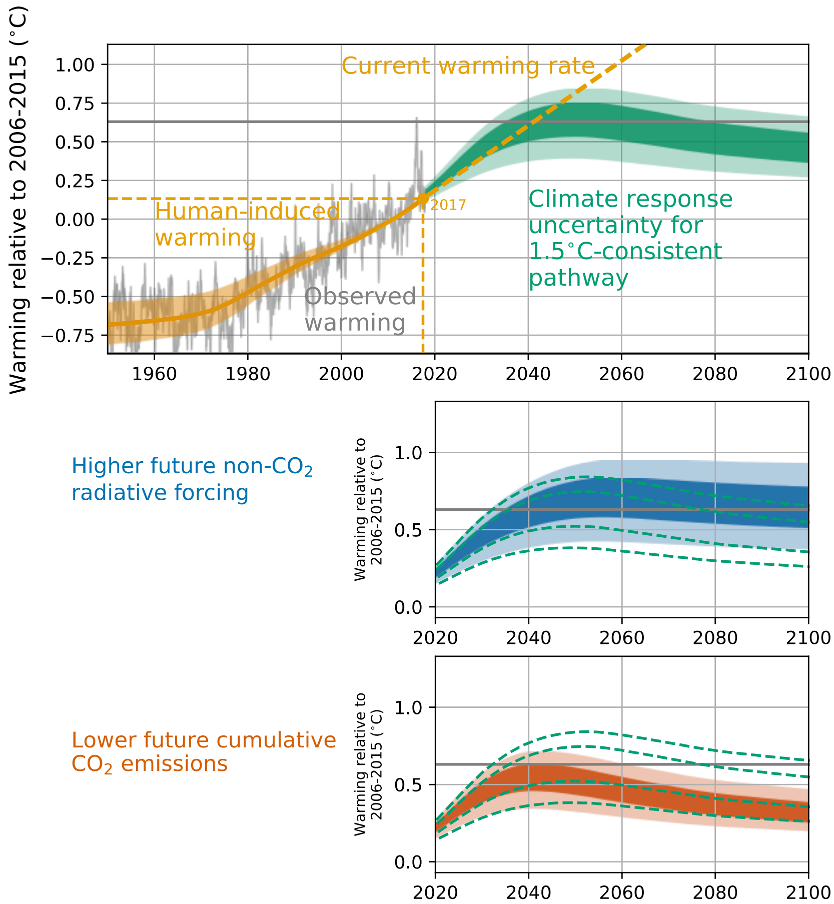
All 1.5°C-consistent scenarios that are also consistent with current emissions and radiative forcing trends show increasing non-CO_2 radiative forcing over the coming decade, as emissions of cooling aerosol precursors are reduced, but there is greater variation between scenarios in non-CO_2 radiative forcing after 2030. The middle panel in figure 12 shows the impact of varying future non-CO_2 radiative forcing (green and blue lines in figure 11, bottom panel), while the green dashed lines show the original percentiles from the top panel. Failure to reduce non-CO_2 forcing after 2030 means that a scenario that would give temperatures *likely* below 1.5°C in 2100 instead give only temperatures *as likely as not* below 1.5°C by 2100. If non-CO_2 forcing were allowed to increase further (as it does in some scenarios due primarily to methane emissions), it would increase 2100 temperatures further.

The bottom panel of figure 12 shows the impact of reducing cumulative CO_2 emissions up to the time they reach net zero by bringing forward the date of net-zero emissions from 2055 to 2040. This reduces future warming, with the impact emerging after 2030, such that the entire *likely* range of future warming is now (on this estimate of the climate response distribution) below 1.5°C in 2100. These changes demonstrate how future warming is determined by cumulative CO_2 emissions up to the time of net-zero and non-CO_2 forcing in the decades immediately prior to that time.

Technical Annex 1.A, Table 1: Climate system properties in the versions of the FAIR model used in figures 12 and 13 of this Technical Annex as well as the FAQ 1.2 figure and figure SPM1. TCR, ECS and total anthropogenic forcing, F_{ant}, in 2011 are set consistent with corresponding distributions in AR5, TCRE is diagnosed from the model while aerosol forcing F_{aer} is adjusted to reproduce the corresponding percentile of human-induced warming in 2017.

Percentile	TCR (°C)	ECS (°C)	TCRE (°C/TtC)	F_{aer} in 2011 (W/m^2)	F_{ant} in 2011 (W/m^2)
17%	1.0	1.5	0.9	-0.67	3.02
33%	1.4	2.0	1.3	-0.95	2.46
50%	1.75	2.6	1.5	-0.99	2.20
67%	2.1	3.3	1.75	-0.95	2.01
83%	2.5	4.5	2.2	-0.84	1.84

Carbon budget calculations in Chapter 2 are based on temperatures relative to 2006-2015, offset by a constant 0.87°C representing the best-estimate observed warming from pre-industrial to that decade. This has little effect on median estimates of future warming, because the median estimated human-induced warming to the decade 2006-2015 was close to the observed warming, but it does affect uncertainties: the uncertainty in 2030 warming relative to 2006-2015 is lower than the uncertainty in 2030 warming relative to pre-industrial because of the additional information provided by the current climate state and trajectory. This additional information is particularly important for the response to rapid mitigation scenarios in which peak warming occurs a small number of decades into the future (Millar et al, 2017a; Leach et al, 2018), highlighting the particular importance of a "seamless" approach to seasonal-to-decadal forecasting (Palmer et al, 2008; Boer et al, 2016) in the context of 1.5°C. The impact of this additional information is illustrated in figure 13, which is constructed identically to figure 12 but shows all time-series expressed as anomalies relative to 2006-2015 rather than 1850-1900. The thick grey line at 0.63°C shows 1.5°C relative to pre-industrial expressed relative to this more recent decade. The central estimate is unaffected, as is the estimate of the time at which temperatures reach 1.5°C if the current rate of warming continues, but uncertainties are reduced. For example, the idealised pathway with CO_2 emissions reaching zero in 2040 is *likely* to limit warming to less than 0.63°C above 2006-2015, even though it just overshoots 1.5°C relative to 1850-1900.



Technical Annex 1.A, Figure 13: As figure 12, but showing time-series of observed and human-induced warming to 2017 and responses to idealised 1.5°C-consistent pathways relative to 2006-2015. Level of warming corresponding to 1.5°C relative to pre-industrial given central estimate of observed warming of 0.87°C from 1850-1900 to 2006-2015 is shown by horizontal line at 0.63°C.

Annex 1.A.7: Recent trends in emissions and radiative forcing

Figure 1.2 shows a small increase in the estimated rate of human–induced warming since 2000, reaching 0.2°C per decade in the past few years. This is attributed (Haustein et al., 2017) to recent changes in a range of climate forcers, reviewed in this section.

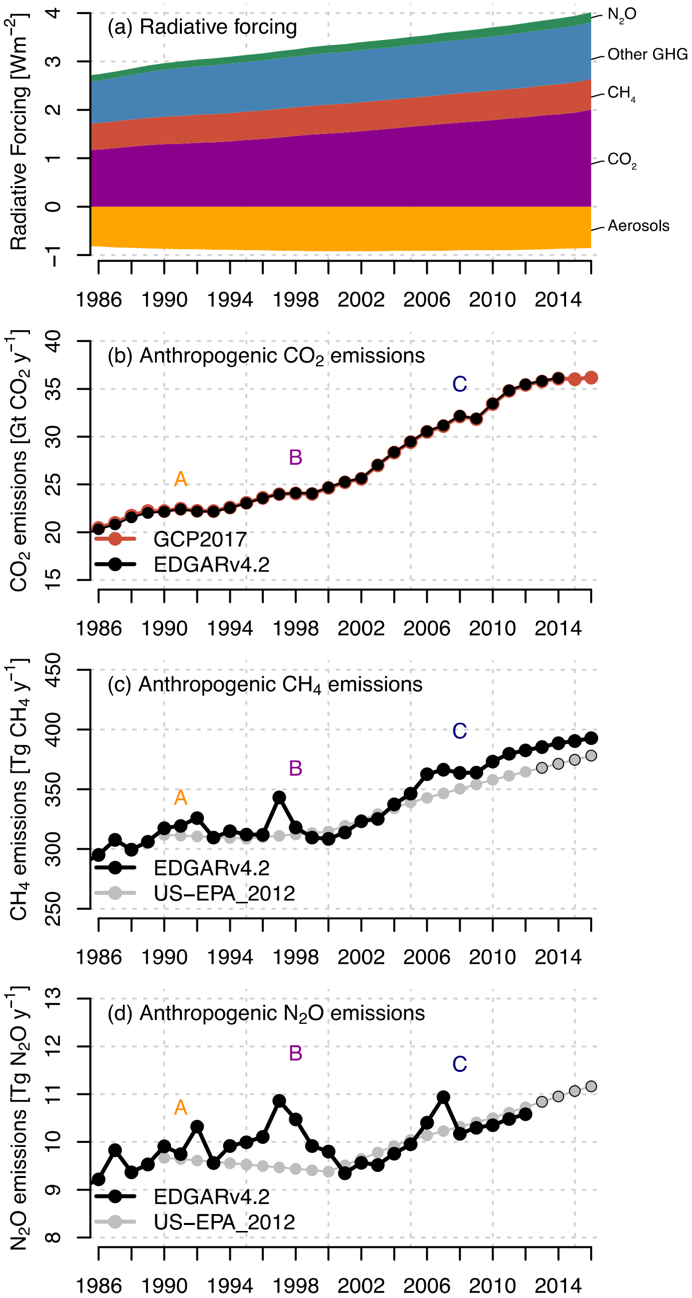
Most studies partition anthropogenic climate forcers into two groups by their lifetime. CO_2 and other long–lived greenhouse gases such as nitrous oxide, sulphur hexafluoride and some halogenated gases contribute to forcing over decades and centuries. Other halogenated gases, ozone precursors and aerosols are defined as short–lived climate forcers (SLCF) due to their residence time of less than several years in the atmosphere. Although methane is either considered as a LLCF or SLCF in published studies or reports (Bowerman et al., 2013; Estrada et al., 2013; Heede, 2014; Jacobson, 2010; Kerr, 2013; Lamarque et al., 2011; Saunois et al., 2016a; WMO, 2015), we assign methane as a SLCF for the purpose of climate assessment, because its lifetime is comparable to or shorter than the thermal adjustment time of the climate system (Smith et al., 2012).

CO_2, methane and nitrous oxide are the most prominent contributors of anthropogenic radiative forcing, contributing 63%, 20% and 6% of the anthropogenic radiative forcing in 2016 respectively, as shown in Figure 14(a). Other long-lived greenhouse gases, including halogenated gases, and SLCFs such as tropospheric ozone are responsible of about 37% of the anthropogenic radiative forcing (figures add up to more than 100% because of the compensating effect of aerosols). Emissions such as black carbon and sulphur dioxide form different types of aerosol particles, which interact with both shortwave and longwave radiation and alter clouds. The resulting net aerosol radiative forcing is spatially inhomogeneous and uncertain. Globally averaged, it is estimated to have reduced the globally averaged anthropogenic forcing by about 27% (figures from Myhre et al. (2013), updated: uncertainties in aerosol forcing in particular are reviewed in AR5, and will be reassessed in AR6. This report continues to work from the AR5 estimates.).

As shown in Figure 14 (b), the growth of CO_2 emissions has slowed since 2013 because of changes in the energy mix moving from coal to natural gas and increased renewable energy generation (Boden et al., 2015). This slowdown in CO_2 emission growth has occurred despite global GDP growth increasing to 3% y^{-1} in 2015, implying a structural shift away from carbon intensive activities (Jackson et al., 2015; Le Quéré et al., 2018). In 2016, however, anthropogenic CO_2 emissions are 36.18 $GtCO_2\ y^{-1}$ and have begun to grow again by 0.4% with respect to 2015 (Le Quéré et al., 2018). Global average concentration in 2016 has reached 402.3 ppm, which represents an increase of about 38.4% from 1850–1900 average (290.7 ppm).

Figure 14 (c) and (d) show that methane and nitrous oxide emissions, unlike $CO_{2,}$ have followed the most emission–intensive pathways assessed in AR5 (Saunois et al., 2016b; Thompson et al., 2014). However, current trends in methane and nitrous oxide emissions are not driven in the same way by human activities. About 60% of methane emissions are attributed to human activities (e.g. ruminants, rice agriculture, fossil fuel exploitation, landfills and biomass burning, Saikawa et al., 2014; Saunois et al., 2016b), while about 40% of nitrous oxide emissions are caused by various industrial processes and agriculture (Bodirsky et al., 2012; Thompson et al., 2014). It is thus more complicated to link rates of emissions to economic trends or energy demands than is the case with CO_2 (Peters et al., 2011).

Estimates of anthropogenic emissions for methane and nitrous oxide are uncertain as shown by the difference between datasets in Figure 1.4 EDGARV4.2 (JRC, 2011) estimates and US–EPA projections give a global amount of methane emission ranging between 392.87 and 378.29 $TgCH_4y^{-1}$ by 2016 which corresponds to a relative increase of 0.6–1% compared to 2015 emissions. However, livestock emissions in these databases are considered to be underestimated (Wolf et al., 2017). Similar uncertainties exist for anthropogenic N_2O emissions for which only US–EPA projections are available. According to US–EPA projections, anthropogenic N_2O emissions reach 11.2 $TgN_2O\ y^{-1}$, representing a relative increase of about 1% compared to 2016. Anthropogenic CH_4 and N_2O emissions also appear to respond to major economic crises.



Technical Annex 1.A, Figure 14: Time series of anthropogenic radiative forcing (a), CO_2, methane (CH_4) and nitrous oxide (N_2O) emissions (b–d) for the period 1986–2016. Anthropogenic radiative forcing data is from Myhre et al., (2013), extended from 2011 until the end of 2017 with greenhouse gas data from Dlugokencky and Tans (2016), updated radiative forcing approximations for greenhouse gases (Etminan et al., 2016) and extended aerosol forcing following (Myhre et al., 2017). Bar graph shows the sum of different forcing agents. Anthropogenic CO_2 emissions are from the Global Carbon Project (GCP2017; Le Quéré et al., 2018), and EDGAR (Joint Research Centre, 2011) datasets. Anthropogenic emissions of CH_4 and N_2O (e) are estimated from EDGAR (JRC, 2011) and the US Environmental Protection Agency (EPA, 1990). Economic crisis (Former Soviet Union, A; Asian financial crisis, B; global financial crisis, C) are reported following the methodology of (Peters et al., 2011).

References

Bindoff, N. L., Stott, P. A., AchutaRao, K. M., Allen, M. R., Gillett, N., Gutzler, D., et al. (2013). "Detection and Attribution of Climate Change: from Global to Regional," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Cambridge, UK and New York, NY, USA: Cambridge University Press), 426–488.

Cowtan, K., Hausfather, Z., Hawkins, E., Jacobs, P., Mann, M. E., Miller, S. K., et al. (2015). Robust comparison of climate models with observations using blended land air and ocean sea surface temperatures. *Geophys. Res. Lett.* 42, 6526–6534. doi:10.1002/2015GL064888.

Cowtan, K., and Way, R. G. (2014). Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. *Q. J. R. Meteorol. Soc.* 140, 1935–1944. doi:10.1002/qj.2297.

Doxsey-Whitfield, E., MacManus, K., Adamo, S. B., Pistolesi, L., Squires, J., Borkovska, O., et al. (2015). Taking Advantage of the Improved Availability of Census Data: A First Look at the Gridded Population of the World, Version 4. *Pap. Appl. Geogr.* 1, 226–234. doi:10.1080/23754931.2015.1014272.

Etminan, M., Myhre, G., Highwood, E. J., and Shine, K. P. (2016). Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophys. Res. Lett.* 43, 12,614-12,623. doi:10.1002/2016GL071930.

Foster, G., and Rahmstorf, S. (2011). Global temperature evolution 1979–2010. *Environ. Res. Lett.* 6, 044022. doi:10.1088/1748-9326/6/4/044022.

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., et al. (2017). The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Glob. Environ. Chang.* 42, 251–267. doi:10.1016/j.gloenvcha.2016.06.004.

Geoffroy, O., Saint-Martin, D., Olivié, D. J. L., Voldoire, A., Bellon, G., and Tytéca, S. (2013). Transient climate response in a two-layer energy-balance model. Part I: Analytical solution and parameter calibration using CMIP5 AOGCM experiments. *J. Clim.* 26, 1841–1857. doi:10.1175/JCLI-D-12-00195.1.

Ghan, S. J., Smith, S. J., Wang, M., Zhang, K., Pringle, K., Carslaw, K., et al. (2013). A simple model of global aerosol indirect effects. *J. Geophys. Res. Atmos.* 118, 6688–6707. doi:10.1002/jgrd.50567.

Gregory, J. M., Andrews, T., Good, P., Mauritsen, T., and Forster, P. M. (2016). Small global-mean cooling due to volcanic radiative forcing. *Clim. Dyn.* 47, 3979–3991. doi:10.1007/s00382-016-3055-1.

Hartmann, D. J., Klein Tank, A. M. G., Rusticucci, M., Alexander, L. V, Brönnimann, S., Charabi, Y. A.-R., et al. (2013). "Observations: Atmosphere and Surface," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Cambridge, UK and New York, NY, USA: Cambridge University Press), 159–254. doi:10.1017/CBO9781107415324.008.

Haustein, K., Allen, M. R., Forster, P. M., Otto, F. E. L., Mitchell, D. M., Matthews, H. D., et al. (2017). A real-time Global Warming Index. *Sci. Rep.* 7, 15417. doi:10.1038/s41598-017-14828-5.

Kirtman, B., Adedoyin, A., and Bindoff, N. (2013). "Near-term Climate Change: Projections and Predictability," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Cambridge, UK and New York, NY, USA: Cambridge University Press), 953–1028. doi:10.1017/CBO9781107415324.023.

Kopp, R. E., Kemp, A. C., Bittermann, K., Horton, B. P., Donnelly, J. P., Gehrels, W. R., et al. (2016). Temperature-driven global sea-level variability in the Common Era. *Proc. Natl. Acad. Sci.* 113, 1–8. doi:10.1073/pnas.1517056113.

Marcott, S. A., Shakun, J. D., Clark, P. U., and Mix, A. C. (2013). A reconstruction of regional and global temperature for the past 11,300 years. *Science (80-.).* 339, 1198–201. doi:10.1126/science.1228026.

Matthes, K., Funke, B., Andersson, M. E., Barnard, L., Beer, J., Charbonneau, P., et al. (2017). Solar forcing for CMIP6 (v3.2). *Geosci. Model Dev.* 10, 2247–2302. doi:10.5194/gmd-10-2247-2017.

Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T., Lamarque, J., et al. (2011). The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Clim. Change* 109, 213–241. doi:10.1007/s10584-011-0156-z.

Millar, R. J., Nicholls, Z. R., Friedlingstein, P., and Allen, M. R. (2017). A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions. *Atmos. Chem. Phys.* 17, 7213–7228. doi:10.5194/acp-17-7213-2017.

Myhre, G., Highwood, E. J., Shine, K. P., and Stordal, F. (1998). New estimates of radiative forcing due to well mixed greenhouse gases. *Geophys. Res. Lett.* 25, 2715–2718. doi:10.1029/98GL01908.

Myhre, G., Samset, B. H., Schulz, M., Balkanski, Y., Bauer, S., Berntsen, T. K., et al. (2013a). Radiative forcing of the direct aerosol effect from AeroCom Phase II simulations. *Atmos. Chem. Phys.* 13, 1853–1877. doi:10.5194/acp-13-1853-2013.

Myhre, G., Shindell, D., Bréon, F., Collins, W., Fuglestvedt, J., Huang, J., et al. (2013b). “Anthropogenic and natural radiative forcing,” in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Cambridge, UK and New York, NY, USA: Cambridge University Press), 658–740. doi:0.1017/CBO9781107415324.018.

Prather, M., Flato, G., Friedlingstein, P., Jones, C., Lamarque, J.-F., Liao, H., et al. (2013). “Annex II: Climate System Scenario Tables,” in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, MA, USA and London, England: Cambridge Univeristy Press).

Richardson, M., Cowtan, K., and Millar, R. J. (2018). Global temperature definition affects achievement of long-term climate goals. *Environ. Res. Lett.* 13, 054004.

Sachs, J., Schmidt-Traub, G., Kroll, C., Durand-Delacre, D., and Teksoz, K. (2017). An SDG Index and Dashboards - Global Report. New York, NY, USA.

Smith, C. J., Forster, P. M., Allen, M., Leach, N., Millar, R. J., Passerello, G. A., et al. (2018). FAIR v1.3: A simple emissions-based impulse response and carbon cycle model. *Geosci. Model Dev.* doi:10.5194/gmd-2017-266.

Stevenson, D. S., Young, P. J., Naik, V., Lamarque, J. F., Shindell, D. T., Voulgarakis, A., et al. (2013). Tropospheric ozone changes, radiative forcing and attribution to emissions in the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP). *Atmos. Chem. Phys.* 13, 3063–3085. doi:10.5194/acp-13-3063-2013.

Toohey, M., Stevens, B., Schmidt, H., and Timmreck, C. (2016). Easy Volcanic Aerosol (EVA v1.0): an idealized forcing generator for climate simulations. *Geosci. Model Dev.* 9, 4049–4070. doi:10.5194/gmd-9-4049-2016.

Chapter 2: Mitigation pathways compatible with 1.5°C in the context of sustainable development

Coordinating Lead Authors: Joeri Rogelj (Belgium/Austria), Drew Shindell (USA), Kejun Jiang (China)

Lead Authors: Solomone Fifita (Fiji), Piers Forster (UK), Veronika Ginzburg (Russia), Collins Handa (Kenya), Haroon Kheshgi (USA), Shigeki Kobayashi (Japan), Elmar Kriegler (Germany), Luis Mundaca (Chile/Sweden), Roland Séférian (France), Maria Virginia Vilariño (Argentina)

Contributing Authors: Katherine Calvin (USA), Oreane Edelenbosch (Netherlands), Johannes Emmerling (Germany/Italy), Sabine Fuss (Germany), Thomas Gasser (France/Austria), Nathan Gillet (Canada), Chenmin He (China), Edgar Hertwich (Austria/USA), Lena Höglund-Isaksson (Sweden/Austria), Daniel Huppmann (Austria), Gunnar Luderer (Germany), Anil Markandya (UK/Spain), David L. McCollum (USA/Austria), Richard Millar (UK), Malte Meinshausen (Germany/Australia), Alexander Popp (Germany), Joana Correia de Oliveira de Portugal Pereira (Portugal/UK), Pallav Purohit (India/Austria), Keywan Riahi (Austria), Aurélien Ribes (France), Harry Saunders (Canada/USA), Christina Schädel (Switzerland/USA), Chris Smith (UK), Pete Smith (UK), Evelina Trutnevyte (Lithuania/Switzerland), Yang Xiu (China), Kirsten Zickfeld (Germany/Canada), Wenji Zhou (China/Austria)

Chapter Scientist: Daniel Huppmann (Austria), Chris Smith (UK)

Review Editors: Greg Flato (Canada), Jan Fuglestvedt (Norway), Rachid Mrabet (Morocco), Roberto Schaeffer (Brazil)

Date of Draft: 4 June 2018

Notes: TSU compiled version

EXECUTIVE SUMMARY **4**

2.1 INTRODUCTION TO MITIGATION PATHWAYS AND THE SUSTAINABLE DEVELOPMENT CONTEXT **8**

2.1.1 Mitigation pathways consistent with 1.5°C 8
2.1.2 The Use of Scenarios 9
2.1.3 New scenario information since AR5 9
2.1.4 Utility of integrated assessment models (IAMs) in the context of this report 11

2.2 GEOPHYSICAL RELATIONSHIPS AND CONSTRAINTS **13**

2.2.1 Geophysical characteristics of mitigation pathways 13
2.2.1.1 Geophysical uncertainties: non-CO2 forcing agents *15*
2.2.1.2 Geophysical uncertainties: climate and Earth-system feedbacks *16*
2.2.2 The remaining 1.5°C carbon budget 17
2.2.2.1 Carbon budget estimates *17*
2.2.2.2 CO_2 and non-CO_2 contributions to the remaining carbon budget *19*

2.3 OVERVIEW OF 1.5°C MITIGATION PATHWAYS **23**

2.3.1 Range of assumptions underlying 1.5°C pathways 23
2.3.1.1 Socio-economic drivers and the demand for energy and land in 1.5°C-consistent pathways *24*
2.3.1.2 Mitigation options in 1.5°C-consistent pathways *27*
2.3.1.3 Policy assumptions in 1.5°C-consistent pathways *28*
2.3.2 Key characteristics of 1.5°C-consistent pathways 28
2.3.2.1 Variation in system transformations underlying 1.5°C-consistent pathways *28*
2.3.2.2 Pathways keeping warming below 1.5°C or temporarily overshooting it *30*
2.3.3 Emissions evolution in 1.5°C pathways 31
2.3.3.1 Emissions of long-lived climate forcers *33*
2.3.3.2 Emissions of short-lived climate forcers and fluorinated gases *36*
2.3.4 CDR in 1.5°C-consistent pathways 39
2.3.4.1 CDR technologies and deployment levels in 1.5°C-consistent pathways *39*

BOX 2.1: BIOENERGY AND BECCS DEPLOYMENT IN INTEGRATED ASSESSMENT MODELLING **44**

2.3.4.2 Sustainability implications of CDR deployment in 1.5°C-consistent pathways *45*
2.3.5 Implications of near-term action in 1.5°C-consistent pathways 47

2.4 DISENTANGLING THE WHOLE-SYSTEM TRANSFORMATION **51**

2.4.1 Energy System Transformation 51
2.4.2 Energy supply 52
2.4.2.1 Evolution of primary energy contributions over time *52*
2.4.2.2 Evolution of electricity supply over time *56*
2.4.2.3 Deployment of Carbon Capture and Storage *57*
2.4.3 Energy end-use sectors 58
2.4.3.1 Industry *61*
2.4.3.2 Buildings *64*
2.4.3.3 Transport *66*
2.4.4 Land-use transitions and changes in the agricultural sector 68

2.5 CHALLENGES, OPPORTUNITIES AND CO-IMPACTS OF TRANSFORMATIVE MITIGATION PATHWAYS **75**

2.5.1 Policy frameworks and enabling conditions 75

CROSS-CHAPTER BOX 5: ECONOMICS OF 1.5°C PATHWAYS AND THE SOCIAL COST OF CARBON **77**

2.5.2 Economic and financial implications of 1.5°C Pathways 79
2.5.2.1 Price of carbon emissions *79*
2.5.2.2 Investments *82*
2.5.3 Sustainable development features of 1.5°C pathways 85

2.6 KNOWLEDGE GAPS **87**

2.6.1 Geophysical understanding 87
2.6.2 Integrated assessment approaches 87

2.6.3 CARBON DIOXIDE REMOVAL (CDR) 88
FREQUENTLY ASKED QUESTIONS 90
FAQ 2.1: WHAT KIND OF PATHWAYS LIMIT WARMING TO 1.5°C AND ARE WE ON TRACK? 90
FAQ 2.2: WHAT DO ENERGY SUPPLY AND DEMAND HAVE TO DO WITH LIMITING WARMING TO 1.5°C? 92
REFERENCES 94

Executive Summary

This chapter assesses mitigation pathways consistent with limiting warming to 1.5°C above preindustrial levels. In doing so, it explores the following key questions: What role do CO_2 and non-CO_2 emissions play? {2.2, 2.3, 2.4, 2.6} To what extent do 1.5°C pathways involve overshooting and returning below 1.5°C during the 21st century? {2.2, 2.3} What are the implications for transitions in energy, land use and sustainable development? {2.3, 2.4, 2.5} How do policy frameworks affect the ability to limit warming to 1.5°C? {2.3, 2.5} What are the associated knowledge gaps? {2.6}

The assessed pathways describe integrated, quantitative evolutions of all emissions over the 21st century associated with global energy and land use, and the world economy. The assessment is contingent upon available integrated assessment literature and model assumptions, and is complemented by other studies with different scope, for example those focusing on individual sectors. In recent years, integrated mitigation studies have improved the characterizations of mitigation pathways. However, limitations remain, as climate damages, avoided impacts, or societal co-benefits of the modelled transformations remain largely unaccounted for, while concurrent rapid technological changes, behavioural aspects, and uncertainties about input data present continuous challenges. *(high confidence)* {2.1.3, 2.3, 2.5.1, 2.6, Technical Annex 2}

The chances of limiting warming to 1.5°C and the requirements for urgent action

1.5°C-consistent pathways can be identified under a range of assumptions about economic growth, technology developments and lifestyles. However, lack of global cooperation, lack of governance of the energy and land transformation, and growing resource-intensive consumption are key impediments for achieving 1.5°C-consistent pathways. Governance challenges have been related to scenarios with high inequality and high population growth in the 1.5°C pathway literature. {2.3.1, 2.3.2, 2.5}

Under emissions in line with current pledges under the Paris Agreement (known as Nationally-Determined Contributions or NDCs), global warming is expected to surpass 1.5°C, even if they are supplemented with very challenging increases in the scale and ambition of mitigation after 2030 (*high confidence*). This increased action would need to achieve net zero CO_2 emissions in less than 15 years. Even if this is achieved, temperatures remaining below 1.5°C would depend on the geophysical response being towards the low end of the currently-estimated uncertainty range. Transition challenges as well as identified trade-offs can be reduced if global emissions peak before 2030 and already achieve marked emissions reductions by 2030 compared to today.[1] {2.2, 2.3.5, Cross-Chapter Box 9 in Chapter 4}

Limiting warming to 1.5°C depends on greenhouse gas (GHG) emissions over the next decades, where lower GHG emissions in 2030 lead to a higher chance of peak warming being kept to 1.5°C (*high confidence*). Available pathways that aim for no or limited (0–0.2°C) overshoot of 1.5°C keep GHG emissions in 2030 to 25–30 $GtCO_2e\ yr^{-1}$ in 2030 (interquartile range). This contrasts with median estimates for current NDCs of 50–58 $GtCO_2e\ yr^{-1}$ in 2030. Pathways that aim for limiting warming to 1.5°C by 2100 after a temporary temperature overshoot rely on large-scale deployment of Carbon Dioxide Removal (CDR) measures, which are uncertain and entail clear risks. {2.2, 2.3.3, 2.3.5, 2.5.3, Cross-Chapter Boxes 6 in Chapter 3 and 9 in Chapter 4, 4.3.7}

Limiting warming to 1.5°C implies reaching net zero CO_2 emissions globally around 2050 and concurrent deep reductions in emissions of non-CO_2 forcers, particularly methane (*high confidence*). Such mitigation pathways are characterized by energy-demand reductions, decarbonisation of electricity and other fuels, electrification of energy end use, deep reductions in agricultural emissions, and some form of CDR with carbon storage on land or sequestration in geological reservoirs. Low energy demand and low demand for land- and GHG-intensive consumption goods facilitate limiting warming to as close as possible to 1.5°C. {2.2.2, 2.3.1, 2.3.5, 2.5.1, Cross-Chapter Box 9 in Chapter 4}.

[1] FOOTNOTE: Kyoto-GHG emissions in this statement are aggregated with GWP-100 values of the IPCC Second Assessment Report.

In comparison to a 2°C limit, required transformations to limit warming to 1.5°C are qualitatively similar but more pronounced and rapid over the next decades (*high confidence*). 1.5°C implies very ambitious, internationally cooperative policy environments that transform both supply and demand *(high confidence)*. {2.3, 2.4, 2.5}

Policies reflecting a high price on emissions are necessary in models to achieve cost-effective 1.5°C-consistent pathways *(high confidence)*. Other things being equal, modelling suggests the price of emissions for limiting warming to 1.5°C being about three four times higher compared to 2°C, with large variations across models and socioeconomic assumptions. A price on carbon can be imposed directly by carbon pricing or implicitly by regulatory policies. Other policy instruments, like technology policies or performance standards, can complement carbon pricing in specific areas. {2.5.1, 2.5.2, 4.4.5}

Limiting warming to 1.5°C requires a marked shift in investment patterns *(limited evidence, high agreement)*. Investments in low-carbon energy technologies and energy efficiency would need to approximately double in the next 20 years, while investment in fossil-fuel extraction and conversion decrease by about a quarter. Uncertainties and strategic mitigation portfolio choices affect the magnitude and focus of required investments. {2.5.2}

Future emissions in 1.5°C-consistent pathways

Mitigation requirements can be quantified using carbon budget approaches that relate cumulative CO_2 emissions to global-mean temperature increase. Robust physical understanding underpins this relationship, but uncertainties become increasingly relevant as a specific temperature limit is approached. These uncertainties relate to the transient climate response to cumulative carbon emissions (TCRE), non-CO_2 emissions, radiative forcing and response, potential additional Earth-system feedbacks (such as permafrost thawing), and historical emissions and temperature. {2.2.2, 2.6.1}

Cumulative CO_2 emissions are kept within a budget by reducing global annual CO_2 emissions to net-zero. This assessment suggests a remaining budget for limiting warming to 1.5°C with a two-thirds chance of about 550 $GtCO_2$, and of about 750 $GtCO_2$ for an even chance (*medium confidence*). The remaining carbon budget is defined here as cumulative CO_2 emissions from the start of 2018 until the time of net-zero global emissions. Remaining budgets applicable to 2100, would approximately be 100 $GtCO_2$ lower than this to account for permafrost thawing and potential methane release from wetlands in the future. These estimates come with an additional geophysical uncertainty of at least ±50%, related to non-CO_2 response and TCRE distribution. In addition, they can vary by ±250 $GtCO_2$ depending on non-CO_2 mitigation strategies as found in available pathways. {2.2.2, 2.6.1}

Staying within a remaining carbon budget of 750 $GtCO_2$ implies that CO_2 emissions reach carbon neutrality in about 35 years, reduced to 25 years for a 550 $GtCO_2$ remaining carbon budget (*high confidence*). The ±50% geophysical uncertainty range surrounding a carbon budget translates into a variation of this timing of carbon neutrality of roughly ±15–20 years. If emissions do not start declining in the next decade, the point of carbon neutrality would need to be reached at least two decades earlier to remain within the same carbon budget. {2.2.2, 2.3.5}

Non-CO_2 emissions contribute to peak warming and thus affect the remaining carbon budget. The evolution of methane and sulphur dioxide emissions strongly influences the chances of limiting warming to 1.5°C. In the near-term, a weakening of aerosol cooling would add to future warming, but can be tempered by reductions in methane emissions *(high confidence)*. Uncertainty in radiative forcing estimates (particularly aerosol) affects carbon budgets and the certainty of pathway categorizations. Some non-CO_2 forcers are emitted alongside CO_2, particularly in the energy and transport sectors, and can be largely addressed through CO_2 mitigation. Others require specific measures, for example to target agricultural N_2O and CH_4, some sources of black carbon, or hydrofluorocarbons *(high confidence)*. In many cases, non-CO_2 emissions reductions are similar in 2°C pathways, indicating reductions near their assumed maximum potential by integrated assessment models. Emissions of N_2O and NH_3 increase in some pathways with strongly increased bioenergy demand. {2.2.2, 2.3.1, 2.4.2, 2.5.3}

The role of Carbon-Dioxide Removal (CDR)

All analysed 1.5°C-consistent pathways use CDR to some extent to neutralize emissions from sources for which no mitigation measures have been identified and, in most cases, also to achieve net-negative emissions that allow temperature to return to 1.5°C following an overshoot (*high confidence*). The longer the delay in reducing CO_2 emissions towards zero, the larger the likelihood of exceeding 1.5°C, and the heavier the implied reliance on net-negative emissions after mid-century to return warming to 1.5°C (*high confidence*). The faster reduction of net CO_2 emissions in 1.5°C- compared to 2°C-consistent pathways is predominantly achieved by measures that result in less CO_2 being produced and emitted, and only to a smaller degree through additional CDR. Limitations on the speed, scale, and societal acceptability of CDR deployment also limit the conceivable extent of temperature overshoot. Limits to our understanding of how the carbon cycle responds to net negative emissions increase the uncertainty about the effectiveness of CDR to decline temperatures after a peak. {2.2, 2.3, 2.6, 4.3.7}

CDR deployed at scale is unproven and reliance on such technology is a major risk in the ability to limit warming to 1.5°C. CDR is needed less in pathways with particularly strong emphasis on energy efficiency and low demand. The scale and type of CDR deployment varies widely across 1.5°C-consistent pathways, with different consequences for achieving sustainable development objectives (*high confidence*). Some pathways rely more on bioenergy with carbon capture and storage (BECCS), while others rely more on afforestation, which are the two CDR methods most often included in integrated pathways. Trade-offs with other sustainability objectives occur predominantly through increased land, energy, water and investment demand. Bioenergy use is substantial in 1.5°C-consistent pathways with or without BECCS due to its multiple roles in decarbonizing energy use. {2.3.1, 2.5.3, 2.6, 4.3.7}

Properties of energy transitions in 1.5°C-consistent pathways

The share of primary energy from renewables increases while coal usage decreases across 1.5°C-consistent pathways *(high confidence)*. By 2050, renewables (including bioenergy, hydro, wind and solar, with direct-equivalence method) supply a share of 49–67% (interquartile range) of primary energy in 1.5°C-consistent pathways; while the share from coal decreases to 1–7% (interquartile range), with a large fraction of this coal use combined with Carbon Capture and Storage (CCS). From 2020 to 2050 the primary energy supplied by oil declines in most pathways (–32 to –74% interquartile range). Natural gas changes by –13% to –60% (interquartile range), but some pathways show a marked increase albeit with widespread deployment of CCS. The overall deployment of CCS varies widely across 1.5°C-consistent pathways with cumulative CO_2 stored through 2050 ranging from zero up to 460 $GtCO_2$ (minimum-maximum range), of which zero up to 190 $GtCO_2$ stored from biomass. Primary energy supplied by bioenergy ranges from 40–310 EJ yr^{-1} in 2050 (minimum-maximum range), and nuclear from 3–120 EJ/yr (minimum-maximum range). These ranges reflect both uncertainties in technological development and strategic mitigation portfolio choices. {2.4.2}

1.5°C-consistent pathways include a rapid decline in the carbon intensity of electricity and an increase in electrification of energy end use *(high confidence)*. By 2050, the carbon intensity of electricity decreases to -92 to +11 gCO_2/MJ (minimum-maximum range) from about 140 gCO_2/MJ in 2020, and electricity covers 34–71% (minimum-maximum range) of final energy across 1.5°C-consistent pathways from about 20% in 2020. By 2050, the share of electricity supplied by renewables increases to 36–97% (minimum-maximum range) across 1.5°C-consistent pathways. Pathways with higher chances of holding warming to below 1.5°C generally show a faster decline in the carbon intensity of electricity by 2030 than pathways that temporarily overshoot 1.5°C. {2.4.1, 2.4.2, 2.4.3}

Demand-side mitigation and behavioural changes

Demand-side measures are key elements of 1.5°C-consistent pathways. Lifestyle choices lowering energy demand and the land- and GHG-intensity of food consumption can further support achievement of 1.5°C-consistent pathways (*high confidence*). By 2030 and 2050, all end-use sectors (including building, transport, and industry) show marked energy demand reductions in modelled 1.5°C-consistent pathways, comparable and beyond those projected in 2°C-consistent pathways. Sectorial models support the scale of these reductions. {2.3.4, 2.4.3}

Links between 1.5°C-consistent pathways and sustainable development

Choices about mitigation portfolios for limiting warming to 1.5°C can positively or negatively impact the achievement of other societal objectives, such as sustainable development (*high confidence*). In particular, demand-side and efficiency measures, and lifestyle choices that limit energy, resource, and GHG-intensive food demand support sustainable development *(medium confidence)*. Limiting warming to 1.5°C can be achieved synergistically with poverty alleviation and improved energy security and can provide large public health benefits through improved air quality, preventing millions of premature deaths. However, specific mitigation measures, such as bioenergy, may result in trade-offs that require consideration. {2.5.1, 2.5.2, 2.5.3}

2.1 Introduction to Mitigation Pathways and the Sustainable Development Context

This chapter assesses the literature on mitigation pathways to limit or return global mean warming to 1.5°C (relative to the preindustrial base period 1850–1900). Key questions addressed are: What types of mitigation pathways have been developed that could be consistent with 1.5°C? What changes in emissions, energy and land use do they entail? What do they imply for climate policy and implementation, and what impacts do they have on sustainable development? In terms of feasibility (see Cross-Chapter Box 3 in Chapter 1), this chapter focuses on geophysical dimensions and technological and economic enabling factors, with social and institutional dimensions as well as additional aspects of technical feasibility covered in Chapter 4.

Mitigation pathways are typically designed to reach a pre-defined climate target alone. Minimization of mitigation expenditures, but not climate-related damages or sustainable development impacts, is often the basis for these pathways to the desired climate target (see Cross-Chapter Box 5 in Chapter 2 for additional discussion). However, there are interactions between mitigation and multiple other sustainable development goals (see Sections 1.1 and 5.4) that provide both challenges and opportunities for climate action. Hence there are substantial efforts to evaluate the effects of the various mitigation pathways on sustainable development, focusing in particular on aspects for which Integrated Assessment Models (IAMs) provide relevant information (e.g., land-use changes and biodiversity, food security, and air quality). More broadly, there are efforts to incorporate climate change mitigation as one of multiple objectives that in general reflect societal concerns more completely and could potentially provide benefits at lower costs than simultaneous single objective policies (e.g., Clarke et al., 2014). For example, with carefully selected policies, universal energy access can be achieved while simultaneously reducing air pollution and mitigating climate change (McCollum et al., 2011; Riahi et al., 2012; IEA, 2017d). This chapter thus presents both the pathways and an initial discussion of their context within sustainable development objectives (Section 2.5), with the latter along with equity and ethical issues discussed in more detail in Chapter 5.

As described in Cross-Chapter Box 1 in Chapter 1, scenarios are comprehensive, plausible, integrated descriptions of possible futures based on specified, internally consistent underlying assumptions, with pathways often used to describe the clear temporal evolution of specific scenario aspects or goal-oriented scenarios. We include both these usages of ‘pathways’ here.

2.1.1 Mitigation pathways consistent with 1.5°C

Emissions scenarios need to cover all sectors and regions over the 21st century to be associated with a climate change projection out to 2100. Assumptions regarding future trends in population, consumption of goods and services (including food), economic growth, behaviour, technology, policies and institutions are all required to generate scenarios (Section 2.3.1). These societal choices must then be linked to the drivers of climate change, including emissions of well-mixed greenhouse gases and aerosol and ozone precursors, and land-use and land-cover changes. Deliberate solar radiation modification is not included in these scenarios (see Cross-Chapter Box 10 in Chapter 4).

Plausible developments need to be anticipated in many facets of the key sectors of energy and land use. Within energy, these consider energy resources like biofuels, energy supply and conversion technologies, energy consumption, and supply and end-use efficiency. Within land use, agricultural productivity, food demand, terrestrial carbon management, and biofuel production are all considered. Climate policies are also considered, including carbon pricing and technology policies such as research and development funding and subsidies. The scenarios incorporate regional differentiation in sectoral and policy development. The climate changes resulting from such scenarios are derived using models that typically incorporate physical understanding of the carbon-cycle and climate response derived from complex geophysical models evaluated against observations (Sections 2.2 and 2.6).

The temperature response to a given emission pathway is uncertain and therefore quantified in terms of a probabilistic outcome. Chapter 1 assesses the climate objectives of the Paris agreement in terms of human-induced warming, thus excluding potential impacts of natural forcing such as volcanic eruptions or solar output changes or unforced internal variability. Temperature responses in this chapter are assessed using simple geophysically-based models that evaluate the anthropogenic component of future temperature change and do not incorporate internal natural variations and are thus fit for purpose in the context of this assessment (Section 2.2.1). Hence a scenario that is consistent with 1.5°C may in fact lead to either a higher or lower temperature change, but within quantified and generally well-understood bounds (see also Section 1.2.3). Consistency with avoiding a human-induced temperature change limit must therefore also be defined probabilistically, with likelihood values selected based on risk avoidance preferences. Responses beyond global mean temperature are not typically evaluated in such models and are assessed in Chapter 3.

2.1.2 The Use of Scenarios

Variations in scenario assumptions and design define to a large degree which questions can be addressed with a specific scenario set, for example, the exploration of implications of delayed climate mitigation action. In this assessment, the following classes of 1.5°C – and 2°C – consistent scenarios are of particular interest to the topics addressed in this chapter: (a) scenarios with the same climate target over the 21st century but varying socio-economic assumptions (Sections 2.3 and 2.4); (b) pairs of scenarios with similar socio-economic assumptions but with forcing targets aimed at 1.5°C and 2°C (Section 2.3); (c) scenarios that follow the Nationally Determined Contributions or NDCs[2] until 2030 with much more stringent mitigation action thereafter (Section 2.3.5).

Characteristics of these pathways such as emissions reduction rates, time of peaking, and low-carbon energy deployment rates can be assessed as being consistent with 1.5°C. However, they cannot be assessed as ‘requirements’ for 1.5°C, unless a targeted analysis is available that specifically asked whether there could be pathways without the characteristics in question. AR5 already assessed such targeted analyses, for example asking which technologies are important to keep open the possibility to limit warming to 2°C (Clarke et al., 2014). By now, several such targeted analyses are also available for questions related to 1.5°C (Luderer et al., 2013; Rogelj et al., 2013b; Bauer et al., 2018; Strefler et al., 2018b; van Vuuren et al., 2018). This assessment distinguishes between consistent and the much stronger concept of required characteristics of 1.5°C pathways wherever possible.

Ultimately, society will adjust as new information becomes available and technical learning progresses, and these adjustments can be in either direction. Earlier scenario studies have shown, however, that deeper emissions reductions in the near term hedge against the uncertainty of both climate response and future technology availability (Luderer et al., 2013; Rogelj et al., 2013b; Clarke et al., 2014). Not knowing what adaptations might be put in place in the future, and due to limited studies, this chapter examines prospective rather than iteratively adaptive mitigation pathways (Cross-Chapter Box 1 in Chapter 1). Societal choices illustrated by scenarios may also influence what futures are envisioned as possible or desirable and hence whether those come into being (Beck and Mahony, 2017).

2.1.3 New scenario information since AR5

In this chapter, we extend the AR5 mitigation pathway assessment based on new scenario literature. Updates in understanding of climate sensitivity, transient climate response, radiative forcing, and the cumulative carbon budget consistent with 1.5°C are discussed in Sections 2.2.

Mitigation pathways developed with detailed process-based IAMs covering all sectors and regions over the 21st century describe an internally consistent and calibrated (to historical trends) way to get from current developments to meeting long-term climate targets like 1.5°C (Clarke et al., 2014). The overwhelming majority of available 1.5°C pathways were generated by such IAMs and these can be directly linked to climate outcomes and their consistency with the 1.5°C goal evaluated. The AR5 similarly relied upon such studies, which were mainly discussed in Chapter 6 of Working Group III (WGIII) (Clarke et al., 2014).

Since the AR5, several new integrated multi-model studies have appeared in the literature that explore

[2] FOOTNOTE: Current pledges include those from the US although they have stated their intention to withdraw in the future.

specific characteristics of scenarios more stringent than the lowest scenario category assessed in AR5 that was assessed to limit warming below 2°C with greater that 66% likelihood (Rogelj et al., 2015b, 2018; Akimoto et al., 2017; Su et al., 2017; Liu et al., 2017; Marcucci et al., 2017; Bauer et al., 2018; Strefler et al., 2018a; van Vuuren et al., 2018; Vrontisi et al., 2018; Zhang et al., 2018; Bertram et al., 2018; Grubler et al., 2018; Kriegler et al., 2018b; Luderer et al., 2018). Those scenarios explore 1.5°C-consistent pathways from multiple perspectives (see Annex 2.A.3), examining sensitivity to assumptions regarding:

- socio-economic drivers and developments including energy and food demand as, for example, characterized by the shared socio-economic pathways (SSPs; Cross-Chapter Box 1 in Chapter 1)
- near-term climate policies describing different levels of strengthening the NDCs
- the use of bioenergy and availability and desirability of carbon-dioxide-removal (CDR) technologies

A large number of these scenarios were collected in a scenario database established for the assessment of this Special Report (Annex 2.A.3). Mitigation pathways were classified by four factors: consistency with a temperature limit (as defined by Chapter 1), whether they temporarily overshoot that limit, the extent of this potential overshoot, and the likelihood of falling within these bounds. Specifically, they were put into classes that either kept surface temperatures below a given threshold throughout the 21st century or returned to a value below 1.5°C at some point before 2100 after temporarily exceeding that level earlier, referred to as an overshoot (OS). Both groups were further separated based on the probability of being below the threshold and the degree of overshoot, respectively (Table 2.1). Pathways are uniquely classified, with 1.5°C-related classes given higher priority than 2°C classes in cases where a pathway would be applicable to either class.

The probability assessment used in the scenario classification are based on simulations using two reduced complexity carbon-cycle, atmospheric composition and climate models: the ‘Model for the Assessment of Greenhouse Gas Induced Climate Change’ (MAGICC) (Meinshausen et al., 2011a), and the ‘Finite Amplitude Impulse Response’ (FAIRv1.3) model (Smith et al., 2018). For the purpose of this report, and to facilitate comparison with AR5, the range of the key carbon-cycle and climate parameters for MAGICC and its setup are identical to those used in AR5 WGIII (Clarke et al., 2014). For each mitigation pathway, MAGICC and FAIR simulations provide probabilistic estimates of atmospheric concentrations, radiative forcing and global temperature outcomes until 2100. However, the classification uses MAGICC probabilities directly for traceability with AR5 and since this model is more established in the literature. Nevertheless, the overall uncertainty assessment is based on results from both models, which are considered in the context of the latest radiative forcing estimates and observed temperatures (Etminan et al., 2016; Smith et al., 2018) (Section 2.2 and Annex 2.A.1). The comparison of these lines of evidence shows *high agreement* in the relative temperature response of pathways, with *medium agreement* on the precise absolute magnitude of warming, introducing a level of imprecision in these attributes. Consideration of the combined evidence here leads to *medium confidence* in the overall geophysical characteristics of the pathways reported here.

Table 2.1: Classification of pathways this chapter draws upon along with the number of available pathways in each class. The definition of each class is based on probabilities derived from the MAGICC model in a setup identical to AR5 WGIII (Clarke et al., 2014), as detailed in Annex 2.A.4.

Pathway Group	***Pathway Class***	***Pathway selection criteria and description***	***Number of scenarios***	***Number of scenarios***
1.5°C or 1.5°C-consistent	*Below-1.5°C*	*Pathways limiting peak warming to below 1.5°C during the entire 21st century with 50-66% likelihood**	*9*	*90*
	1.5°C-low-OS	*Pathways limiting median warming to below 1.5°C in 2100 and with a 50-67% probability of temporarily overshooting that level earlier, generally implying less than 0.1°C higher peak warming than Below-1.5°C pathways*	*44*	
	1.5°C-high-OS	*Pathways limiting median warming to below 1.5°C in 2100 and with a greater than 67% probability of temporarily overshooting that level earlier, generally implying 0.1–0.4°C higher peak warming than Below-1.5°C pathways*	*37*	
2°C or 2°C-consistent	*Lower-2°C*	*Pathways limiting peak warming to below 2°C during the entire 21st century with greater than 66% likelihood*	*74*	*132*
	Higher-2°C	*Pathways assessed to keep peak warming to below 2°C during the entire 21st century with 50-66% likelihood*	*58*	
** No pathways were available that achieve a greater than 66% probability of limiting warming below 1.5°C during the entire 21st century based on the MAGICC model projections.*				

In addition to the characteristics of the above-mentioned classes, four illustrative pathway archetypes have been selected and are used throughout this chapter to highlight specific features of and variations across 1.5°C pathways. These are chosen in particular to illustrate the spectrum of CO_2 emissions reduction patterns consistent with 1.5°C, ranging from very rapid and deep near-term decreases facilitated by efficiency and demand-side measures that lead to limited CDR requirements to relatively slower but still rapid emissions reductions that lead to a temperature overshoot and necessitate large CDR deployment later in the century (Section 2.3).

2.1.4 Utility of integrated assessment models (IAMs) in the context of this report

IAMs lie at the basis of the assessment of mitigation pathways in this chapter as much of the quantitative global scenario literature is derived with such models. IAMs combine insights from various disciplines in a single framework resulting in a dynamic description of the coupled energy-economy-land-climate system that cover the largest sources of anthropogenic greenhouse gas (GHG) emissions from different sectors. Many of the IAMs that contributed mitigation scenarios to this assessment include a process-based description of the land system in addition to the energy system (e.g., Popp et al., 2017), and several have been extended to cover air pollutants (Rao et al., 2017) and water use (Hejazi et al., 2014; Fricko et al., 2016; Mouratiadou et al., 2016). Such integrated pathways hence allow the exploration of the whole-system transformation, as well as the interactions, synergies, and trade-offs between sectors, and increasing with questions beyond climate mitigation (von Stechow et al., 2015). The models do not, however, fully account for all constraints that could affect realization of pathways (see Chapter 4).

Section 2.3 assesses the overall characteristics of 1.5°C pathways based on fully integrated pathways, while Sections 2.4 and 2.5 describe underlying sectorial transformations, including insights from sector-specific assessment models and pathways that are not derived from IAMs. Such models provide detail in their domain of application and make exogenous assumptions about cross-sectoral or global factors. They often focus on a specific sector, such as the energy (Bruckner et al., 2014; IEA, 2017a; Jacobson, 2017; OECD/IEA and IRENA, 2017), buildings (Lucon et al., 2014) or transport (Sims et al., 2014) sector, or a specific country or region (Giannakidis et al., 2018). Sector-specific pathways are assessed in relation to integrated pathways because they cannot be directly linked to 1.5°C by themselves if they do not extend to 2100 or do not include all GHGs or aerosols from all sectors.

AR5 found sectorial 2°C decarbonisation strategies from IAMs to be consistent with sector-specific studies (Clarke et al., 2014). A growing body of literature on 100%-renewable energy scenarios has emerged (e.g., see Creutzig et al., 2017; Jacobson et al., 2017), which goes beyond the wide range of IAM projections of renewable energy shares in 1.5°C and 2°C pathways. While the representation of renewable energy resource potentials, technology costs and system integration in IAMs has been updated since AR5, leading to higher renewable energy deployments in many cases (Luderer et al., 2017; Pietzcker et al., 2017), none of the IAM projections identify 100% renewable energy solutions for the global energy system as part of cost-effective mitigation pathways (Section 2.4.2). Bottom-up studies find higher mitigation potentials in the industry, buildings, and transport sector in 2030 than realized in selected 2°C pathways from IAMs (UNEP 2017), indicating the possibility to strengthen sectorial decarbonisation strategies until 2030 beyond the integrated 1.5°C pathways assessed in this chapter (Luderer et al., 2018).

Detailed process-based IAMs are a diverse set of models ranging from partial equilibrium energy-land models to computable general equilibrium models of the global economy, from myopic to perfect foresight models, and from models with to models without endogenous technological change (Annex 2.A.2). The IAMs used in this chapter have limited to no coverage of climate impacts. They typically use GHG pricing mechanisms to induce emissions reductions and associated changes in energy and land uses consistent with the imposed climate goal. The scenarios generated by these models are defined by the choice of climate goals and assumptions about near-term climate policy developments. They are also shaped by assumptions about mitigation potentials and technologies as well as baseline developments such as, for example, those represented by different Shared Socioeconomic Pathways (SSPs), especially those pertaining to energy and food demand (Riahi et al., 2017). See Section 2.3.1 for discussion of these assumptions. Since the AR5, the scenario literature has greatly expanded the exploration of these dimensions. This includes low demand scenarios (Grubler et al., 2018; van Vuuren et al., 2018), scenarios taking into account a larger set of sustainable development goals (Bertram et al., 2018), scenarios with restricted availability of CDR technologies (Bauer et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018b; Strefler et al., 2018b; van Vuuren et al., 2018), scenarios with near-term action dominated by regulatory policies (Kriegler et al., 2018b) and scenario variations across the Shared Socioeconomic Pathways (Riahi et al., 2017; Rogelj et al., 2018). IAM results depend upon multiple underlying assumptions, for example the extent to which global markets and economies are assumed to operate frictionless and policies are cost-optimised, assumptions about technological progress and availability and costs of mitigation and CDR measures, assumptions about underlying socio-economic developments and future energy, food and materials demand, and assumptions about the geographic and temporal pattern of future regulatory and carbon pricing policies (see Annex 2.A.2 for additional discussion on IAMs and their limitations).

2.2 Geophysical relationships and constraints

Emissions pathways can be characterised by various geophysical characteristics such as radiative forcing (Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; van Vuuren et al., 2011b), atmospheric concentrations (van Vuuren et al., 2007, 2011a; Clarke et al., 2014) or associated temperature outcomes (Meinshausen et al., 2009; Rogelj et al., 2011; Luderer et al., 2013). These attributes can be used to derive geophysical relationships for specific pathway classes, such as cumulative CO_2 emissions compatible with a specific level of warming also known as 'carbon budgets' (Meinshausen et al., 2009; Rogelj et al., 2011; Stocker et al., 2013; Friedlingstein et al., 2014a), the consistent contributions of non-CO_2 GHGs and aerosols to the remaining carbon budget (Bowerman et al., 2011; Rogelj et al., 2015a, 2016b) or to temperature outcomes (Lamarque et al., 2011; Bowerman et al., 2013; Rogelj et al., 2014b). This section assesses geophysical relationships for both CO_2 and non-CO_2 emissions.

2.2.1 Geophysical characteristics of mitigation pathways

This section employs the pathway classification introduced in Section 2.1, with geophysical characteristics derived from simulations with the MAGICC reduced-complexity carbon-cycle and climate model and supported by simulations with the FAIR reduced-complexity model (Section 2.1). Within a specific category and between models, there remains a large degree of variance. Most pathways exhibit a temperature overshoot which has been highlighted in several studies focusing on stringent mitigation pathways (Huntingford and Lowe, 2007; Wigley et al., 2007; Nohara et al., 2015; Rogelj et al., 2015d; Zickfeld and Herrington, 2015; Schleussner et al., 2016; Xu and Ramanathan, 2017). Only very few of the scenarios collected in the database for this report hold the average future warming projected by MAGICC below 1.5°C during the entire 21st century (Table 2.1, Figure 2.1). Most 1.5°C-consistent pathways available in the database overshoot 1.5°C around mid-century before peaking and then reducing temperatures so as to return below that level in 2100. However, because of numerous geophysical uncertainties and model dependencies (Section 2.2.1.1, Annex 2.A.1), absolute temperature characteristics of the various pathway categories are more difficult to distinguish than relative features (Figure 2.1, Annex 2.A.1) and actual probabilities of overshoot are imprecise. However, all lines of evidence available for temperature projections indicate a probability greater than 50% of overshooting 1.5°C by mid-century in all but the most stringent pathways currently available (Annex 2.A.1, 2.A.4).

Most 1.5°C-consistent pathways exhibit a peak in temperature by mid-century whereas 2°C-consistent pathways generally peak after 2050 (Annex 2.A.4). The peak in median temperature in the various pathway categories occurs about ten years before reaching net zero CO_2 emissions due to strongly reduced annual CO_2 emissions and deep reductions in CH_4 emissions (Section 2.3.3). The two reduced-complexity climate models used in this assessment suggest that virtually all available 1.5°C-consistent pathways peak and decline global-mean temperature rise, but with varying rates of temperature decline after the peak (Figure 2.1). The estimated decadal rates of temperature change by the end of the century are smaller than the amplitude of the climate variability as assessed in AR5 (1σ of about ±0.1°C), which hence complicates the detection of a global peak and decline of warming in observations on timescales of on to two decades (Bindoff et al., 2013). In comparison, many pathways limiting warming to 2°C or higher by 2100 still have noticeable increasing trends at the end of the century, and thus imply continued warming.

By 2100, the difference between 1.5°C- and 2°C-consistent pathways becomes clearer compared to mid-century, and not only for the temperature response (Figure 2.1) but also for atmospheric CO_2 concentrations. In 2100, the median CO_2 concentration in 1.5°C-consistent pathways is below 2016 levels (Le Quéré et al., 2018), whereas it remains higher by about 5-10% compared to 2016 in the 2°C-consistent pathways.

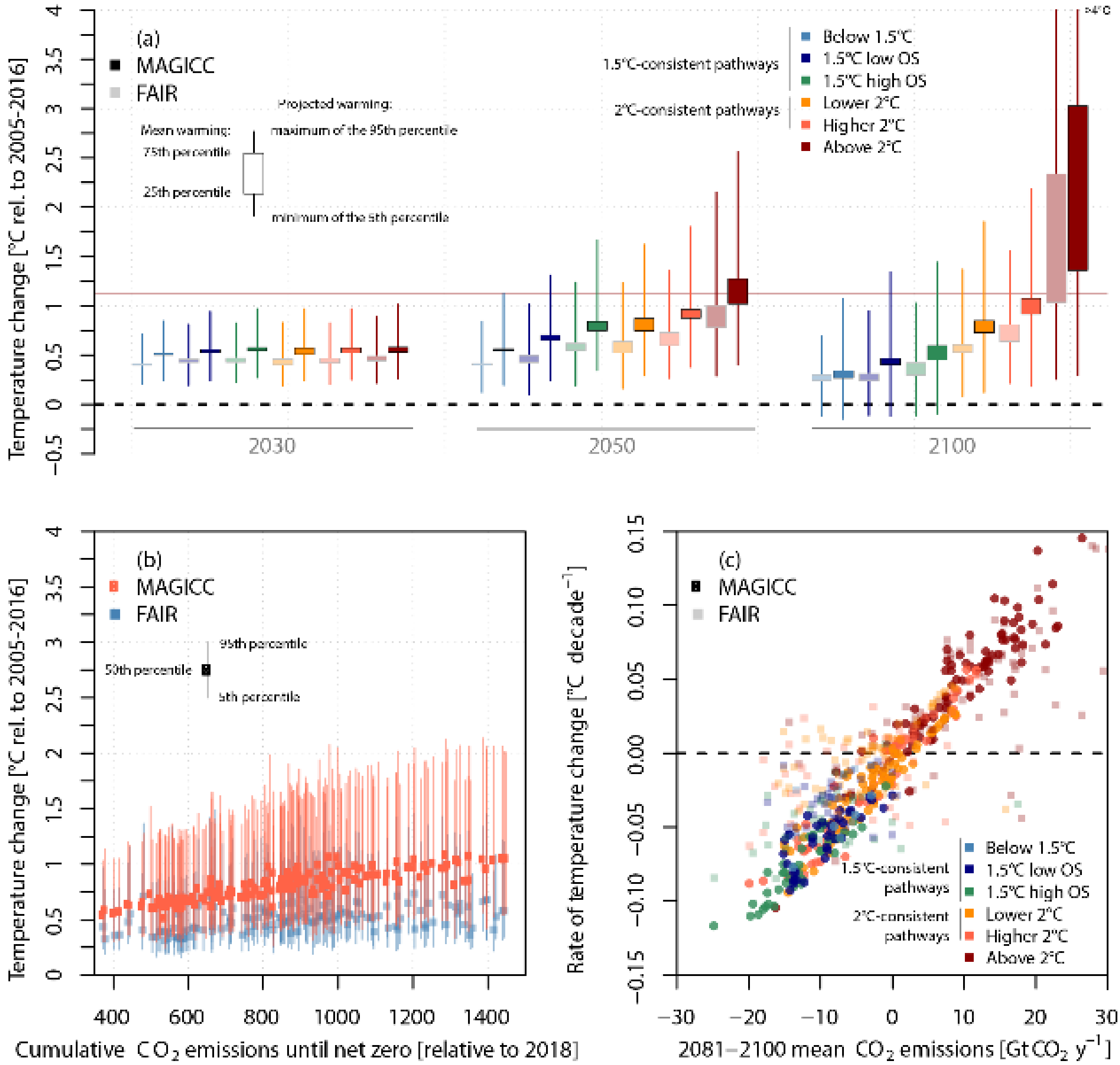


Figure 2.1: Pathways classification overview. (a) Average global-mean temperature increase relative to 2010 as projected by FAIR and MAGICC in 2030, 2050 and 2100; (b) response of peak warming to cumulative CO_2 emissions until net zero by MAGICC (red) and FAIR (blue); (c) decadal rate of average global-mean temperature change from 2081 to 2100 as a function of the annual CO_2 emissions averaged over the same period as given by FAIR (transparent squares) and MAGICC (filled circles). In panel (a), horizontal lines at 0.63°C and 1.13°C are indicative of the 1.5°C and 2°C warming thresholds with the respect to 1850–1900, taking into account the assessed historical warming of 0.87°C ±0.12°C between the 1850–1900 and 2006–2015 periods (Section 1.2.1). In panel (a), vertical lines illustrate both the physical and the scenario uncertainty as captured by MAGICC and FAIR and show the minimal warming of the 5th percentile of projected warming and the maximal warming of the 95th percentile of projected warming per scenario class. Boxes show the interquartile range of mean warming across scenarios, and thus represent scenario uncertainty only.

2.2.1.1 Geophysical uncertainties: non-CO2 forcing agents

Impacts of non-CO_2 climate forcers on temperature outcomes are particularly important when evaluating stringent mitigation pathways (Weyant et al., 2006; Shindell et al., 2012; Rogelj et al., 2014b, 2015a; Samset et al., 2018). However, many uncertainties affect the role of non-CO_2 climate forcers in stringent mitigation pathways.

A first uncertainty arises from the magnitude of the radiative forcing attributed to non-CO_2 climate forcers. Figure 2.2 illustrates how, for one representative 1.5°C-consistent pathway (SSP2-1.9) (Fricko et al., 2017; Rogelj et al., 2018), the effective radiative forcings as estimated by MAGICC and FAIR can differ (see Annex 2.A.1 for further details). This large spread in non-CO_2 effective radiative forcings leads to considerable uncertainty in the predicted temperature response. This uncertainty ultimately affects the assessed temperature outcomes for pathway classes used in this chapter (Section 2.1) and also affects the carbon budget (Section 2.2.2). Figure 2.2 highlights the important role of methane emissions reduction in this scenario in agreement with the recent literature focussing on stringent mitigation pathways (Shindell et al., 2012; Rogelj et al., 2014b, 2015a; Stohl et al., 2015; Collins et al., 2018).

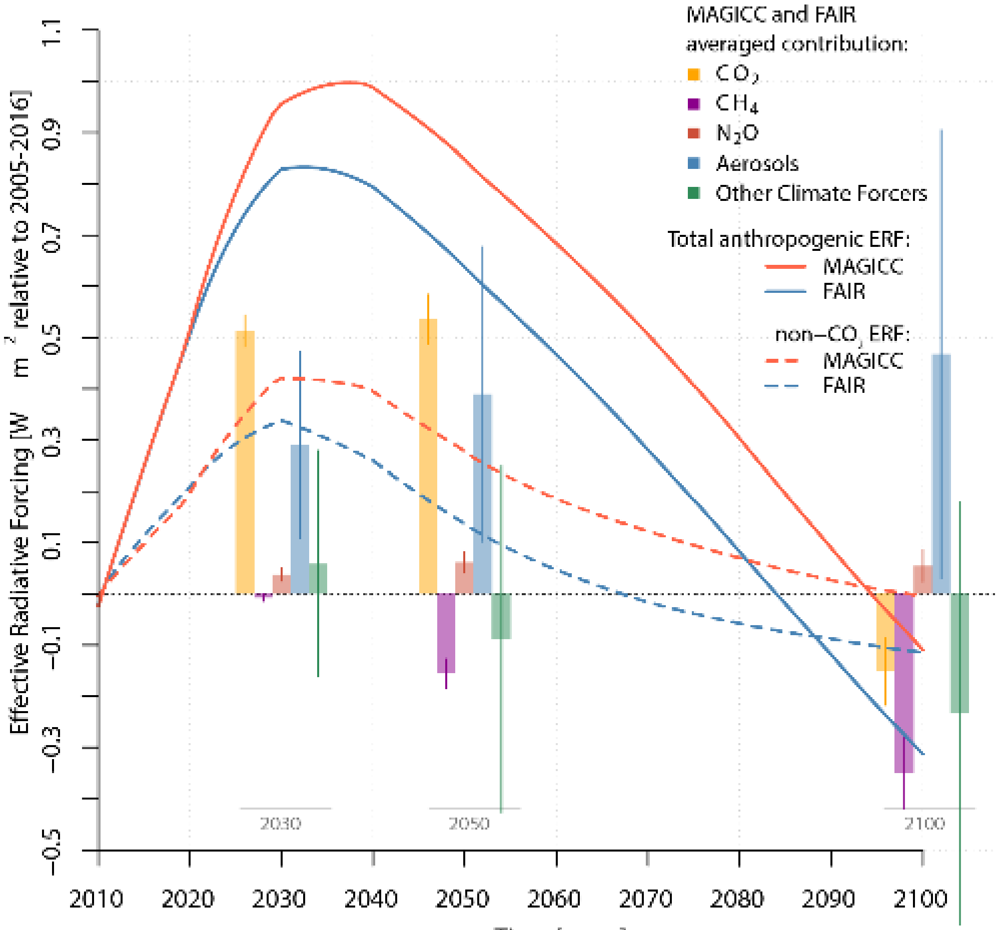


Figure 2.2: Changes and uncertainties in effective radiative forcings (ERF) for one 1.5°C-consistent pathway (SSP2-19) as estimated by MAGICC and FAIR. Solid and dashed lines are indicative of the effective radiative forcing for CO_2 and non-CO_2 agents as represented by MAGICC (red) and FAIR (blue) relative to 2010, respectively. Vertical bars show the mean radiative forcing as predicted by MAGICC and FAIR of relevant non-CO_2 agents for year 2030, 2050 and 2100. The vertical lines give the uncertainty (1σ) of the ERFs for the represented species.

For mitigation pathways that aim at halting and reversing radiative forcing increase during this century, the aerosol radiative forcing is a considerable source of uncertainty (Figure 2.2) (Samset et al., 2018; Smith et al., 2018). Indeed, reductions in SO_2 (and NO_x) emissions largely associated with fossil-fuel burning are expected to reduce the cooling effects of both aerosol radiative interactions and aerosol cloud interactions, leading to warming (Myhre et al., 2013; Samset et al., 2018). A multi-model analysis (Myhre et al., 2017) and a study based on observational constraints (Malavelle et al., 2017) largely support the AR5 best estimate and uncertainty range of aerosol forcing. The partitioning of total aerosol radiative forcing between aerosol precursor emissions is important (Ghan et al., 2013; Jones et al., 2018; Smith et al., 2018) as this affects the estimate of the mitigation potential from different sectors that have aerosol precursor emission sources. The total aerosol effective radiative forcing change in stringent mitigation pathways is expected to be dominated by the effects from the phase-out of SO_2, although the magnitude of this aerosol-warming effect depends on how much of the present-day aerosol cooling is attributable to SO_2, particularly the cooling associated with aerosol-cloud interaction (Figure 2.2). Regional differences in the linearity of aerosol-cloud interaction (Carslaw et al., 2013; Kretzschmar et al., 2017) make it difficult to separate the role of individual precursors. Precursors that are not fully mitigated will continue to affect the Earth system. If, for example, the role of nitrate aerosol cooling is at the strongest end of the assessed IPCC AR5 uncertainty range, future temperature increases may be more modest if ammonia emissions continue to rise (Hauglustaine et al., 2014).

Figure 2.2 shows that there are substantial differences in the evolution of estimated effective radiative forcing of non-CO_2 forcers between MAGICC and FAIR. These forcing differences result in MAGICC simulating a larger warming trend in the near term compared to both the FAIR model and the recent observed trends of 0.2°C per decade reported in Chapter 1 (Figure 2.1, Annex 2.A.1, Section 1.2.1.3). The aerosol effective forcing is stronger in MAGICC compared to either FAIR or the AR5 best estimate, though it is still well within the AR5 uncertainty range (Annex 2.A.1.1). A recent revision (Etminan et al., 2016) increases the methane forcing by 25%. This revision is used in the FAIR but not in the AR5 setup of MAGICC that is applied here. Other structural differences exist in how the two models relate emissions to concentrations that contribute to differences in forcing (see Annex 2.A.1.1).

Non-CO_2 climate forcers exhibit a greater geographical variation in radiative forcings than CO_2, which lead to important uncertainties in the temperature response (Myhre et al., 2013). This uncertainty increases the relative uncertainty of the temperature pathways associated with low emission scenarios compared to high emission scenarios (Clarke et al., 2014). It is also important to note that geographical patterns of temperature change and other climate responses, especially those related to precipitation, depend significantly on the forcing mechanism (Myhre et al., 2013; Shindell et al., 2015; Marvel et al., 2016; Samset et al., 2016) (see also Section 3.6.2.2).

2.2.1.2 Geophysical uncertainties: climate and Earth-system feedbacks

Climate sensitivity uncertainty impacts future projections as well as carbon-budget estimates (Schneider et al., 2017). AR5 assessed the equilibrium climate sensitivity (ECS) to be *likely* in the 1.5–4.5°C range, *extremely unlikely* less than 1°C and *very unlikely* greater than 6°C. The lower bound of this estimate is lower than the range of CMIP5 models (Collins et al., 2013). The evidence for the 1.5°C lower bound on ECS in AR5 was based on analysis of energy-budget changes over the historical period. Work since AR5 has suggested that the climate sensitivity inferred from such changes has been lower than the $2xCO_2$ climate sensitivity for known reasons (Forster, 2016; Gregory and Andrews, 2016; Rugenstein et al., 2016; Armour, 2017; Ceppi and Gregory, 2017; Knutti et al., 2017; Proistosescu and Huybers, 2017). Both a revised interpretation of historical estimates and other lines of evidence based on analysis of climate models with the best representation of today's climate (Sherwood et al., 2014; Zhai et al., 2015; Tan et al., 2016; Brown and Caldeira, 2017; Knutti et al., 2017) suggest that the lower bound of ECS could be revised upwards which would decrease the chances of limiting warming below 1.5°C in assessed pathways. However, such a reassessment has been challenged (Lewis and Curry, 2018), albeit from a single line of evidence. Nevertheless, it is premature to make a major revision to the lower bound. The evidence for a possible revision of the upper bound on ECS is less clear with cases argued from different lines of evidence for both decreasing (Lewis and Curry, 2015, 2018; Cox et al., 2018) and increasing (Brown and Caldeira, 2017) the bound presented in the literature. The tools used in this chapter employ ECS ranges consistent with the AR5 assessment. The MAGICC ECS distribution has not been selected to explicitly reflect this but is nevertheless consistent (Rogelj et al., 2014a). The FAIR model used here to estimate carbon budgets explicitly constructs log-normal distributions of ECS and transient climate response based on a multi parameter fit to the AR5 assessed ranges of climate sensitivity and individual historic effective radiative forcings (Smith et al., 2018) (Annex 2.A.1.1).

Several feedbacks of the Earth system, involving the carbon cycle, non-CO_2 GHGs and/or aerosols, may also impact the future dynamics of the coupled carbon-climate system's response to anthropogenic emissions. These feedbacks are caused by the effects of nutrient limitation (Duce et al., 2008; Mahowald et al., 2017), ozone exposure (de Vries et al., 2017), fire emissions (Narayan et al., 2007) and changes associated with natural aerosols (Cadule et al., 2009; Scott et al., 2017). Among these Earth-system feedbacks, the importance of the permafrost feedback's influence has been highlighted in recent studies. Combined evidence from both models (MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018) and field studies (like Schädel et al., 2014; Schuur et al., 2015) shows *high agreement* that permafrost thawing will release both CO_2 and CH_4 as the Earth warms, amplifying global warming. This thawing could also release N_2O (Voigt et al., 2017a, 2017b). Field, laboratory and modelling studies estimate that the vulnerable fraction in permafrost is about 5–15% of the permafrost soil carbon (~5300–5600 $GtCO_2$ in Schuur et al., 2015) and that carbon emissions are expected to occur beyond 2100 because of system inertia and the large proportion of slowly decomposing carbon in permafrost (Schädel et al., 2014). Published model studies suggest that a large part of the carbon release to the atmosphere is in the form of CO_2 (Schädel et al., 2016), while the amount of CH_4 released by permafrost thawing is estimated to be much smaller than that CO_2. Cumulative CH_4 release by 2100 under RCP2.6 ranges from 0.13 to 0.45 Gt of methane (Burke et al., 2012; Schneider von Deimling et al., 2012, 2015) with fluxes being the highest in the middle of the century because of maximum thermokarst lake extent by mid-century (Schneider von Deimling et al., 2015).

The reduced complexity climate models employed in this assessment do not take into account permafrost or non-CO_2 Earth-system feedbacks, although the MAGICC model has a permafrost module that can be enabled. Taking the current climate and Earth-system feedbacks understanding together, there is a possibility that these models would underestimate the longer-term future temperature response to stringent emission pathways (Section 2.2.2).

2.2.2 The remaining 1.5°C carbon budget

2.2.2.1 Carbon budget estimates

Since the AR5, several approaches have been proposed to estimate carbon budgets compatible with 1.5°C or 2°C. Most of these approaches indirectly rely on the approximate linear relationship between peak global-mean temperature and cumulative emissions of carbon (the transient climate response to cumulative emissions of carbon, TCRE (Collins et al., 2013; Friedlingstein et al., 2014a; Rogelj et al., 2016b) whereas others base their estimates on equilibrium climate sensitivity (Schneider et al., 2017). The AR5 employed two approaches to determine carbon budgets. Working Group I (WGI) computed carbon budgets from 2011 onwards for various levels of warming relative to the 1861–1880 period using RCP8.5 (Meinshausen et al., 2011b; Stocker et al., 2013) whereas WGIII estimated their budgets from a set of available pathways that were assessed to have a >50% probability to exceed 1.5°C by mid-century, and return to 1.5°C or below in 2100 with greater than 66% probability (Clarke et al., 2014). These differences made AR5 WGI and WGIII carbon budgets difficult to compare as they are calculated over different time periods, derived from a different sets of multi-gas and aerosol emission scenarios and use different concepts of carbon budgets (exceedance for WGI, avoidance for WGIII) (Rogelj et al., 2016b; Matthews et al., 2017).

Carbon budgets can be derived from CO_2-only experiments as well as from multi-gas and aerosol scenarios. Some published estimates of carbon budgets compatible with 1.5°C or 2°C refer to budgets for CO_2-induced warming only, and hence do not take into account the contribution of non-CO_2 climate forcers (Allen et al., 2009; Matthews et al., 2009; Zickfeld et al., 2009; IPCC, 2013a). However, because the projected changes in non-CO_2 climate forcers tend to amplify future warming, CO_2-only carbon budgets overestimate the total net cumulative carbon emissions compatible with 1.5°C or 2°C (Friedlingstein et al., 2014a; Rogelj et al., 2016b; Matthews et al., 2017; Mengis et al., 2018; Tokarska et al., 2018).

Since the AR5, many estimates of the remaining carbon budget for 1.5°C have been published (Friedlingstein et al., 2014a; MacDougall et al., 2015; Peters, 2016; Rogelj et al., 2016b; Matthews et al., 2017; Millar et al., 2017; Goodwin et al., 2018b; Kriegler et al., 2018a; Lowe and Bernie, 2018; Mengis et al., 2018; Millar and Friedlingstein, 2018; Rogelj et al., 2018; Schurer et al., 2018; Séférian et al., 2018;

Tokarska et al., 2018; Tokarska and Gillett, 2018). These estimates cover a wide range as a result of differences in the models used, and of methodological choices, as well as physical uncertainties. Some estimates are exclusively model-based while others are based on observations or on a combination of both. Remaining carbon budgets limiting warming below 1.5°C or 2°C that are derived from Earth-system models of intermediate complexity (MacDougall et al., 2015; Goodwin et al., 2018a), IAMs (Luderer et al., 2018; Rogelj et al., 2018), or based on Earth-system model results (Lowe and Bernie, 2018; Séférian et al., 2018; Tokarska and Gillett, 2018) give remaining carbon budgets of the same order of magnitude than the IPCC AR5 Synthesis Report (SYR) estimates (IPCC, 2014a). This is unsurprising as similar sets of models were used for the AR5 (IPCC, 2013b). The range of variation across models stems mainly from either the inclusion or exclusion of specific Earth-system feedbacks (MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018) or different budget definitions (Rogelj et al., 2018).

In contrast to the model-only estimates discussed above and employed in the AR5, this report additionally uses observations to inform its evaluation of the remaining carbon budget. Table 2.2 shows that the assessed range of remaining carbon budgets consistent with 1.5°C or 2°C is larger than the AR5 SYR estimate and is part way towards estimates constrained by recent observations (Millar et al., 2017; Goodwin et al., 2018a; Tokarska and Gillett, 2018). Figure 2.3 illustrates that the change since AR5 is, in very large part, due to the application of a more recent observed baseline to the historic temperature change and cumulative emissions; here adopting the baseline period of 2006-2015 (see Section 1.2.1). AR5 SYR Figures SPM.10 and 2.3 already illustrated the discrepancy between models and observations, but did not apply this as a correction to the carbon budget because they were being used to illustrate the overall linear relationship between warming and cumulative carbon emissions in the CMIP5 models since 1870, and were not specifically designed to quantify residual carbon budgets relative to the present for ambitious temperature goals. The AR5 SYR estimate was also dependent on a subset of Earth-system models illustrated in Figure 2.3 of this report. Although, as outlined below and in Table 2.2, considerably uncertainties remain, there is *high agreement* across various lines of evidence assessed in this report that the remaining carbon budget for 1.5°C or 2°C would be larger than the estimates at the time of the AR5. However, the overall remaining budget for 2100 is assessed to be smaller than that derived from the recent observational-informed estimates, as Earth-system feedbacks such as permafrost thawing reduce the budget applicable to centennial scales (see Section 2.2.2.2).

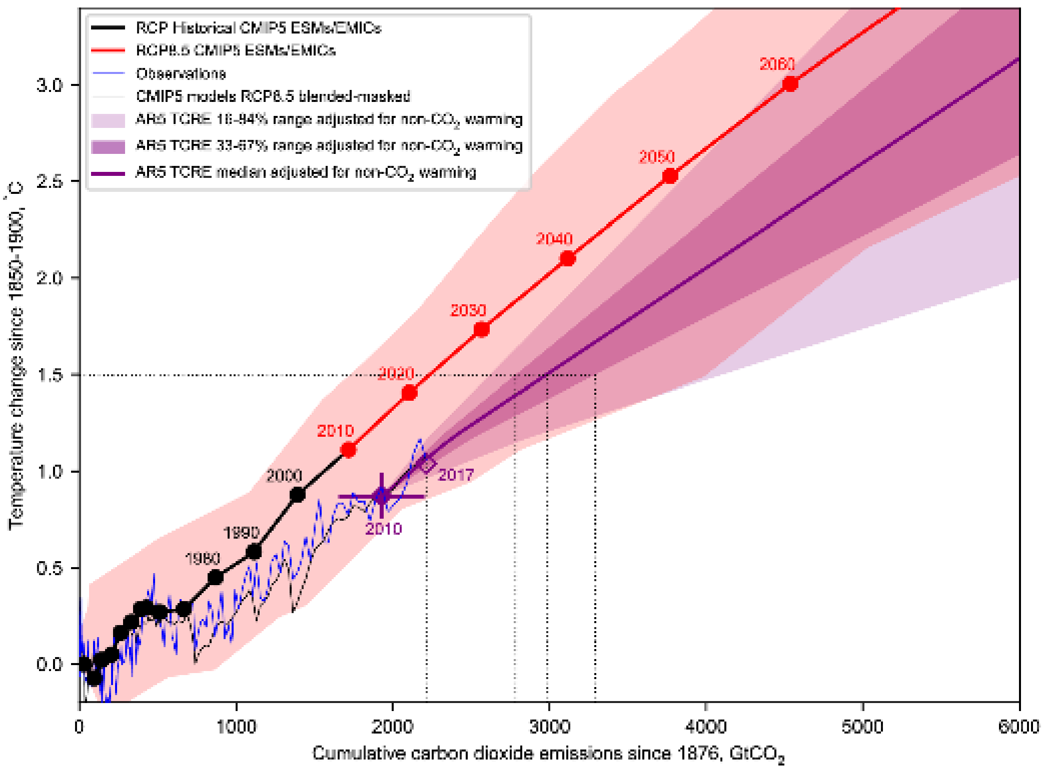


Figure 2.3: Temperature changes from 1850-1900 versus cumulative CO_2 emissions since 1st January 1876. Solid lines with dots reproduce the temperature response to cumulative CO_2 emissions plus non-CO_2 forcers as assessed in Figure SPM10 of WGI AR5, except that points marked with years relate to a

particular year, unlike in WGI AR5 Fig. SPM10 where each point relates to the mean over the previous decade. The AR5 data was derived from available Earth-system models and Earth-system models of Intermediate Complexity for the historic observations (black) and RCP 8.5 scenario (red) and the red shaded plume shows the uncertainty range across the models as presented in the AR5. The purple shaded plume and the line are indicative of the temperature response to cumulative CO_2 emissions and non-CO_2 warming adopted in this report. The non-CO_2 warming contribution is averaged from the MAGICC and FAIR models and the purple shaded range assumes the AR5 WGI TCRE distribution (Annex 2.A.1.2). The 2010 observations of temperature anomaly (0.87°C based on 2006-2015 mean compared to 1850-1900, Section 1.2.1) and cumulative carbon dioxide emissions from 1876 to the end of 2010 of 1,930 $GtCO_2$ (Le Quéré et al., 2018) is shown as a filled purple diamond. 2017 values based on the latest cumulative carbon emissions up to the end of 2017 of 2,220 $GtCO_2$ (Version 1.3 accessed 22 May 2018) and a temperature anomaly of 1.04°C based on an assumed temperature increase of 0.2°C per decade is shown as a hollow purple diamond. The thin blue line shows annual observations, with CO_2 emissions from (Le Quéré et al., 2018) and temperatures from the average of datasets in Chapter 1, Figure 1.2. The thin black line shows the CMIP5 models blended-masked estimates with CO_2 emissions also from (Le Quéré et al., 2018). Dotted black lines illustrate the remaining carbon budget estimates for 1.5°C given in Table 2.2. Note these remaining budgets exclude possible Earth-system feedbacks that could reduce the budget, such as CO_2 and CH_4 release from permafrost thawing and tropical wetlands (see Section 2.2.2.2).

2.2.2.2 CO_2 and non-CO_2 contributions to the remaining carbon budget

A remaining carbon budget can be estimated from calculating the amount of CO_2 emissions consistent, given a certain value of TCRE, with an allowable additional amount of warming. Here, the allowable warming is the 1.5°C warming threshold minus the current warming taken as the 2006-2015 average, with a further amount removed to account for the estimated non-CO_2 temperature contribution to the remaining warming (Peters, 2016; Rogelj et al., 2016b). This assessment uses the TCRE range from AR5 WGI (Collins et al., 2013) supported by estimates of non-CO_2 contributions that are based on published methods and integrated pathways (Friedlingstein et al., 2014a; Allen et al., 2016, 2018; Peters, 2016; Smith et al., 2018). Table 2.2 and Figure 2.3 show the assessed remaining carbon budgets and key uncertainties for a set of additional warming levels relative to the 2006–2015 period (see Annex 2.A.1.2 for details). With an assessed historical warming of 0.87°C ±0.12°C from 1850–1900 to 2006–2015 (Section 1.2.1), 0.63°C of additional warming would be approximately consistent with a global-mean temperature increase of 1.5°C relative to preindustrial levels. For this level of additional warming, remaining carbon budgets have been estimated (Table 2.2, Annex 2.A.1.2).

The remaining carbon budget calculation presented in the Table 2.2 and illustrated in Figure 2.3 does not consider additional Earth-system feedbacks such as permafrost thawing. These are uncertain but estimated to reduce the remaining carbon budget by an order of magnitude of about 100 $GtCO_2$. Accounting for such feedbacks would make the carbon budget more applicable for 2100 temperature targets, but would also increase uncertainty (Table 2.2 and see below). Excluding such feedbacks, the assessed range for the remaining carbon budget is estimated to be 1100, 750, and 550 $GtCO_2$ (rounded to the nearest 50 $GtCO_2$) for the 33rd, 50th and, 67th percentile of TCRE, respectively, with a median non-CO_2 warming contribution and starting from 1 January 2018 onward. Note that future research and ongoing observations over the next years will provide a better indication as to how the 2006–2015 base period compares with the long-term trends and might bias the budget estimates. Similarly, improved understanding in Earth-system feedbacks would result in a better quantification of their impacts on remaining carbon budgets for 1.5°C and 2°C.

After TCRE uncertainty, a major additional source of uncertainty is the magnitude of non-CO_2 forcing and its contribution to the temperature change between the present day and the time of peak warming. Integrated emissions pathways can be used to ensure consistency between CO_2 and non-CO_2 emissions (Bowerman et al., 2013; Collins et al., 2013; Clarke et al., 2014; Rogelj et al., 2014b, 2015a; Tokarska et al., 2018). Friedlingstein et al. (2014a) used pathways with limited to no climate mitigation to find a variation due to non-CO_2 contributions of about ±33% for a 2°C carbon budget. Rogelj et al. (2016b) showed no particular bias in non-CO_2 radiative forcing or warming at the time of exceedance of 2°C or at peak warming between scenarios with increasing emissions and strongly mitigated scenarios (consistent with Stocker et al., 2013). However, clear differences of the non-CO_2 warming contribution at the time of deriving a 2°C-consistent carbon budget were reported for the four RCPs. Although the spread in non-CO_2 forcing across scenarios can be smaller in absolute terms at lower levels of cumulative emissions, it can be larger in relative terms compared to the remaining carbon budget (Stocker et al., 2013; Friedlingstein et al., 2014a; Rogelj et al., 2016b). Tokarska and Gillett (2018) find no statistically significant differences in 1.5°C-consistent cumulative emissions budgets when calculated for different RCPs from consistent sets of CMIP5 simulations.

The mitigation pathways assessed in this report indicate that emissions of non-CO_2 forcers contribute an average additional warming of around 0.15°C relative to 2006–2015 at the time of net zero CO_2 emissions, reducing the remaining carbon budget by roughly 320 $GtCO_2$. This arises from a weakening of aerosol cooling and continued emissions of non-CO_2 GHGs (Sections 2.2.1, 2.3.3). This non-CO_2 contribution at the time of net zero CO_2 emissions varies by about ±0.1°C across scenarios resulting in a carbon budget uncertainty of about ±250 $GtCO_2$ and takes into account marked reductions in methane emissions (Section 2.3.3). In case these would not be achieved, remaining carbon budgets are further reduced. Uncertainties in the non-CO_2 forcing and temperature response are asymmetric and can influence the remaining carbon budget by -400 to +200 $GtCO_2$ with the uncertainty in aerosol radiative forcing being the largest contributing factor (Table 2.2). The MAGICC and FAIR models in their respective parameter setups and model versions used to assess the non-CO_2 warming contribution give noticeable different non-CO_2 effective radiative forcing and warming for the same scenarios while both being within plausible ranges of future response (Fig. 2.2 and Annex 2.A.1–2). For this assessment, it is premature to assess the accuracy of their results, so it is assumed that both are equally representative of possible futures. Their non-CO_2 warming estimates are therefore averaged for the carbon budget assessment and their differences used to guide the uncertainty assessment of the role of non-CO_2 forcers. Nevertheless, the findings are robust enough to give *high confidence* that the changing emissions non-CO_2 forcers (particularly the reduction in cooling aerosol precursors) cause additional near-term warming and reduce the remaining carbon budget compared to the CO_2 only budget.

TCRE uncertainty directly impacts carbon budget estimates (Peters, 2016; Matthews et al., 2017; Millar and Friedlingstein, 2018). Based on multiple lines of evidence, AR5 WGI assessed a *likely* range for TCRE of 0.2–0.7°C per 1000 $GtCO_2$ (Collins et al., 2013). The TCRE of the CMIP5 Earth-system models ranges from 0.23 to 0.66°C per 1000 $GtCO_2$ (Gillett et al., 2013). At the same time, studies using observational constraints find best estimates of TCRE of 0.35–0.41°C per 1000 $GtCO_2$ (Matthews et al., 2009; Gillett et al., 2013; Tachiiri et al., 2015; Millar and Friedlingstein, 2018). This assessment continues to use the assessed AR5 TCRE range under the working assumption that TCRE is normally distributed (Stocker et al., 2013). Observation-based estimates have reported log-normal distributions of TCRE (Millar and Friedlingstein, 2018). Assuming a log-normal instead of normal distribution of the assessed AR5 TCRE range would result in about a 200 $GtCO_2$ increase for the median budget estimates but only about half at the 67th percentile, while historical temperature uncertainty and uncertainty in recent emissions contribute ±150 and ±50 $GtCO_2$ to the uncertainty, respectively (Table 2.2).

Calculating carbon budgets from the TCRE requires the assumption that the instantaneous warming in response to cumulative CO_2 emissions equals the long-term warming or, equivalently, that the residual warming after CO_2 emissions cease is negligible. The magnitude of this residual warming, referred to as the zero-emission commitment, ranges from slightly negative (i.e., a slight cooling) to slightly positive for CO_2 emissions up to present-day (Section 1.2.4) (Lowe et al., 2009; Frölicher and Joos, 2010; Gillett et al., 2011; Matthews and Zickfeld, 2012). The delayed temperature change from a pulse CO_2 emission introduces uncertainties in emission budgets, which have not been quantified in the literature for budgets consistent with limiting warming to 1.5°C. As a consequence, this uncertainty does not affect our carbon budget estimates directly but it is included as an additional factor in the assessed Earth-system feedback uncertainty (as detailed below) of roughly 100 $GtCO_2$ on decadal timescales presented in Table 2.2.

Remaining carbon budgets are further influenced by Earth-system feedbacks not accounted for in CMIP5 models, such as the permafrost carbon feedback (Friedlingstein et al., 2014b; MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018), and their influence on the TCRE. Lowe and Bernie (2018) used a simple climate sensitivity scaling approach to estimate that Earth-system feedbacks (such as CO_2 released by permafrost thawing or methane released by wetlands) could reduce carbon budgets for 1.5°C and 2°C by roughly 100 $GtCO_2$ on centennial time scales. Their findings are based on older previous Earth-system feedbacks understanding (Arneth et al., 2010). This estimate is broadly supported by more recent analysis of individual feedbacks. Schädel et al. (2014) suggest an upper bound of 24.4 PgC (90 $GtCO_2$) emitted from carbon release from permafrost over the next forty years for a RCP4.5 scenario. Burke et al. (2017) use a single model to estimate permafrost emissions between 0.3 and 0.6 $GtCO_2\ y^{-1}$ from the point of 1.5°C stabilization, which would reduce the budget by around 20 $GtCO_2$ by 2100. Comyn-Platt et al. (2018) include methane emissions from permafrost and suggest the 1.5°C remaining carbon budget is reduced by 180 $GtCO_2$. Additionally, Mahowald et al. (2017) find there is possibility of 0.5–1.5 $GtCO_2\ y^{-1}$ being released from aerosol-biogeochemistry changes if aerosol emissions cease. In summary, these additional Earth system feedbacks taken together are assessed to reduce the remaining carbon budget applicable to 2100 by an order of magnitude of 100 $GtCO_2$, compared to the budgets based on the assumption of a constant TCRE presented in Table 2.2 (*limited evidence*, *medium agreement*), leading to overall *medium confidence* in their assessed impact.

The uncertainties presented in Table 2.2 cannot be formally combined, but current understanding of the assessed geophysical uncertainties suggests at least a ±50% possible variation for remaining carbon budgets for 1.5°C-consistent pathways. When put in the context of year-2017 CO_2 emissions (about 41 $GtCO_2\ yr^{-1}$) (Le Quéré et al., 2018), a remaining carbon budget of 750 $GtCO_2$ (550 $GtCO_2$) suggests meeting net zero global CO_2 emissions in about 35 years (25 years) following a linear decline starting from 2018 (rounded to the nearest five years), with a variation of ±15–20 years due to the above mentioned geophysical uncertainties (*high confidence*).

The remaining carbon budgets assessed in this section are consistent with limiting peak warming to the indicated levels of additional warming. However, if these budgets are exceeded and the use of CDR (see Sections 2.3 and 2.4) is envisaged to return cumulative CO_2 emissions to within the carbon budget at a later point in time, additional uncertainties apply because the TCRE is different under increasing and decreasing atmospheric CO_2 concentrations due to ocean thermal and carbon-cycle inertia (Herrington and Zickfeld, 2014; Krasting et al., 2014; Zickfeld et al., 2016). This asymmetrical behaviour makes carbon budgets path-dependent in case of a budget and/or temperature overshoot (MacDougall et al., 2015). Although potentially large for scenarios with large overshoot (MacDougall et al., 2015), this path-dependence of carbon budgets has not been well quantified for 1.5°C- and 2°C-consistent scenarios and as such remains an important knowledge gap. This assessment does not explicitly account for path dependence but takes it into consideration for its overall confidence assessment.

This assessment finds a larger remaining budget from the 2006-2015 base period than the 1.5°C and 2°C remaining budgets inferred from AR5 from the start of 2011, approximately 1000 $GtCO_2$ for the 2°C (66% of model simulations) and approximately 400 $GtCO_2$ for the 1.5°C budget (66% of model simulations). In contrast, this assessment finds approximately 1600 $GtCO_2$ for the 2°C (66th TCRE percentile) and approximately 860 $GtCO_2$ for the 1.5°C budget (66th TCRE percentile) from 2011. However, these budgets are not directly equivalent as AR5 reported budgets for fractions of CMIP5 simulations and other lines of evidence, while this report uses the assessed range of TCRE and an assessment of the non-CO_2 contribution at net zero CO_2 emissions to provide remaining carbon budget estimates at various percentiles of TCRE. Furthermore, AR5 did not specify remaining budgets to carbon neutrality as we do here, but budgets until the time the temperature limit of interest was reached, assuming negligible zero emission commitment and taking into account the non-CO_2 forcing at that point in time.

In summary, although robust physical understanding underpins the carbon budget concept, relative uncertainties become larger as a specific temperature limit is approached. For the budget, applicable to the mid-century, the main uncertainties relate to the TCRE, non-CO_2 emissions, radiative forcing and response. For 2100, uncertain Earth-system feedbacks such as permafrost thawing would further reduce the available budget. The remaining budget is also conditional upon the choice of baseline, which is affected by uncertainties in both historical emissions, and in deriving the estimate of globally averaged human-induced warming. As a result, only *medium confidence* can be assigned to the assessed remaining budget values for 1.5°C and 2.0°C and their uncertainty.

Table 2.2: The assessed remaining carbon budget and its uncertainties. Shaded grey horizontal bands illustrate the uncertainty in historical temperature increase from the 1850-1900 base period until the 2006-2015 period, which impacts the additional warming until a specific temperature limit like 1.5°C or 2°C relative to the 1850-1900 period.

Additional warming since 2006-2015 [°C]*(1)	Approximate warming since 1850-1900 [°C]*(1)	Remaining carbon budget (excluding additional Earth-system feedbacks*(5)) [$GtCO_2$ from 1.1.2018]*(2)			Key uncertainties and variations*(4)					
		Percentiles of TCRE*(3)			Additional Earth-system feedbacks*(5)	Non-CO_2 scenario variation*(6)	Non-CO_2 forcing and response uncertainty	TCRE distribution uncertainty*(7)	Historical temperature uncertainty*(1)	Recent emissions uncertainty*(8)
		33rd	*50th*	*67th*	*[$GtCO_2$]*	*[$GtCO_2$]*	*[$GtCO_2$]*	*[$GtCO_2$]*	*[$GtCO_2$]*	*[$GtCO_2$]*
0.3		290	160	80						
0.4		530	350	230						
0.5		770	530	380						
0.6		1010	710	530						
0.63	**~1.5°C**	**1080**	**770**	**570**	Budgets on the left are reduced by about 100 $GtCO_2$ If evaluated to 2100 and potentially more on centennial time scales	+-250	-400 to +200	+100 to +200	+-250	+-20
0.7		1240	900	680						
0.8		1480	1080	830						
0.9		1720	1260	980						
1		1960	1450	1130						
1.1		2200	1630	1280						
1.13	**~2.°C**	**2270**	**1690**	**1320**						
1.2		2440	1820	1430						

*(1) Chapter 1 has assessed historical warming between the 1850-1900 and 2006-2015 periods to be 0.87°C with a +/- 0.12°C *likely* (1-σ) range
*(2) Historical CO_2 emissions since the middle of the 1850-1900 historical base period (1 January 1876) are estimated at 1930 $GtCO_2$ (1630-2230 $GtCO_2$, 1-σ range) until end 2010. Since 1 January 2011, an additional 290 $GtCO_2$ (270-310 $GtCO_2$, 1-σ range) has been emitted until the end of 2017 (Le Quéré et al., 2018, Version 1.3 - accessed 22 May 2018).
*(3) TCRE: transient climate response to cumulative emissions of carbon, assessed by AR5 to fall *likely* between 0.8-2.5°C / 1000 PgC (Collins et al., 2013), considering a normal distribution consistent with AR5 (Stocker et al., 2013). Values are rounded to the nearest 10 $GtCO_2$ in the table and to the nearest 50 $GtCO_2$ in the text.
*(4) Focussing on the impact of various key uncertainties on median budgets for 0.63°C of additional warming.
*(5) Earth system feedbacks include CO_2 released by permafrost thawing or methane released by wetlands, see main text.
*(6) Variations due to different scenario assumptions related to the future evolution of non-CO_2 emissions.
*(7) The distribution of TCRE is not precisely defined. Here the influence of assuming a log-normal instead of a normal distribution shown.
*(8) Historical emissions uncertainty reflects the uncertainty in historical emissions since 1 January 2011.

2.3 Overview of 1.5°C mitigation pathways

Limiting global mean temperature increase at any level requires global CO_2 emissions to become net zero at some point in the future (Zickfeld et al., 2009; Collins et al., 2013). At the same time, limiting the residual warming of short-lived non-CO_2 emissions, can be achieved by reducing their annual emissions as far as possible (Section 2.2, Cross-Chapter Box 2 in Chapter 1). This will require large-scale transformations of the global energy-agriculture-land-economy system, affecting the way in which energy is produced, agricultural systems are organised, and food, energy and materials are consumed (Clarke et al., 2014). This section assesses key properties of pathways consistent with limiting global mean temperature to 1.5°C relative to pre-industrial levels, including their underlying assumptions and variations.

Since the AR5, an extensive body of literature has appeared on integrated pathways consistent with 1.5°C (Rogelj et al., 2015b; Akimoto et al., 2017; Liu et al., 2017; Löffler et al., 2017; Marcucci et al., 2017; Su et al., 2017; Bauer et al., 2018; Bertram et al., 2018; Grubler et al., 2018; Kriegler et al., 2018b; Luderer et al., 2018; Rogelj et al., 2018; Strefler et al., 2018a; van Vuuren et al., 2018; Vrontisi et al., 2018; Zhang et al., 2018) (Section 2.1). These pathways have global coverage and represent all GHG-emitting sectors and their interactions. Such integrated pathways allow the exploration of the whole-system transformation, and hence provide the context in which the detailed sectorial transformations assessed in Section 2.4 of this chapter are taking place.

The overwhelming majority of published integrated pathways have been developed by global IAMs that represent key societal systems and their interactions, like the energy system, agriculture and land use, and the economy (see Section 6.2 in Clarke et al., 2014). Very often these models also include interactions with a representation of the geophysical system, for example, by including spatially explicit land models or carbon-cycle and climate models. The complex features of these subsystems are approximated and simplified in these models. IAMs are briefly introduced in Section 2.1 and important knowledge gaps identified in Section 2.6. An overview to the use, scope and limitations of IAMs is provided in Annex 2.A.2.

The pathway literature is assessed in two ways in this section. First, various insights on specific questions reported by studies can be assessed to identify robust or divergent findings. Second, the combined body of scenarios can be assessed to identify salient features of pathways in line with a specific climate goal across a wide range of models. The latter can be achieved by assessing pathways available in the database to this assessment (Section 2.1, Annex 2.A.2–4). The ensemble of scenarios available to this assessment is an ensemble of opportunity: it is a collection of scenarios from a diverse set of studies that was not developed with a common set of questions and a statistical analysis of outcomes in mind. This means that ranges can be useful to identify robust and sensitive features across available scenarios and contributing modelling frameworks, but do not lend themselves to a statistical interpretation. To understand the reasons underlying the ranges, an assessment of the underlying scenarios and studies is required. To this end, this section highlights illustrative pathway archetypes that help to clarify the variation in assessed ranges for 1.5°C-consistent pathways.

2.3.1 Range of assumptions underlying 1.5°C pathways

Earlier assessments have highlighted that there is no single pathway to achieve a specific climate objective (e.g., Clarke et al., 2014). Pathways depend on the underlying development processes, and societal choices, which affect the drivers of projected future baseline emissions. Furthermore, societal choices also affect climate change solutions in pathways, like the technologies that are deployed, the scale at which they are deployed, or whether solutions are globally coordinated. A key finding is that 1.5°C-consistent pathways could be identified under a considerable range of assumptions in model studies despite the tightness of the 1.5°C emissions budget (Figures 2.4, 2.5) (Rogelj et al., 2018).

The AR5 provided an overview of how differences in model structure and assumptions can influence the outcome of transformation pathways (Section 6.2 in Clarke et al., 2014, as well as Table A.II.14 in Krey et al., 2014b) and this was further explored by the modelling community in recent years with regard to, e.g., socio-economic drivers (Kriegler et al., 2016; Marangoni et al., 2017; Riahi et al., 2017), technology assumptions (Bosetti et al., 2015; Creutzig et al., 2017; Pietzcker et al., 2017), and behavioural factors (van

Sluisveld et al., 2016; McCollum et al., 2017).

2.3.1.1 Socio-economic drivers and the demand for energy and land in 1.5°C-consistent pathways

There is deep uncertainty about the ways humankind will use energy and land in the 21st century. These ways are intricately linked to future population levels, secular trends in economic growth and income convergence, behavioural change and technological progress. These dimensions have been recently explored in the context of the Shared Socioeconomic Pathways (SSP) (Kriegler et al., 2012; O'Neill et al., 2014) which provide narratives (O'Neill et al., 2017) and quantifications (Crespo Cuaresma, 2017; Dellink et al., 2017; KC and Lutz, 2017; Leimbach et al., 2017; Riahi et al., 2017) of different future worlds in which scenario dimensions are varied to explore differential challenges to adaptation and mitigation (Cross-Chapter Box 1 in Chapter 1). This framework is increasingly adopted by IAMs to systematically explore the impact of socio-economic assumptions on mitigation pathways (Riahi et al., 2017), including 1.5°C-consistent pathways (Rogelj et al., 2018). The narratives describe five worlds (SSP1–5) with different socio-economic predispositions to mitigate and adapt to climate change (Table 2.3). As a result, population and economic growth projections can vary strongly across integrated scenarios, including available 1.5°C-consistent pathways (Fig. 2.4). For example, based on alternative future fertility, mortality, migration and educational assumptions, population projections vary between 8.5-10.0 billion people by 2050, and 6.9–12.6 billion people by 2100 across the SSPs. An important factor for these differences is future female educational attainment, with higher attainment leading to lower fertility rates and therewith decreased population growth up to a level of 1 billion people by 2050 (Lutz and KC, 2011; Snopkowski et al., 2016; KC and Lutz, 2017). Consistent with population development, GDP per capita also varies strongly in SSP baselines varying about 20 to more than 50 thousand USD_{2010} per capita in 2050 (in power purchasing parity values, PPP), in part driven by assumptions on human development, technological progress and development convergence between and within regions (Crespo Cuaresma, 2017; Dellink et al., 2017; Leimbach et al., 2017). Importantly, none of the GDP projections in the mitigation pathway literature assessed in this chapter included the feedback of climate damages on economic growth (Hsiang et al., 2017).

Baseline projections for energy-related GHG emissions are sensitive to economic growth assumptions, while baseline projections for land-use emissions are more directly affected by population growth (assuming unchanged land productivity and per capita demand for agricultural products) (Kriegler et al., 2016). SSP-based modelling studies of mitigation pathways have identified high challenges to mitigation for worlds with a focus on domestic issues and regional security combined with high population growth (SSP3), and for worlds with rapidly growing resource and fossil-fuel intensive consumption (SSP5) (Riahi et al., 2017). No model could identify a 2°C-consistent pathway for SSP3, and high mitigation costs were found for SSP5. This picture translates to 1.5°C-consistent pathways that have to remain within even tighter emissions constraints (Rogelj et al., 2018). No model found a 1.5°C-consistent pathway for SSP3 and some models could not identify 1.5°C-consistent pathways for SSP5 (2 of 4 models, compared to 1 of 4 models for 2°C-consistent pathways). The modelling analysis also found that the effective control of land-use emissions becomes even more critical in 1.5°C-consistent pathways. Due to high inequality levels in SSP4, land use can be less well managed. This caused 2 of 3 models to no longer find an SSP4-based 1.5°C-consistent pathway even though they identified SSP4-based 2°C-consistent pathways at relatively moderate mitigation costs (Riahi et al., 2017). Rogelj et al. (2018) further reported that all six participating models identified 1.5°C-consistent pathways in a sustainability oriented world (SSP1) and four of six models found 1.5°C-consistent pathways for middle-of-the-road developments (SSP2). These results show that 1.5°C-consistent pathways can be identified under a broad range of assumptions, but that lack of global cooperation (SSP3), high inequality (SSP4) and/or high population growth (SSP3) that limit the ability to control land use emissions, and rapidly growing resource-intensive consumption (SSP5) are key impediments.

Table 2.3: Key characteristics of the five Shared Socio-economic Pathways (O'Neill et al., 2017).

<table>
<tr><th rowspan="2">Socio-economic challenges to mitigation</th><th colspan="3">Socio-economic challenges to adaptation</th></tr>
<tr><th>Low</th><th>Medium</th><th>High</th></tr>
<tr><td>High</td><td>SSP5: Fossil-fuelled development
• low population
• very high economic growth per capita
• high human development
• high technological progress
• ample fossil fuel resources
• resource intensive lifestyles
• high energy and food demand per capita
• convergence and global cooperation</td><td></td><td>SSP3: Regional rivalry
• high population
• low economic growth per capita
• low human development
• low technological progress
• resource intensive lifestyles
• resource constrained energy and food demand per capita
• focus on regional food and energy security
• regionalization and lack of global cooperation</td></tr>
<tr><td>Medium</td><td></td><td>SSP2: Middle of the road
• medium population
• medium and uneven economic growth
• medium and uneven human development
• medium and uneven technological progress
• resource intensive lifestyles
• medium and uneven energy and food demand per capita
• limited global cooperation and convergence</td><td></td></tr>
<tr><td>Low</td><td>SSP1: Sustainable development
• low population
• high economic growth per capita
• high human development
• high technological progress
• environmentally oriented technological and behavioural change
• resource efficient lifestyles
• low energy and food demand per capita
• convergence and global cooperation</td><td></td><td>SSP4: Inequality
• Medium to high population
• Unequal low to medium economic growth per capita
• Unequal low to medium human development
• unequal technological progress: high in globalized high tech sectors, slow in domestic sectors
• unequal lifestyles and energy / food consumption: resource intensity depending on income
• Globally connected elite, disconnected domestic work forces</td></tr>
</table>

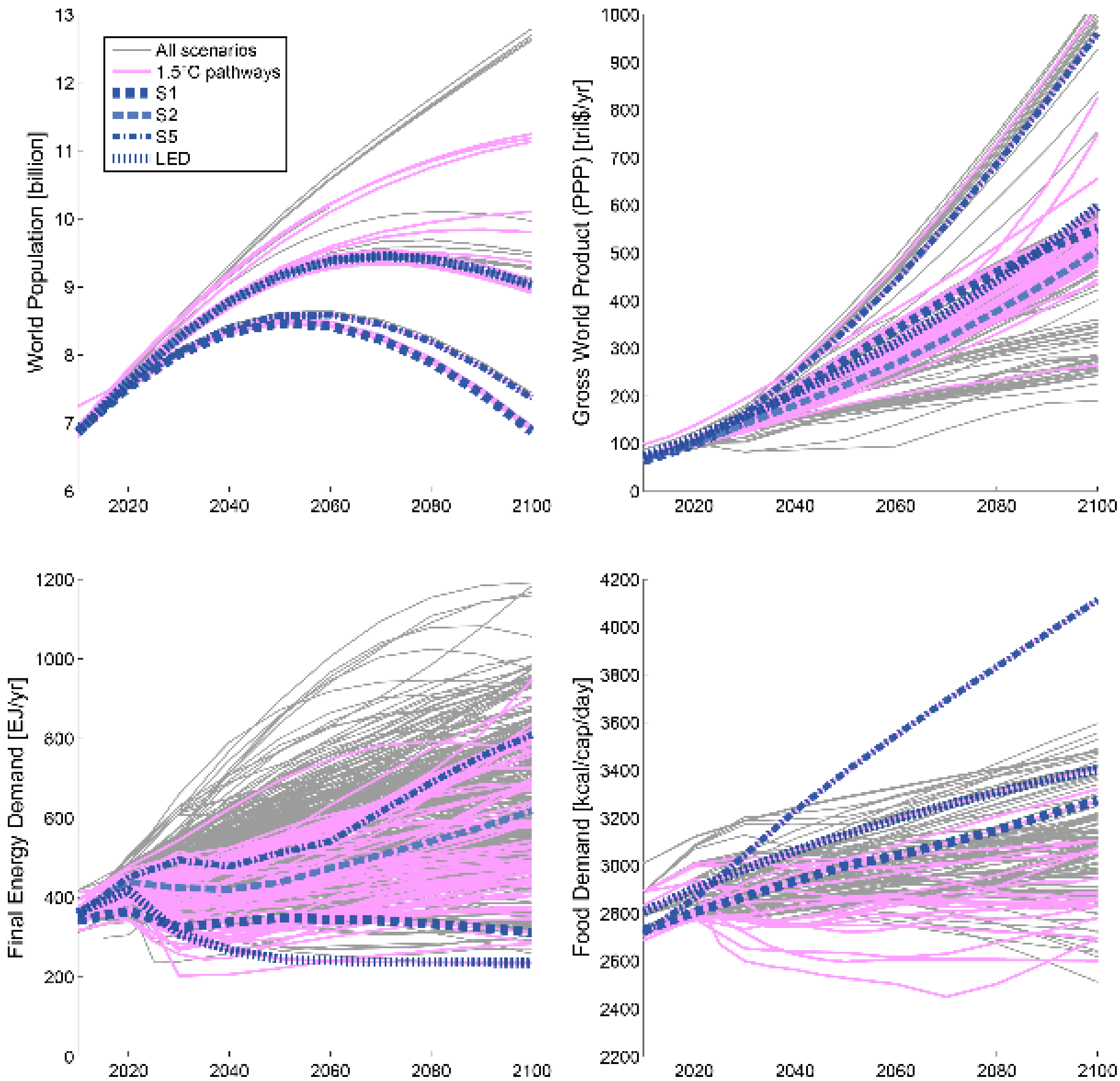


Figure 2.4: Range of assumptions about socio-economic drivers and projections for energy and food demand in the pathways available to this assessment. 1.5°C-consistent pathways are pink, other pathways grey. Trajectories for the illustrative 1.5°C-consistent archetypes used in this Chapter (*S1*, *S2*, *S3*, *LED*) are highlighted. Population assumptions in *S2* and *LED* are identical.

Figure 2.4 compares the range of underlying socio-economic developments as well as energy and food demand in available 1.5°C-consistent pathways with the full set of published scenarios that were submitted to this assessment. While 1.5°C-consistent pathways broadly cover the full range of population and economic growth developments (except of the high population development in SSP3-based scenarios), they tend to cluster on the lower end for energy and food demand. They still encompass, however, a wide range of developments from decreasing to increasing demand levels relative to today. For the purpose of this assessment, a set of four illustrative 1.5°C-consistent pathway archetypes were selected to show the variety of underlying assumptions and characteristics (Fig. 2.4). They comprise three 1.5°C-consistent pathways based on the SSPs (Rogelj et al., 2018): a sustainability oriented scenario (*S1* based on SSP1) developed with the AIM model (Fujimori, 2017), a fossil-fuel intensive and high energy demand scenario (*S5*, based on SSP5) developed with the REMIND-MAgPIE model (Kriegler et al., 2017), and a middle-of-the-road scenario (*S2*, based on SSP2) developed with the MESSAGE-GLOBIOM model (Fricko et al., 2017). In addition, we include a scenario with low energy demand (*LED*) (Grubler et al., 2018), which reflects recent literature with a stronger focus on demand-side measures (Liu et al., 2017; Bertram et al., 2018; Grubler et al., 2018; van Vuuren et al., 2018).

2.3.1.2 Mitigation options in 1.5°C-consistent pathways

In the context of 1.5°C-consistent pathways, the portfolio of mitigation options available to the model becomes an increasingly important factor. IAMs include a wide variety of mitigation options, as well as measures that achieve CDR from the atmosphere (Krey et al., 2014a, 2014b) (see Section 4.3 for a broad assessment of available mitigation measures). For the purpose of this assessment, we elicited technology availability in models that submitted scenarios to the database as summarized in Annex 2.A.2, where a detailed picture of the technology variety underlying available 1.5°C-consistent pathways is provided. Modelling choices on whether a particular mitigation measure is included are influenced by an assessment of its global mitigation potential, the availability of data and literature describing its techno-economic characteristics and future prospects, and computational challenge to represent the measure, e.g., in terms of required spatio-temporal and process detail.

This elicitation (Annex 2.A.2) confirms that IAMs cover most supply-side mitigation options on the process level, while many demand-side options are treated as part of underlying assumptions, which can be varied (Clarke et al., 2014). In recent years, there has been increasing attention on improving the modelling of integrating variable renewable energy into the power system (Creutzig et al., 2017; Luderer et al., 2017; Pietzcker et al., 2017) and of behavioural change and other factors influencing future demand for energy and food (van Sluisveld et al., 2016; McCollum et al., 2017; Weindl et al., 2017), including in the context of 1.5°C-consistent pathways (Grubler et al., 2018; van Vuuren et al., 2018). The literature on the many diverse CDR options only recently started to develop strongly (Minx et al., 2017) (see Section 4.3.7 for a detailed assessment), and hence these options are only partially included in IAM analyses. IAMs mostly incorporate afforestation and bioenergy with carbon capture and storage (BECCS) and only in few cases also include direct air capture with CCS (DACCS) (Chen and Tavoni, 2013; Marcucci et al., 2017; Strefler et al., 2018b).

Several studies have either directly or indirectly explored the dependence of 1.5°C-consistent pathways on specific (sets of) mitigation and CDR technologies (Liu et al., 2017; Bauer et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018b; Rogelj et al., 2018; Strefler et al., 2018b; van Vuuren et al., 2018). However, there are a few potentially disruptive technologies that are typically not yet well covered in IAMs and that have the potential to alter the shape of mitigation pathways beyond the ranges in the IAM-based literature. Those are also included in Annex 2.A.2. The configuration of carbon-neutral energy systems projected in mitigation pathways can vary widely, but they all share a substantial reliance on bioenergy under the assumption of effective land-use emissions control. There are other configurations with less reliance on bioenergy that are not yet comprehensively covered by global mitigation pathway modelling. One approach is to dramatically reduce and electrify energy demand for transportation and manufacturing to levels that make residual non-electric fuel use negligible or replaceable by limited amounts of electrolytic hydrogen. Such an approach is presented in a first-of-its kind low energy demand scenario (Grubler et al., 2018) which is part of this assessment. Other approaches rely less on energy demand reductions, but employ cheap renewable electricity to push the boundaries of electrification in the industry and transport sectors (Breyer et al., 2017; Jacobson, 2017). In addition, these approaches deploy renewable-based Power-2-X (read: Power to “x”) technologies to substitute residual fossil-fuel use (Brynolf et al., 2018). An important element of carbon-neutral Power-2-X applications is the combination of hydrogen generated from renewable electricity and CO_2 captured from the atmosphere (Zeman and Keith, 2008). Alternatively, algae are considered as a bioenergy source with more limited implications for land use and agricultural systems than energy crops (Williams and Laurens, 2010; Walsh et al., 2016; Greene et al., 2017).

Furthermore, a range of measures could radically reduce agricultural and land-use emissions and are not yet well-covered in IAM modelling. This includes plant-based proteins (Joshi and Kumar, 2015) and cultured meat (Post, 2012) with the potential to substitute for livestock products at much lower GHG footprints (Tuomisto and Teixeira de Mattos, 2011). Large-scale use of synthetic or algae-based proteins for animal feed could free pasture land for other uses (Madeira et al., 2017; Pikaar et al., 2018). Novel technologies such as methanogen inhibitors and vaccines (Wedlock et al., 2013; Hristov et al., 2015; Herrero et al., 2016; Subharat et al., 2016) as well as synthetic and biological nitrification inhibitors (Subbarao et al., 2013; Jie Di and Cameron, 2016) could substantially reduce future non-CO_2 emissions from agriculture if commercialised successfully. Enhancing carbon sequestration in soils (Paustian et al., 2016; Frank et al., 2017; Zomer et al., 2017) can provide the dual benefit of CDR and improved soil quality. A range of conservation, restoration and land management options can also increase terrestrial carbon uptake (Griscom et al., 2017). In addition, the literature discusses CDR measures to permanently sequester atmospheric carbon in rocks (mineralisation and enhanced weathering, see Section 4.3.7) as well as carbon capture and usage in long-lived products like plastics and carbon fibres (Mazzotti et al., 2005; Hartmann et al., 2013). Progress in the understanding of the technical viability, economics, and sustainability of these ways to achieve and maintain carbon neutral energy and land use can affect the characteristics, costs and feasibility of 1.5°C-consistent pathways significantly.

2.3.1.3 Policy assumptions in 1.5°C-consistent pathways

Besides assumptions related to socio-economic drivers and mitigation technology, scenarios are also subject to assumptions about the mitigation policies that can be put in place. Mitigation policies can either be applied immediately in scenarios or follow staged or delayed approaches. Policies can span many sectors (e.g., economy-wide carbon pricing), or policies can be applicable to specific sectors only (like the energy sector) with other sectors (e.g., the agricultural or the land-use sector) treated differently. These variations can have an important impact on the ability of models to generate scenarios compatible with stringent climate targets like 1.5°C (Luderer et al., 2013; Rogelj et al., 2013; Bertram et al., 2015b; Kriegler et al., 2018b; Michaelowa et al., 2018). In the scenario ensemble available to this assessment, several variations of near-term mitigation policy implementation can be found: immediate and cross-sectorial global cooperation from 2020 onward towards a global climate objective, a phase-in of globally coordinated mitigation policy from 2020 to 2040, and a more short-term oriented and regionally diverse global mitigation policy, following NDCs until 2030 (Kriegler et al., 2018b; Luderer et al., 2018; McCollum et al., 2018; Rogelj et al., 2018; Strefler et al., 2018b). For example, above-mentioned SSP quantifications assume regionally scattered mitigation policies until 2020, and vary in global convergence thereafter (Kriegler et al., 2014a; Riahi et al., 2017). The impact of near-term policy choices on 1.5°C-consistent pathways is discussed in Section 2.3.5. The literature has also explored 1.5°C-consistent pathways building on a portfolio of policy approaches until 2030, including the combination of regulatory policies and carbon pricing (Kriegler et al., 2018b) and a variety of ancillary policies to safeguard other sustainable development goals (Bertram et al., 2018; van Vuuren et al., 2018). A further discussion of policy implications of 1.5°C-consistent pathways is provided in Section 2.5.1, while a general discussion of policies and options to strengthen action are subject of Section 4.4.

2.3.2 Key characteristics of 1.5°C-consistent pathways

1.5°C-consistent pathways are characterised by a rapid phase out of CO_2 emissions and deep emissions reductions in other GHGs and climate forcers (Section 2.2.2 and 2.3.3). This is achieved by broad transformations in the energy, industry, transport, buildings, Agriculture, Forestry and Other Land-Use (AFOLU) sectors (Section 2.4) (Liu et al., 2017; Bauer et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018a; Luderer et al., 2018; Rogelj et al., 2018; van Vuuren et al., 2018; Zhang et al., 2018). Here we assess 1.5°C-consistent pathways with and without overshoot during the 21st century. One study also explores pathways overshooting 1.5°C for longer than the 21st century (Akimoto et al., 2017), but these are not considered 1.5°C-consistent pathways in this report (Section 1.1.3). This subsection summarizes robust and varying properties of 1.5°C-consistent pathways regarding system transformations, emission reductions and overshoot. It aims to provide an introduction to the detailed assessment of the emissions evolution (Section 2.3.3), CDR deployment (Section 2.3.4), energy (Section 2.4.1, 2.4.2), industry (2.4.3.1), buildings (2.4.3.2), transport (2.4.3.3) and land-use transformations (Section 2.4.4) in 1.5°C-consistent pathways. Throughout Sections 2.3 and 2.4, pathway properties are highlighted with four 1.5°C-consistent pathway archetypes (*S1*, *S2*, *S5*, *LED*) covering a wide range of different socio-economic and technology assumptions (Fig. 2.5, Section 2.3.1).

2.3.2.1 Variation in system transformations underlying 1.5°C-consistent pathways

Be it for the energy, transport, buildings, industry, or AFOLU sector, the literature shows that multiple options and choices are available in each of these sectors to pursue stringent emissions reductions (Section

2.3.1.2, Annex 2.A.2, Section 4.3). Because the overall emissions total under a pathway is limited by a geophysical carbon budget (Section 2.2.2), choices in one sector affect the efforts that are required from others (Clarke et al., 2014). A robust feature of 1.5°C-consistent pathways, as highlighted by the set of pathway archetypes in Figure 2.5, is a virtually full decarbonisation of the power sector around mid-century, a feature shared with 2°C-consistent pathways. The additional emissions reductions in 1.5°C-consistent compared to 2°C-consistent pathways come predominantly from the transport and industry sectors (Luderer et al., 2018). Emissions can be apportioned differently across sectors, for example, by focussing on reducing the overall amount of CO_2 produced in the energy end use sectors, and using limited contributions of CDR by the AFOLU sector (afforestation and reforestation, *S1* and *LED* pathways in Figure 2.5) (Grubler et al., 2018; Holz et al., 2018b; van Vuuren et al., 2018), or by being more lenient about the amount of CO_2 that continues to be produced in the above-mentioned end-use sectors (both by 2030 and mid-century) and strongly relying on technological CDR options like BECCS (*S2* and *S5* pathways in Figure 2.5) (Luderer et al., 2018; Rogelj et al., 2018). Major drivers of these differences are assumptions about energy and food demand and the stringency of near term climate policy (see the difference between early action in the scenarios *S1*, *LED* and more moderate action until 2030 in the scenarios *S2*, *S5*). Furthermore, the carbon budget in each of these pathways depends also on the non-CO_2 mitigation measures implemented in each of them, particularly for agricultural emissions (Sections 2.2.2, 2.3.3) (Gernaat et al., 2015). Those pathways differ not only in terms of their deployment of mitigation and CDR measures (Sections 2.3.4 and 2.4), but also in terms of the temperature overshoot they imply (Figure 2.1). Furthermore, they have very different implications for the achievement of sustainable development objectives, as further discussed in Section 2.5.3.

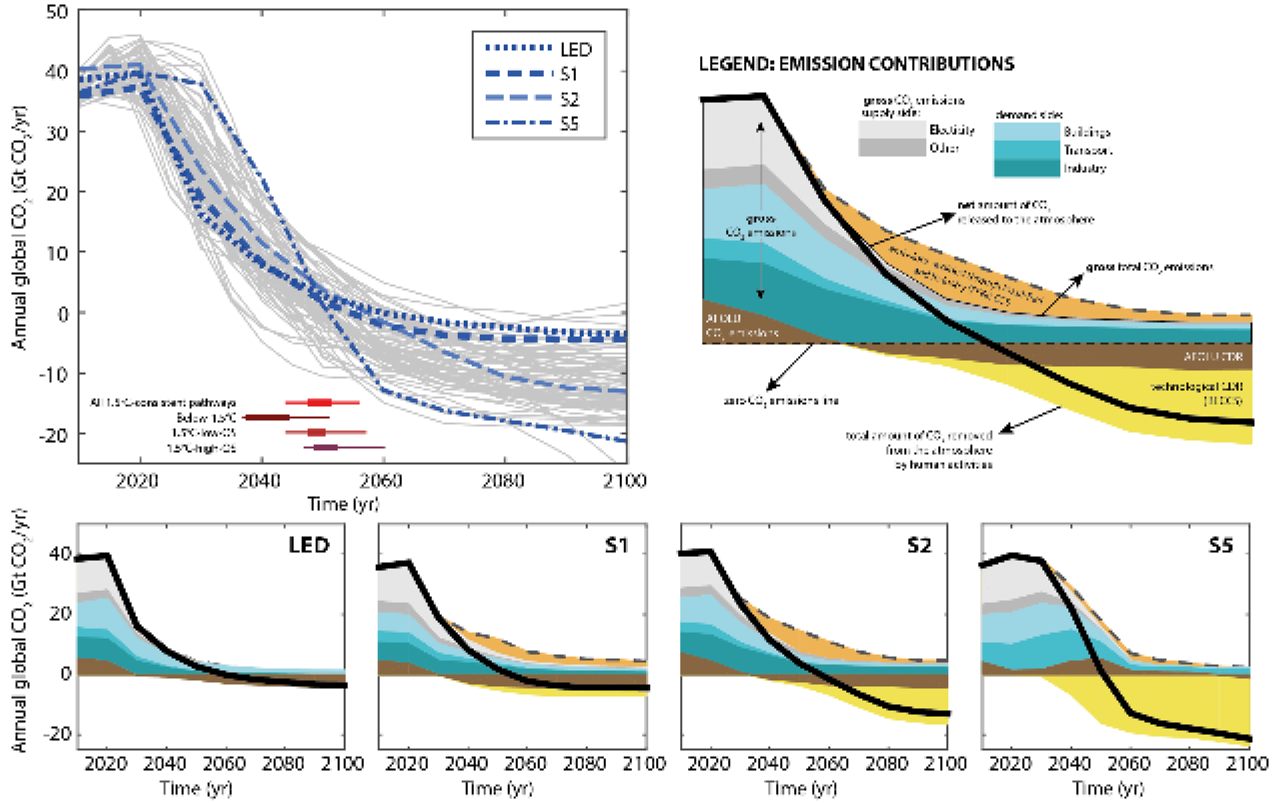


Figure 2.5: **Evolution and break down of global anthropogenic CO_2 emissions until 2100.** The top-left panel shows global net CO_2 emissions in Below-1.5°C, 1.5°C-low-OS, and 1.5°C-high-OS pathways, with the four illustrative 1.5°C-consistent pathway archetypes of this chapter highlighted. Ranges at the bottom of the top-left panel show the 10th–90th percentile range (thin line) and interquartile range (thick line) of the time that global CO_2 emissions reach net zero per pathway class, and for all pathways classes combined. The top-right panel provides a schematic legend explaining all CO_2 emissions contributions to global CO_2 emissions. The bottom row shows how various CO_2 contributions are deployed and used in the four illustrative pathway archetypes (*S1*, *S2*, *S5*, and *LED*) used in this chapter. Note that the S5 scenario reports the building and industry sector emissions jointly. Green-blue areas hence show emissions from the transport, and building & industry demand sectors, respectively.

2.3.2.2 Pathways keeping warming below 1.5°C or temporarily overshooting it

This subsection explores the conditions that would need to be fulfilled to stay below 1.5°C warming without overshoot. As discussed in Section 2.2.2, to keep warming below 1.5°C with a two-in-three (one-in-two) chance, the cumulative amount of CO_2 emissions from 2018 onwards need to remain below a carbon budget of 550 (750) $GtCO_2$, further reduced by 100 $GtCO_2$ when accounting for additional Earth-system feedbacks until 2100. Based on the current state of knowledge, exceeding this remaining carbon budget at some point in time would give a one-in-three (one-in-two) chance that the 1.5°C limit is overshot (Table 2.2). For comparison, around 290 ±20 (1-sigma range) $GtCO_2$ have been emitted in the years 2011-2017 with annual CO_2 emissions in 2017 slightly above 40 $GtCO_2\ yr^{-1}$ (Jackson et al., 2017; Le Quéré et al., 2018). Committed fossil-fuel emissions from existing fossil-fuel infrastructure as of 2010 have been estimated at around 500 ±200 $GtCO_2$ (with ca. 200 $GtCO_2$ already emitted until 2017) (Davis and Caldeira, 2010). Coal-fired power plants contribute the largest part. Committed emissions from existing coal-fired power plants built until the end of 2016 are estimated to add up to roughly 200 $GtCO_2$ and a further 100–150 $GtCO_2$ from coal-fired power plants are under construction or planned (González-Eguino et al., 2017; Edenhofer et al., 2018). However, there has been a marked slowdown of planned coal-power projects in recent years, and some estimates indicate that the committed emissions from coal plants that are under construction or planned have halved since 2015 (Shearer et al., 2018). Despite these uncertainties, the committed fossil-fuel emissions are assessed to already amount to more than half (a third) of the remaining carbon budget.

An important question is to what extent the nationally determined contributions (NDCs) under the Paris Agreement are aligned with the remaining carbon budget. It was estimated that the NDCs, if successfully implemented, imply a total of 400–560 $GtCO_2$ emissions over the 2018–2030 period (considering both conditional and unconditional NDCs) (Rogelj et al., 2016a). Thus, following an NDC trajectory would exhaust already 70–100% (50–75%) of the remaining two-in-three (one-in-two) 1.5°C carbon budget (unadjusted for additional Earth-system feedbacks) by 2030. This would leave only about 0–8 (9–18) years to bring down global emissions from NDC levels of around 40 $GtCO_2\ yr^{-1}$ in 2030 (Fawcett et al., 2015; Rogelj et al., 2016a) to net zero (further discussion in Section 2.3.5).

Most 1.5°C-consistent pathways show more stringent emissions reductions by 2030 than implied by the NDCs (Section 2.3.5) The lower end of those pathways reach down to below 20 $GtCO_2\ yr^{-1}$ in 2030 (Section 2.3.3, Table 2.4), less than half of what is implied by the NDCs. Whether such pathway will be able to limit warming to 1.5°C without overshoot will depend on whether cumulative net CO_2 emissions over the 21st century can be kept below the remaining carbon budget at any time. Net global CO_2 emissions are derived from the gross amount of CO_2 that humans annually emit into the atmosphere reduced by the amount of anthropogenic CDR in each year. New research has looked more closely at the amount and the drivers of gross CO_2 emissions from fossil-fuel combustion and industrial processes (FFI) in deep mitigation pathways (Luderer et al., 2018), and found that the larger part of remaining CO_2 emissions come from direct fossil-fuel use in the transport and industry sectors, while residual energy supply sector emissions (mostly from the power sector) are limited by a rapid approach to net zero CO_2 emissions until mid-century. The 1.5°C-consistent pathways from the literature that were reported in the scenario database project remaining FFI CO_2 emissions of 620–1410 $GtCO_2$ over the period 2018–2100 (5th–95th percentile range; median: 970 $GtCO_2$). Kriegler et al. (2018a) conducted a sensitivity analysis that explores the four central options for reducing fossil-fuel emissions: lowering energy demand, electrifying energy services, decarbonizing the power sector and decarbonizing non-electric fuel use in energy end-use sectors. By exploring these options to their extremes, they found a lowest value of 500 $GtCO_2$ (2018–2100) gross fossil-fuel CO_2 emissions for the hypothetical case of aligning the strongest assumptions for all four mitigation options. The two lines of evidence and the fact that available 1.5°C pathways cover a wide range of assumptions (Section 2.3.1) give a robust indication of a lower limit of ca. 500 $GtCO_2$ remaining fossil-fuel and industry CO_2 emissions in the 21st century.

To compare these numbers with the remaining carbon budget, Land-Use Change (LUC) CO_2 emissions need to be taken into account. In many of the 1.5°C-consistent pathways LUC CO_2 emissions reach zero at or before mid-century and then turn to negative values (Table 2.4). This means human changes to the land lead to atmospheric carbon being stored in plants and soils. This needs to be distinguished from the natural CO_2

uptake by land which is not accounted for in the anthropogenic LUC CO_2 emissions reported in the pathways. Given the difference in estimating the 'anthropogenic' sink between countries and the global integrated assessment and carbon modelling community (Grassi et al., 2017), the LUC CO_2 estimates included here are not necessarily directly comparable with countries' estimates at global level. The cumulated amount of LUC CO_2 emissions until the time they reach zero combine with the fossil-fuel and industry CO_2 emissions to a total amount of gross emissions of 670–1430 $GtCO_2$ for the period 2018–2100 (5th–95th percentile; median 1040 $GtCO_2$). The lower end of the range is similar to what emerges from a scenario of transformative change that halves CO_2 emissions every decade from 2020 to 2050 (Rockström et al., 2017). All these estimates are above the remaining carbon budget for a two-in-three chance of limiting warming below 1.5°C without overshoot, including the low end of the hypothetical sensitivity analysis of Kriegler et al. (2018a), who assumes 75 $GtCO_2$ LUC emissions adding to a total of 575 $GtCO_2$ gross CO_2 emissions. As only limited, highly idealized cases have been identified that keep gross CO_2 emissions within the 1.5°C carbon budget and based on current understanding of the geophysical response and its uncertainties, the available evidence indicates that avoiding overshoot will require some type of CDR in a broad sense, e.g., via negative LUC CO_2 emissions. (*medium confidence*) (Table 2.2).

Net CO_2 emissions can fall below gross CO_2 emissions, if CDR is brought into the mix. Studies have looked at mitigation and CDR in combination to identify strategies for limiting warming to 1.5°C (Sanderson et al., 2016; Ricke et al., 2017). CDR and/or negative LUC CO_2 emissions are deployed by all 1.5°C-consistent pathways available to this assessment, but the scale of deployment and choice of CDR measure varies widely (Section 2.3.4). Furthermore, no CDR technology has been deployed at scale yet, and all come with concerns about their potential (Fuss et al., 2018), feasibility (Nemet et al., 2018) and/or sustainability (Smith et al., 2015; Fuss et al., 2018) (see Sections 2.3.4, 4.3.2 and 4.3.7 and Cross-Chapter Box 7 in Chapter3 for further discussion). CDR can have two very different functions in 1.5°C-consistent pathways. If deployed in the first half of the century, before net zero CO_2 emissions are reached, it neutralizes some of the remaining CO_2 emissions year by year and thus slows the accumulation of CO_2 in the atmosphere. In this first function it can be used to remain within the carbon budget and avoid overshoot. If CDR is deployed in the second half of the century after carbon neutrality has been established, it can still be used to neutralize some residual emissions from other sectors, but also to create net negative emissions that actively draw down the cumulative amount of CO_2 emissions to return below a 1.5°C warming level. In the second function, CDR enables temporary overshoot. The literature points to strong limitations to upscaling CDR (limiting its first abovementioned function) and to sustainability constraints (limiting both abovementioned functions) (Fuss et al., 2018; Minx et al., 2018; Nemet et al., 2018). Large uncertainty hence exists about what amount of CDR could actually be available before mid-century. Kriegler et al. (2018a) explore a case limiting CDR to 100 $GtCO_2$ until 2050, and the 1.5°C-consistent pathways available in the report's database project 40–260 $GtCO_2$ CDR until the point of carbon neutrality (5^{th} to 95^{th} percentile; median 120 $GtCO_2$). Because gross CO_2 emissions in most cases exceed the remaining carbon budget by several hundred $GtCO_2$ and given the limits to CDR deployment until 2050, most of the 1.5°C-consistent pathways available to this assessment are overshoot pathways. However, the scenario database also contains nine non-overshoot pathways that remain below 1.5°C throughout the 21st century and that are assessed in the chapter.

2.3.3 Emissions evolution in 1.5°C pathways

This section assesses the salient temporal evolutions of climate forcers over the 21st century. It uses the classification of 1.5°C-consisten pathways presented in Section 2.1, which includes a Below-1.5°C class, as well as other classes with varying levels of projected overshoot (1.5°C-low-OS and 1.5°C-high-OS). First, aggregate-GHG benchmarks for 2030 are assessed. Subsequent sections assess long-lived climate forcers (LLCF) and short-lived climate forcers (SLCF) separately because they contribute in different ways to near-term, peak and long-term warming (Section 2.2, Cross-Chapter Box 2 in Chapter 1).

Estimates of aggregated GHG emissions in line with specific policy choices are often compared to near-term benchmark values from mitigation pathways to explore their consistency with long-term climate goals (Clarke et al., 2014; UNEP, 2016, 2017; UNFCCC, 2016). Benchmark emissions or estimates of peak years derived from IAMs provide guidelines or milestones that are consistent with achieving a given temperature level. While they do not set mitigation requirements in a strict sense, exceeding these levels in a given year almost invariably increases the mitigation challenges afterwards by increasing the rates of change and increasing the reliance on speculative technologies, including the possibility that its implementation becomes unachievable (Luderer et al., 2013; Rogelj et al., 2013b; Clarke et al., 2014; Fawcett et al., 2015; Riahi et al., 2015; Kriegler et al., 2018b) (see Cross-Chapter Box 3 in Chapter 1 for a discussion of feasibility concepts). These trade-offs are particularly pronounced in 1.5°C-consistent pathways and are discussed in Section 2.3.5. This section assesses Kyoto-GHG emissions in 2030 expressed in CO_2 equivalent (CO_2e) emissions using 100-year global warming potentials[3].

Appropriate benchmark values of aggregated GHG emissions depend on a variety of factors. First and foremost, they are determined by the desired likelihood to keep warming below 1.5°C and the extent to which projected temporary overshoot is to be avoided (Sections 2.2, 2.3.2, and 2.3.5). For instance, median aggregated 2030 GHG emissions are about 10 $GtCO_2e\ yr^{-1}$ lower in 1.5°C-low-OS compared to 1.5°C-high-OS pathways, with respective interquartile ranges of 26–31 and 36–49 $GtCO_2e\ yr^{-1}$ (Table 2.4). These ranges correspond to 25–30 and 35–48 $GtCO_2e\ yr^{-1}$ in 2030, respectively, when aggregated with 100-year Global Warming Potentials from the IPCC Second Assessment Report. The limited evidence available for pathways aiming to limit warming below 1.5°C without overshoot or with limited amounts of CDR (Grubler et al., 2018; Holz et al., 2018b; van Vuuren et al., 2018) indicates that under these conditions consistent emissions in 2030 would fall at the lower end and below the abovementioned ranges. Ranges for the 1.5°C-low-OS and Lower-2°C classes only overlap outside their interquartile ranges highlighting the more accelerated reductions in 1.5°C-consistent compared to 2°C-consistent pathways.

Appropriate benchmark values also depend on the acceptable or desired portfolio of mitigation measures, representing clearly identified trade-offs and choices (Sections 2.3.4, 2.4, and 2.5.3) (Luderer et al., 2013; Rogelj et al., 2013a; Clarke et al., 2014; Krey et al., 2014a; Strefler et al., 2018b). For example, lower 2030 GHG emissions correlate with a lower dependence on the future availability and desirability of CDR (Strefler et al., 2018b). Explicit choices or anticipation that CDR options are only deployed to a limited degree during the 21st century imply lower benchmarks over the coming decades that are achieved through lower CO_2 emissions. The pathway archetypes used in the chapter illustrate this further (Figure 2.6). Under middle-of-the-road assumptions of technological and socioeconomic development, pathway *S2* suggests emission benchmarks of 34, 12 and -8 $GtCO_2e\ yr^{-1}$ in the years 2030, 2050, and 2100, respectively. In contrast, a pathway that further limits overshoot and aims at eliminating the reliance on negative emissions technologies like BECCS as well as CCS (here labelled as the *LED* pathway) shows deeper emissions reductions in 2030 to limit the cumulative amount of CO_2 until net zero global CO_2 emissions (carbon neutrality). The *LED* pathway here suggest emission benchmarks of 25, 9 and 2 $GtCO_2e\ yr^{-1}$ in the years 2030, 2050, and 2100, respectively. However, a pathway that allows and plans for the successful large-scale deployment of BECCS by and beyond 2050 (*S5*) shows a shift in the opposite direction. The variation within and between the abovementioned ranges of 2030 GHG benchmarks hence depends strongly on societal choices and preferences related to the acceptability and availability of certain technologies.

Overall these variations do not strongly affect estimates of the 1.5°C-consistent timing of global peaking of GHG emissions. Both Below-1.5°C and 1.5°C-low-OS pathways show minimum-maximum ranges in 2030 that do not overlap with 2020 ranges, indicating the global GHG emissions peaked before 2030 in these pathways. Also 2020 and 2030 GHG emissions in 1.5°C-high-OS pathways only overlap outside their interquartile ranges.

Kyoto-GHG emission reductions are achieved by reductions in CO_2 and non-CO_2 GHGs. The AR5 identified two primary factors that influence the depth and timing of reductions in non-CO_2 Kyoto-GHG emissions: (1) the abatement potential and costs of reducing the emissions of these gases and (2) the strategies that allow making trade-offs between them (Clarke et al., 2014). Many studies indicate low-cost near-term mitigation options in some sectors for non-CO_2 gases compared to supply-side measures for CO_2 mitigation (Clarke et al., 2014). A large share of this potential is hence already exploited in mitigation pathways in line with 2°C. At the same time, by mid-century and beyond, estimates of further reductions of non-CO_2 Kyoto-GHGs, in

[3] FOOTNOTE: In this chapter GWP-100 values from the IPCC Fourth Assessement Report are used because emissions of fluorinated gases in the integrated pathways have been reported in this metric to the database. At a global scale, switching between GWP-100 values of the Second, Fourth or Fifth IPCC Assessment Reports could result in variations in aggregated Kyoto-GHG emissions of about ±5% in 2030 (UNFCCC, 2016).

particular CH_4 and N_2O, are hampered by the absence of mitigation options in the current generation of IAMs which are hence not able to reduce residual emissions of sources linked to livestock production and fertilizer use (Clarke et al., 2014; Gernaat et al., 2015) (Sections 2.3.1.2, 2.4.4, Annex 2.A.2). Therefore, while net CO_2 emissions are projected to be markedly lower in 1.5°C-consistent compared to 2°C-consistent pathways, this is much less the case for methane (CH_4) and nitrous-oxide (N_2O) (Figures 2.6–2.7). This results in reductions of CO_2 being projected to take up the largest share of emissions reductions when moving between 1.5°C-consistent and 2°C-consistent pathways (Rogelj et al., 2015b, 2018; Luderer et al., 2018). If additional non-CO_2 mitigation measures are identified and adequately included in IAMs, they are expected to further contribute to mitigation efforts by lowering the floor of residual non-CO_2 emissions. However, the magnitude of these potential contributions has not been assessed as part of this report.

The interplay between residual CO_2 and non-CO_2 emissions, as well as CDR results in different times at which global GHG emissions reach net zero levels in 1.5°C-consistent pathways. Interquartile ranges of the years in which 1.5°C-low-OS and 1.5°C-high-OS reach net zero GHG emissions range from 2060 to 2080 (Table 2.4). A seesaw characteristic can be found between near-term emissions reductions and the timing of net zero GHG emissions as a result of the reliance on net negative emissions of pathways with limited emissions reductions in the next one to two decades (see earlier). Most 1.5°C-high-OS pathways lead to net zero GHG emissions in approximately the third quarter of this century, because all of them rely on significant amounts of annual net negative emissions in the second half of the century to decline temperatures after overshoot (Table 2.4). However, emissions in pathways that aim at limiting overshoot as much as possible or more slowly decline temperatures after their peak reach this point slightly later or at times never. Early emissions reductions in this case result in a lower requirement for net negative emissions. Estimates of 2030 GHG emissions in line with the current NDCs overlap with the highest quartile of 1.5°C-high-OS pathways (Cross-Chapter Box 9 in Chapter 4).

2.3.3.1 Emissions of long-lived climate forcers

Climate effects of long-lived climate forcers (LLCFs) are dominated by CO_2, with smaller contributions of N_2O and some fluorinated gases (Myhre et al., 2013; Blanco et al., 2014). Overall net CO_2 emissions in pathways are the result of a combination of various anthropogenic contributions (Figure 2.5) (Clarke et al., 2014): (a) CO_2 produced by fossil-fuel combustion and industrial processes, (b) CO_2 emissions or removals from the Agriculture, Forestry and Other Land Use (AFOLU) sector, (c) CO_2 capture and sequestration (CCS) from fossil fuels or industrial activities before it is released to the atmosphere, (d) CO_2 removal by technological means, which in current pathways is mainly achieved by BECCS although other options could be conceivable (see Section 4.3.7). Pathways apply these four contributions in different configurations (Figure 2.5) depending on societal choices and preferences related to the acceptability and availability of certain technologies, the timing and stringency of near-term climate policy, and the ability to limit the demand that drives baseline emissions (Marangoni et al., 2017; Riahi et al., 2017; Grubler et al., 2018; Rogelj et al., 2018; van Vuuren et al., 2018), and come with very different implication for sustainable development (Section 2.5.3).

All 1.5°C-consistent pathways see global CO_2 emissions embark on a steady decline to reach (near) net zero levels around 2050, with 1.5°C-low-OS pathways reaching net zero CO_2 emissions around 2045–2055 (Table 2.4; Figure 2.5). Near-term differences between the various pathway classes are apparent, however. For instance, Below-1.5°C and 1.5°C-low-OS pathways show a clear shift towards lower CO_2 emissions in 2030 relative to other 1.5°C and 2°C pathway classes, although in all 1.5°C-consistent classes reductions are clear (Figure 2.6). These lower near-term emissions levels are a direct consequence of the former two pathway classes limiting cumulative CO_2 emissions until carbon neutrality to aim for a higher probability that peak warming is limited to 1.5°C (Section 2.2.2 and 2.3.2.2). In some cases, 1.5°C-low-OS pathways achieve net zero CO_2 emissions one or two decades later, contingent on 2030 CO_2 emissions in the lower quartile of the literature range, i.e. below about 18 $GtCO_2\ yr^{-1}$. Median year-2030 global CO_2 emissions are of the order of 5–10 $GtCO_2\ yr^{-1}$ lower in Below-1.5°C compared to 1.5°C-low-OS pathways, which are in turn lower than 1.5°C-high-OS pathways (Table 2.4). 1.5°C-high-OS pathways show broadly similar emissions levels than the 2°C-consistent pathways in 2030.

The development of CO_2 emissions in the second half of the century in 1.5°C pathways is characterised by the need to stay or return within a carbon budget. Figure 2.6 shows net CO_2 and N_2O emissions from various sources in 2050 and 2100 in 1.5°C-consistent pathways in the literature. Virtually all 1.5°C pathways obtain net negative CO_2 emissions at some point during the 21st century but the extent to which net negative emissions are relied upon varies substantially (Figure 2.6, Table 2.4). This net withdrawal of CO_2 from the atmosphere compensates for residual long-lived non-CO_2 GHG emissions that also accumulate in the atmosphere (like N_2O) or to cancel some of the build-up of CO_2 due to earlier emissions to achieve increasingly higher likelihoods that warming stays or returns below 1.5°C (see Section 2.3.4 for a discussion of various uses of CDR). Even non-overshoot pathways that aim at achieving temperature stabilisation would hence deploy a certain amount of net negative emissions to offset any accumulating long-lived non-CO_2 GHGs. 1.5°C overshoot pathways display significantly larger amounts of annual net negative emissions in the second half of the century. The larger the overshoot the more net negative emissions are required to return temperatures to 1.5°C by the end of the century (Table 2.4, Figure 2.1).

N_2O emissions decline to a much lesser extent than CO_2 in currently available 1.5°C-consistent pathways (Figure 2.6). Current IAMs have limited emissions reduction potentials (Gernaat et al., 2015) (Sections 2.3.1.2, 2.4.4, Annex 2.A.2), reflecting the difficulty of eliminating N_2O emission from agriculture (Bodirsky et al., 2014). Moreover, the reliance of some pathways on significant amounts of bioenergy after mid-century (Section 2.4.2) coupled to a substantial use of nitrogen fertilizer (Popp et al., 2017) also makes reducing N_2O emissions harder (for example, see pathway *S5* in Figure 2.6). As a result, sizeable residual N_2O emissions are currently projected to continue throughout the century, and measures to effectively mitigate them will be of continued relevance for 1.5°C societies. Finally, the reduction of nitrogen use and N_2O emissions from agriculture is already a present-day concern due to unsustainable levels of nitrogen pollution (Bodirsky et al., 2012). Section 2.4.4 provides a further assessment of the agricultural non-CO_2 emissions reduction potential.

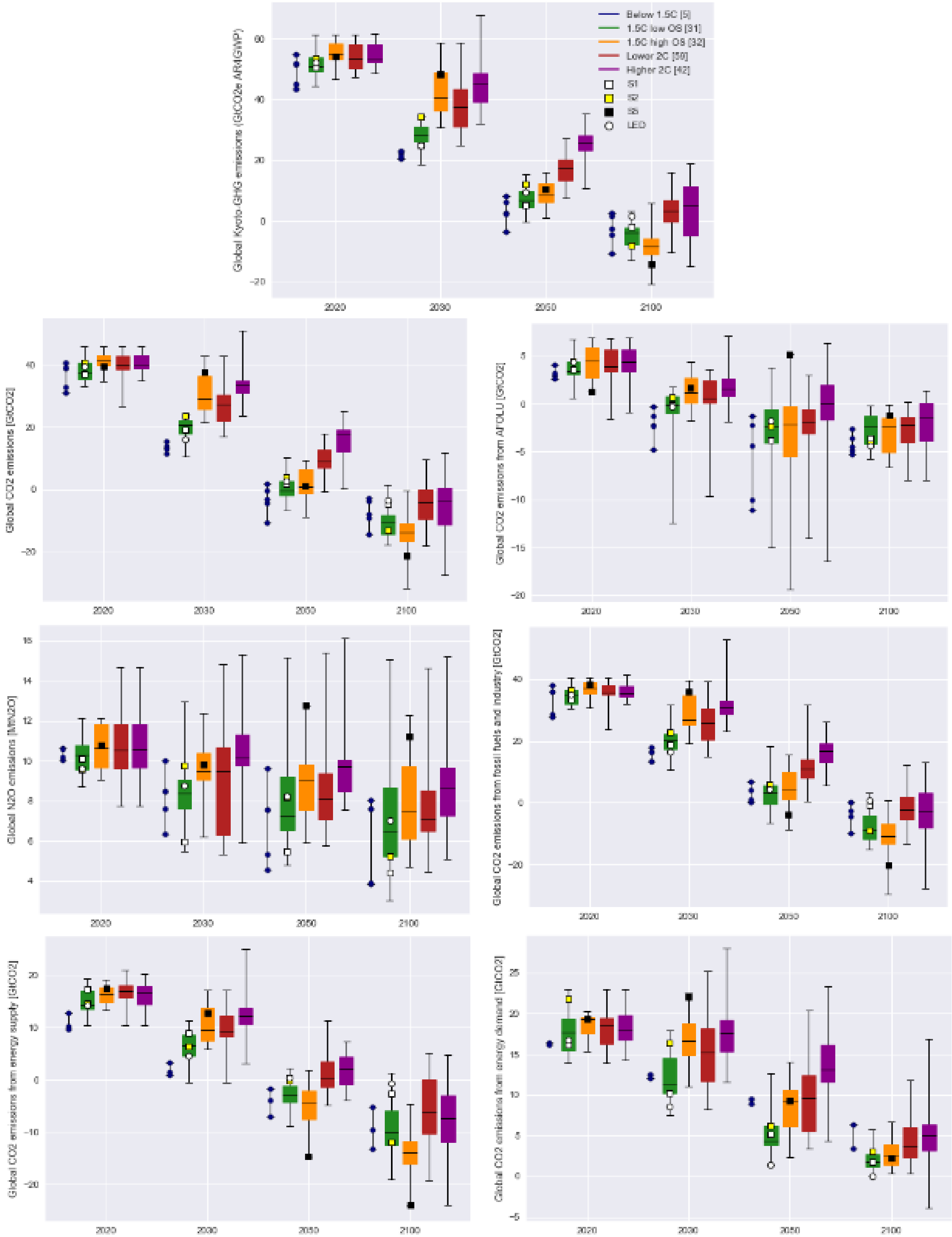


Figure 2.6: Annual global emissions characteristics for 2020, 2030, 2050, 2100. Data are shown for Kyoto-GHG emissions (top panel), and total CO_2 emissions, CO_2 emissions from the AFOLU sector, global N_2O emissions, and CO_2 emissions from fossil-fuel use and industrial processes. The latter is also split into emissions from the energy supply sector (electricity sector and refineries), and direct emissions from fossil-fuel use in energy demand sectors (industry, buildings, transport) (bottom row). Horizontal black lines show the median, boxes show the interquartile range, and whiskers the minimum-maximum range. Icons indicate the four pathway archetypes used in this chapter. In case less than 7 data points are available in a class, the minimum-maximum range and single data points are shown. Kyoto-GHG, emissions in the top panel are aggregated with AR4 GWP-100 and contain CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6. NF_3 is typically not reported by IAMs. Scenarios with year-2010 Kyoto-GHG emissions outside

the range assessed by IPCC AR5 WGIII assessed are excluded (IPCC, 2014b)..

2.3.3.2 Emissions of short-lived climate forcers and fluorinated gases

SLCFs include shorter-lived GHGs like CH_4 and some HFCs, as well as particles (aerosols), their precursors and ozone precursors. SLCFs are strongly mitigated in 1.5°C pathways as is the case for 2°C pathways (Figure 2.7). SLCF emissions ranges of 1.5°C and 2°C pathway classes strongly overlap, indicating that the main incremental mitigation contribution between 1.5°C and 2°C pathways comes from CO_2 (Luderer et al., 2018; Rogelj et al., 2018). CO_2 and SLCF emissions reductions are connected in situations where SLCF and CO_2 are co-emitted by the same process, for example, with coal-fired power plants (Shindell and Faluvegi, 2010) or within the transport sector (Fuglestvedt et al., 2010). Many CO_2-targeted mitigation measures in industry, transport and agriculture (Sections 2.4.3–4) hence also reduce non-CO_2 forcing (Rogelj et al., 2014b; Shindell et al., 2016).

Despite having a strong warming effect (Myhre et al., 2013; Etminan et al., 2016), current 1.5°C-consistent pathways still project significant emissions of CH_4 by 2050, indicating that only limited mitigation options are included and identified in IAM analyses (Gernaat et al., 2015) (Sections 2.3.1.2, 2.4.4, Table 2.A.2). The AFOLU sector contributes an important share of the residual CH_4 emissions until mid-century, with its relative share increasing from slightly below 50% in 2010 to roughly around 55–70% in 2030, and 60–80% in 2050 in 1.5°C-consistent pathways (interquartile range across 1.5°C-consistent pathways for projections). Many of the proposed measures to target CH_4 (Shindell et al., 2012; Stohl et al., 2015) are included in 1.5°C-consistent pathways (Figure 2.7), though not all (Sections 2.3.1.2, 2.4.4, Table 2.A.2). A detailed assessment of measures to further reduce AFOLU CH_4 emissions has not been conducted.

Overall reductions of SLCFs can have effects of either sign on temperature depending on the balance between cooling and warming agents. The reduction in SO_2 emissions is the dominant single effect as it weakens the negative total aerosol forcing. This means that reducing all SLCF emissions to zero would result in a short-term warming, although this warming is unlikely to be more than 0.5°C (Section 2.2 and Figure 1.5 (Samset et al., 2018)). Because of this effect, suggestions have been proposed that target the warming agents only (referred to as short-lived climate pollutants or SLCPs instead of the more general short-lived climate forcers; e.g., Shindell et al., 2012) though aerosols are often emitted in varying mixtures of warming and cooling species (Bond et al., 2013). Black Carbon (BC) emissions reach similar levels across 1.5°C-consistent and 2°C-consistent pathways available in the literature, with interquartile ranges of emissions reductions across pathways of 16–34% and 48–58% in 2030 and 2050, respectively, relative to 2010 (Figure 2.7). Recent studies have identified further reduction potentials for the near term, with global reductions of about 80% being suggested (Stohl et al., 2015; Klimont et al., 2017). Because the dominant sources of certain aerosol mixtures are emitted during the combustion of fossil fuels, the rapid phase-out of unabated fossil-fuels to avoid CO_2 emissions would also result in removal of these either warming or cooling SLCF air-pollutant species. Furthermore, they are also reduced by efforts to reduce particulate air pollution. For example, year-2050 SO_2 emissions, precursor of sulphate aerosol, in 1.5°C-consistent pathways are about 75–85% lower than their 2010 levels. Some caveats apply, for example, if residential biomass use would be encouraged in industrialised countries in stringent mitigation pathways without appropriate pollution control measures, aerosol concentrations could also increase (Sand et al., 2015; Stohl et al., 2015).

Table 2.4: Emissions in 2030, 2050 and 2100 in 1.5°C and 2°C scenario classes and absolute annual rates of change between 2010–2030, 2020–2030 and 2030–2050, respectively. Values show: median (25th and 75th percentile), across available scenarios. If less than seven scenarios are available (*), the minimum-maximum range is given instead. For the timing of global zero of total net CO_2 and Kyoto-GHG emissions, the interquartile range is given. Kyoto-GHG emissions are aggregated with GWP-100 values from IPCC AR4. 2010 emissions for total net CO_2, CO_2 from fossil-fuel use & industry, and AFOLU CO_2 are estimated at 38.5, 33.4, and 5 $GtCO_2$/yr, respectively (Le Quéré et al., 2018). A difference is reported in estimating the "anthropogenic" sink by countries or the global carbon modelling community (Grassi et al., 2017), and AFOLU CO_2 estimates reported here are thus not necessarily comparable with countries' estimates. Scenarios with year-2010 Kyoto-GHG emissions outside the range assessed by IPCC AR5 WGIII are excluded (IPCC, 2014b).

	type					Absolute annual change (GtCO2/yr)			Timing of global zero
name	**category**	**count**	**2030**	**2050**	**2100**	**2010-2030**	**2020-2030**	**2030-2050**	**year**
Total CO_2 (net)	**Below-1.5°C**	5	13 (11 15)	-3 (-11 2)	-8 (-14 -3)	-1.2 (-1.3 -1.0)	-2.5 (-2.8 -1.8)	-0.8 (-1.2 -0.7)	(2037 2054)
	1.5°C-low-OS	37	21 (18 22)	0 (-2 3)	-11 (-14 -8)	-0.8 (-1 -0.7)	-1.7 (-2.3 -1.4)	-1 (-1.2 -0.8)	(2047 2055)
	1.5°C-high-OS	36	29 (26 36)	1 (-1 6)	-14 (-16 -11)	-0.4 (-0.6 0)	-1.1 (-1.5 -0.5)	-1.3 (-1.8 -1.1)	(2049 2059)
	Lower-2°C	67	27 (22 30)	9 (7 13)	-4 (-9 0)	-0.5 (-0.7 -0.3)	-1.2 (-1.9 -0.9)	-0.8 (-1 -0.6)	(2065 2096)
	Higher-2°C	54	33 (31 35)	18 (12 19)	-3 (-11 1)	-0.2 (-0.4 0)	-0.7 (-0.9 -0.5)	-0.8 (-1 -0.6)	(2070 post-2100)
CO_2 from fossil fuels and industry (gross)	**Below-1.5°C**	5	18 (14 21)	10 (0 21)	8 (0 12)	-0.7 (-1.0 -0.6)	-1.5 (-2.2 -0.9)	-0.4 (-0.7 -0.0)	-
	1.5°C-low-OS	37	22 (19 24)	10 (8 14)	6 (3 8)	-0.5 (-0.6 -0.4)	-1.3 (-1.7 -0.9)	-0.6 (-0.7 -0.5)	-
	1.5°C-high-OS	36	28 (26 37)	13 (12 17)	7 (3 9)	-0.2 (-0.3 0.2)	-0.8 (-1.1 -0.2)	-0.7 (-1 -0.6)	-
	Lower-2°C	67	26 (21 31)	14 (11 18)	8 (4 10)	-0.3 (-0.6 -0.1)	-0.9 (-1.4 -0.6)	-0.6 (-0.7 -0.4)	-
	Higher-2°C	54	31 (29 33)	19 (17 23)	8 (5 11)	-0.1 (-0.2 0.1)	-0.5 (-0.7 -0.2)	-0.6 (-0.7 -0.5)	-
CO_2 from fossil fuels and industry (net)	**Below-1.5°C**	5	16 (13 18)	1 (0 7)	-3 (-10 0)	-0.8 (-1.0 -0.7)	-1.8 (-2.2 -1.2)	-0.6 (-0.9 -0.5)	-
	1.5°C-low-OS	37	21 (18 22)	3 (-1 6)	-9 (-12 -4)	-0.6 (-0.7 -0.5)	-1.4 (-1.8 -1.1)	-0.8 (-1.1 -0.7)	-
	1.5°C-high-OS	36	27 (25 35)	4 (1 10)	-11 (-13 -7)	-0.3 (-0.3 0.1)	-0.9 (-1.2 -0.3)	-1.2 (-1.5 -0.9)	-
	Lower-2°C	67	26 (21 30)	11 (8 14)	-2 (-5 2)	-0.3 (-0.6 -0.1)	-1 (-1.4 -0.6)	-0.7 (-1 -0.4)	-
	Higher-2°C	54	31 (29 33)	17 (13 19)	-3 (-8 3)	-0.1 (-0.2 0.1)	-0.5 (-0.7 -0.2)	-0.7 (-1 -0.5)	-
CO_2 from AFOLU	**Below-1.5°C**	5	-2 (-5 0)	-4 (-11 -1)	-4 (-5 -3)	-0.3 (-0.4 -0.2)	-0.5 (-0.8 -0.4)	-0.1 (-0.4 0)	-
	1.5°C-low-OS	37	0 (-1 1)	-2 (-4 -1)	-2 (-4 -1)	-0.2 (-0.3 -0.2)	-0.4 (-0.5 -0.3)	-0.1 (-0.2 -0.1)	-
	1.5°C-high-OS	36	1 (0 3)	-2 (-5 0)	-2 (-5 -1)	-0.1 (-0.3 -0.1)	-0.2 (-0.5 -0.1)	-0.2 (-0.3 0)	-
	Lower-2°C	67	1 (0 2)	-2 (-3 -1)	-2 (-4 -1)	-0.2 (-0.3 -0.1)	-0.3 (-0.4 -0.2)	-0.2 (-0.2 -0.1)	-
	Higher-2°C	54	2 (1 3)	0 (-2 2)	-1 (-4 0)	-0.2 (-0.2 -0.1)	-0.2 (-0.4 -0.1)	-0.1 (-0.1 0)	-
Bioenergy combined with carbon capture and storage (BECCS)	**Below-1.5°C**	5	0 (-1 0)	-3 (-8 0)	-6 (-13 0)	0 (-0.1 0)	0 (-0.1 0)	-0.2 (-0.4 0)	-
	1.5°C-low-OS	37	0 (-1 0)	-5 (-6 -4)	-12 (-16 -7)	0 (-0.1 0)	0 (-0.1 0)	-0.2 (-0.3 -0.2)	-
	1.5°C-high-OS	36	0 (0 0)	-7 (-9 -4)	-15 (-16 -12)	0 (0 0)	0 (0 0)	-0.3 (-0.4 -0.2)	-
	Lower-2°C	54	0 (0 0)	-4 (-5 -2)	-10 (-12 -7)	0 (0 0)	0 (0 0)	-0.2 (-0.2 -0.1)	-
	Higher-2°C	47	0 (0 0)	-3 (-5 -2)	-11 (-15 -8)	0 (0 0)	0 (0 0)	-0.1 (-0.2 -0.1)	-
Kyoto GHG (AR4) [$GtCO_2e$]	**Below-1.5°C**	5	22 (21 23)	3 (-3 8)	-3 (-11 3)	-1.4 (-1.5 -1.3)	-2.9 (-3.3 -2.1)	-0.9 (-1.3 -0.7)	(2044 post-2100)
	1.5°C-low-OS	31	28 (26 31)	7 (5 10)	-4 (-8 -2)	-1.1 (-1.2 -0.9)	-2.3 (-2.8 -1.8)	-1.1 (-1.2 -0.9)	(2061 2080)
	1.5°C-high-OS	32	40 (36 49)	8 (6 12)	-9 (-11 -6)	-0.5 (-0.7 0)	-1.3 (-1.8 -0.6)	-1.5 (-2.1 -1.3)	(2058 2067)
	Lower-2°C	59	38 (31 43)	17 (14 20)	3 (0 7)	-0.6 (-1 -0.3)	-1.8 (-2.4 -1.1)	-1 (-1.1 -0.6)	(2099 post-2100)
	Higher-2°C	42	45 (39 49)	26 (23 28)	5 (-5 11)	-0.2 (-0.6 0)	-1 (-1.2 -0.6)	-1 (-1.2 -0.7)	(2085 post-2100)

Emissions of fluorinated gases (IPCC/TEAP, 2005; US EPA, 2013; Velders et al., 2015; Purohit and Höglund-Isaksson, 2017) in 1.5°C-consistent pathways are reduced by roughly 75–80% relative to 2010 levels (interquartile range across 1.5°C-consistent pathways) in 2050, with no clear differences between the classes. Although unabated HFC evolutions have been projected to increase (Velders et al., 2015), the Kigali Amendment recently added HFCs to the basket of gases controlled under the Montreal Protocol (Höglund-Isaksson et al., 2017). As part of the larger group of fluorinated gases, HFCs are also assumed to decline in 1.5°C-consistent pathways. Projected reductions by 2050 of fluorinated gases under 1.5°C-consistent pathways are deeper than published estimates of what a full implementation of the Montreal Protocol's Kigali Amendment would achieve (Höglund-Isaksson et al., 2017), which project roughly a halving of fluorinated gas emissions in 2050 compared to 2010. Assuming the application of technologies that are currently commercially available and at least to a limited extent already tested and implemented, potential fluorinated gas emissions reductions of more than 90% have been estimated (Höglund-Isaksson et al., 2017).

There is a general agreement across 1.5°C-consistent pathways that until 2030 forcing from the warming SLCFs is reduced less strongly than the net cooling forcing from aerosol effects, compared to 2010. As a result, the net forcing contributions from all SLCFs combined are projected to increase slightly by about 0.2–0.4 W/m^2, compared to 2010. Also, by the end of the century, about 0.1–0.3 W/m^2 of SLCF forcing is generally currently projected to remain in 1.5°C-consistent scenarios (Figure 2.8). This is similar to developments in 2°C-consistent pathways (Rose et al., 2014b; Riahi et al., 2017) which show median forcing contributions from these forcing agents that are generally no more than 0.1 W/m^2 higher. Nevertheless, there can be additional gains from targeted deeper reductions of CH_4 emissions and tropospheric ozone precursors, with some scenarios projecting less than 0.1 W/m^2 forcing from SLCFs by 2100.

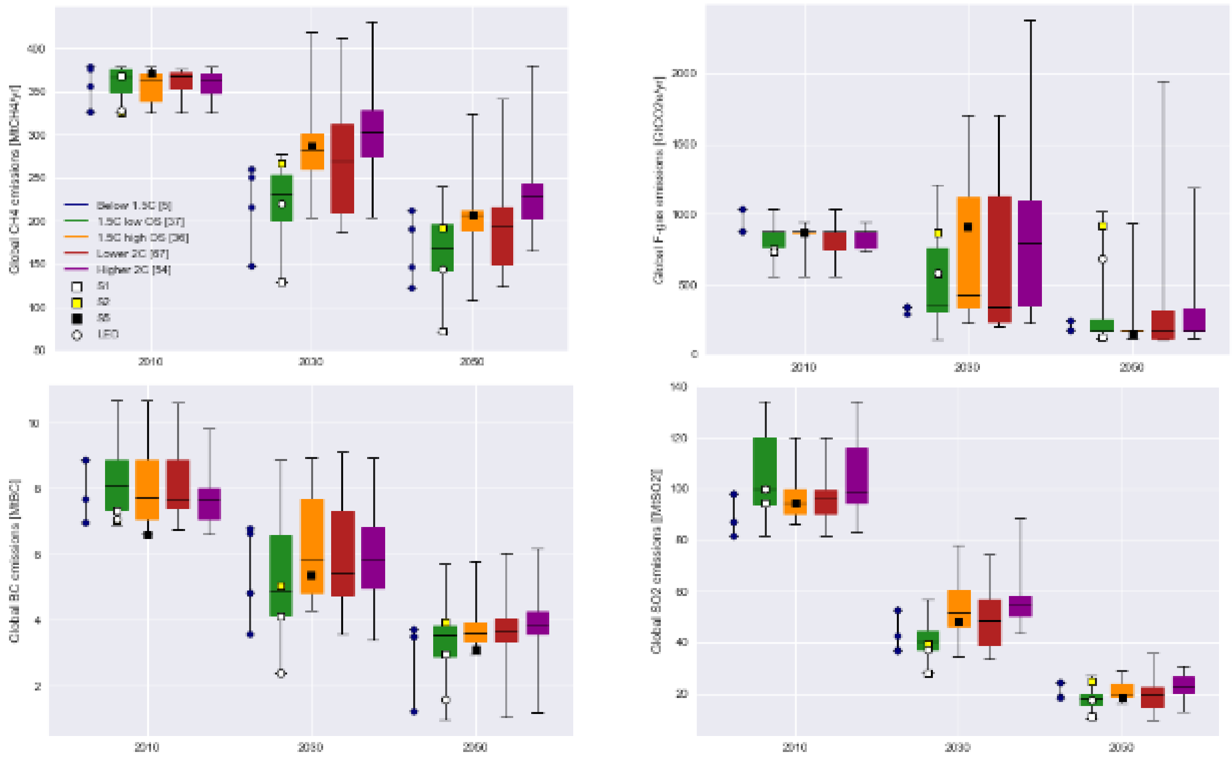


Figure 2.7: Global characteristics of a selection of short-lived non-CO_2 emissions until mid-century for five pathway classes used in this chapter. Data are shown for methane (CH_4), fluorinated gases (F-gas), black carbon (BC), and sulphur dioxide (SO_2) emissions. Boxes with different colours refer to different scenario classes. Icons on top the ranges show four illustrative pathway archetypes that apply different mitigation strategies for limiting warming to 1.5°C. Boxes show the interquartile range, horizontal black lines the median, while whiskers the minimum-maximum range. F-gases are expressed in units of CO_2-equivalence computed with 100-year Global Warming Potentials reported in IPCC AR4.

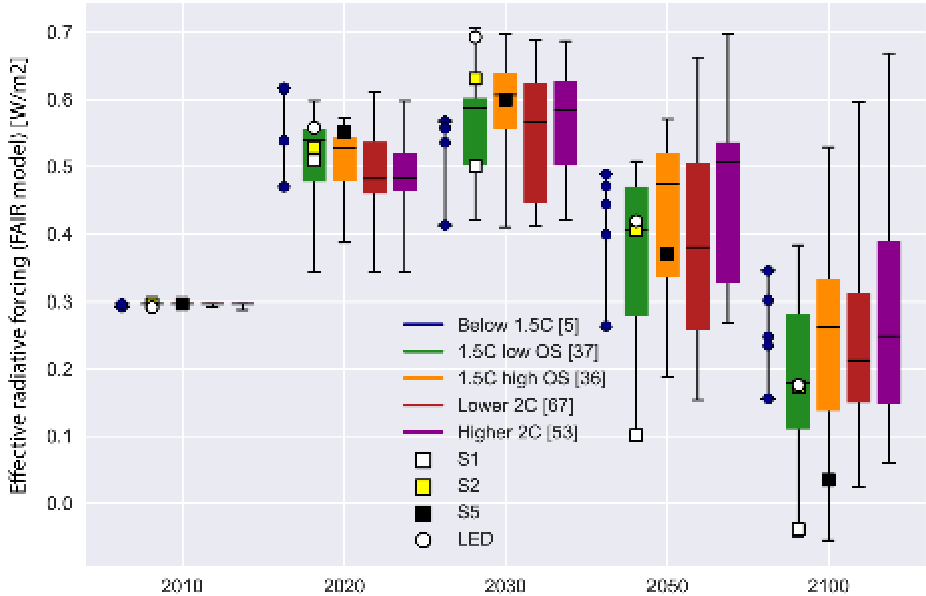


Figure 2.8: Estimated aggregated effective radiative forcing of SLCFs for 1.5°C and 2°C pathway classes in 2010, 2030, 2050, and 2100, as estimated by the FAIR model (Smith et al., 2018). Aggregated SLCF radiative forcing is estimated as the difference between total anthropogenic radiative forcing the sum of CO_2 and N_2O radiative forcing over time and expressed relative to 1750. Symbols indicate the four pathways archetype used in this chapter. Horizontal black lines indicate the median, boxes the interquartile range, and whiskers the minimum-maximum range per pathway class. Due to very few pathways falling into the Below-1.5°C class, only the minimum-maximum is provided here.

2.3.4 CDR in 1.5°C-consistent pathways

Deep mitigation pathways assessed in AR5 showed significant deployment of CDR, in particular through BECCS (Clarke et al., 2014). This has led to increased debate about the necessity, feasibility and desirability of large-scale CDR deployment, sometimes also called 'negative emissions technologies' in the literature (Fuss et al., 2014; Anderson and Peters, 2016; Williamson, 2016; van Vuuren et al., 2017a; Obersteiner et al., 2018). Most CDR technologies remain largely unproven to date and raise substantial concerns about adverse side-effects on environmental and social sustainability (Smith et al., 2015; Dooley and Kartha, 2018). A set of key questions emerge: how strongly do 1.5°C-consistent pathways rely on CDR deployment and what types of CDR measures are deployed at which scale? How does this vary across available 1.5°C-consistent pathways and on which factors does it depend? How does CDR deployment compare between 1.5°C and 2°C-consistent pathways and how does it compare with the findings at the time of the AR5? How does CDR deployment in 1.5°C-consistent pathways relate to questions about availability, policy implementation, and sustainable development implications that have been raised about CDR technologies? The first three questions are assessed in this section with the goal to provide an overview and assessment of CDR deployment in the 1.5°C-consistent pathway literature. The fourth question is only touched upon here and is addressed in greater depth in Section 4.3.7, which assesses the rapidly growing literature on costs, potentials, availability, and sustainability implications of individual CDR measures (Minx et al., 2017, 2018; Fuss et al., 2018; Nemet et al., 2018). In addition, Section 2.3.5 assesses the relationship between delayed mitigation action and increased CDR reliance. CDR deployment is intricately linked to the land-use transformation in 1.5°C-consistent pathways. This transformation is assessed in Section 2.4.4. Bioenergy and BECCS impacts on sustainable land management are further assessed in Section 3.6.2 and Cross-Chapter Box 7 in Chapter 3. Ultimately, a comprehensive assessment of the land implication of land-based CDR measures will be provided in the IPCC AR6 Special Report on Climate Change and Land (SRCCL).

2.3.4.1 CDR technologies and deployment levels in 1.5°C-consistent pathways

A number of approaches to actively remove carbon-dioxide from the atmosphere are increasingly discussed in the literature (Minx et al., 2018) (see also Section 4.3.7). Approaches under consideration include the enhancement of terrestrial and coastal carbon storage in plants and soils such as afforestation and reforestation (Canadell and Raupach, 2008), soil carbon enhancement (Paustian et al., 2016; Frank et al., 2017; Zomer et al., 2017), and other conservation, restoration, and management options for natural and managed land (Griscom et al., 2017) and coastal ecosystems (McLeod et al., 2011). Biochar sequestration (Woolf et al., 2010; Smith, 2016; Werner et al., 2018) provides an additional route for terrestrial carbon storage. Other approaches are concerned with storing atmospheric carbon dioxide in geological formations. They include the combination of biomass use for energy production with carbon capture and storage (BECCS) (Obersteiner et al., 2001; Keith and Rhodes, 2002; Gough and Upham, 2011) and direct air capture with storage (DACCS) using chemical solvents and sorbents (Zeman and Lackner, 2004; Keith et al., 2006; Socolow et al., 2011). Further approaches investigate the mineralisation of atmospheric carbon dioxide (Mazzotti et al., 2005; Matter et al., 2016) including enhanced weathering of rocks (Schuiling and Krijgsman, 2006; Hartmann et al., 2013; Strefler et al., 2018a). A fourth group of approaches is concerned with the sequestration of carbon dioxide in the oceans, for example by means of ocean alkalinisation (Kheshgi, 1995; Rau, 2011; Ilyina et al., 2013; Lenton et al., 2018). The costs, CDR potential and environmental side effects of several of these measures are increasingly investigated and compared in the literature, but large uncertainties remain, in particular concerning the feasibility and impact of large-scale deployment of CDR measures (The Royal Society, 2009; Smith et al., 2015; Psarras et al., 2017; Fuss et al., 2018) (see Chapter 4.3.7). There are also proposals to remove methane, nitrous oxide and halocarbons via photocatalysis from the atmosphere (Boucher and Folberth, 2010; de Richter et al., 2017), but a broader assessment of their effectiveness, cost, and sustainability impacts is lacking to date.

Only some of these approaches have so far been considered in IAMs (see Section 2.3.1.2). The mitigation scenario literature up to AR5 mostly included BECCS and to a more limited extent afforestation and reforestation (Clarke et al., 2014). Since then, some 2°C and 1.5°C-consistent pathways including additional CDR measures such as DACCS (Chen and Tavoni, 2013; Marcucci et al., 2017; Lehtilä and Koljonen, 2018; Strefler et al., 2018b) and soil carbon sequestration (Frank et al., 2017) have become available. Other, more speculative approaches, in particular ocean-based CDR and removal of non-CO_2 gases, have not yet been taken up by the literature on mitigation pathways. See Annex 2.A.2 for an overview on the coverage of CDR measures in models which contributed pathways to this assessment. Chapter 4.3.7 assesses the potential, costs, and sustainability implications of the full range of CDR measures.

Integrated assessment modelling has not yet explored land conservation, restoration and management options to remove carbon dioxide from the atmosphere in sufficient depth, despite land management having a potentially considerable impact on the terrestrial carbon stock (Erb et al., 2018). Moreover, associated CDR measures have low technological requirements, and come with potential environmental and social co-benefits (Griscom et al., 2017). Despite the evolving capabilities of IAMs in accounting for a wider range of CDR measures, 1.5°C-consistent pathways assessed here continue to predominantly rely on BECCS and afforestation / reforestation (See Annex 2.A.2). However, IAMs with spatially explicit land-use modelling include a full accounting of land-use change emissions comprising carbon stored in the terrestrial biosphere and soils. Net CDR in the AFOLU sector, including but not restricted to afforestation and reforestation, can thus in principle be inferred by comparing AFOLU CO_2 emissions between a baseline scenario and a 1.5°C-consistent pathway from the same model and study. However, baseline LUC emissions cannot only be reduced by CDR in the AFOLU sector, but also by measures to reduce deforestation and preserve land carbon stocks. The pathway literature and pathway data available to this assessment do not yet allow to separate the two contributions. As a conservative approximation, the additional net negative AFOLU CO_2 emissions below the baseline are taken as a proxy for AFOLU CDR in this assessment. Because this does not include CDR that was deployed before reaching net zero AFOLU emissions, this approximation is a lower-bound for terrestrial CDR in the AFOLU sector (including the factors that lead to net negative LUC emissions).

The scale and type of CDR deployment in 1.5°C-consistent pathways varies widely (Figure 2.9 and 2.10). Overall CDR deployment over the 21st century is substantial in most of the pathways, and deployment levels cover a wide range (770 [260-1170] $GtCO_2$, for median and 5th–95th percentile range). Both BECCS (560 [0 to 1000] $GtCO_2$) and AFOLU CDR measures including afforestation and reforestation (200 [0-550] $GtCO_2$)

can play a major role[4], but for both cases pathways exist where they play no role at all. This shows the flexibility in substituting between individual CDR measures, once a portfolio of options becomes available. The high end of the CDR deployment range is populated by high overshoot pathways, as illustrated by pathway archetype S5 based on SSP5 (fossil-fuelled development, see Section 2.3.1.1) and characterized by very large BECCS deployment to return warming to 1.5°C by 2100 (Kriegler et al., 2017). In contrast, the low end is populated with pathways with no or limited overshoot that limit CDR to in the order of 100–200 $GtCO_2$ over the 21st century coming entirely from terrestrial CDR measures with no or small use of BECCS. These are pathways with very low energy demand facilitating the rapid phase-out of fossil fuels and process emissions that exclude BECCS and CCS use (Grubler et al., 2018) and/or pathways with rapid shifts to sustainable food consumption freeing up sufficient land areas for afforestation and reforestation (Haberl et al., 2011; van Vuuren et al., 2018). Some pathways uses neither BECCS nor afforestation but still rely on CDR through considerable net negative emissions in the AFOLU sector around mid-century (Holz et al., 2018b). We conclude that the role of BECCS as dominant CDR measure in deep mitigation pathways has been reduced since the time of the AR5. This is related to three factors: a larger variation of underlying assumptions about socio-economic drivers (Riahi et al., 2017; Rogelj et al., 2018) and associated energy (Grubler et al., 2018) and food demand (van Vuuren et al., 2018); the incorporation of a larger portfolio of mitigation and CDR options (Liu et al., 2017; Marcucci et al., 2017; Grubler et al., 2018; Lehtilä and Koljonen, 2018; van Vuuren et al., 2018); and targeted analysis of deployment limits for (specific) CDR measures (Holz et al., 2018b; Kriegler et al., 2018b; Strefler et al., 2018b) including on the availability of bioenergy (Bauer et al., 2018), CCS (Krey et al., 2014a; Grubler et al., 2018) and afforestation (Popp et al., 2014b, 2017). As additional CDR measures are being built into IAMs, the prevalence of BECCS is expected to be further reduced.

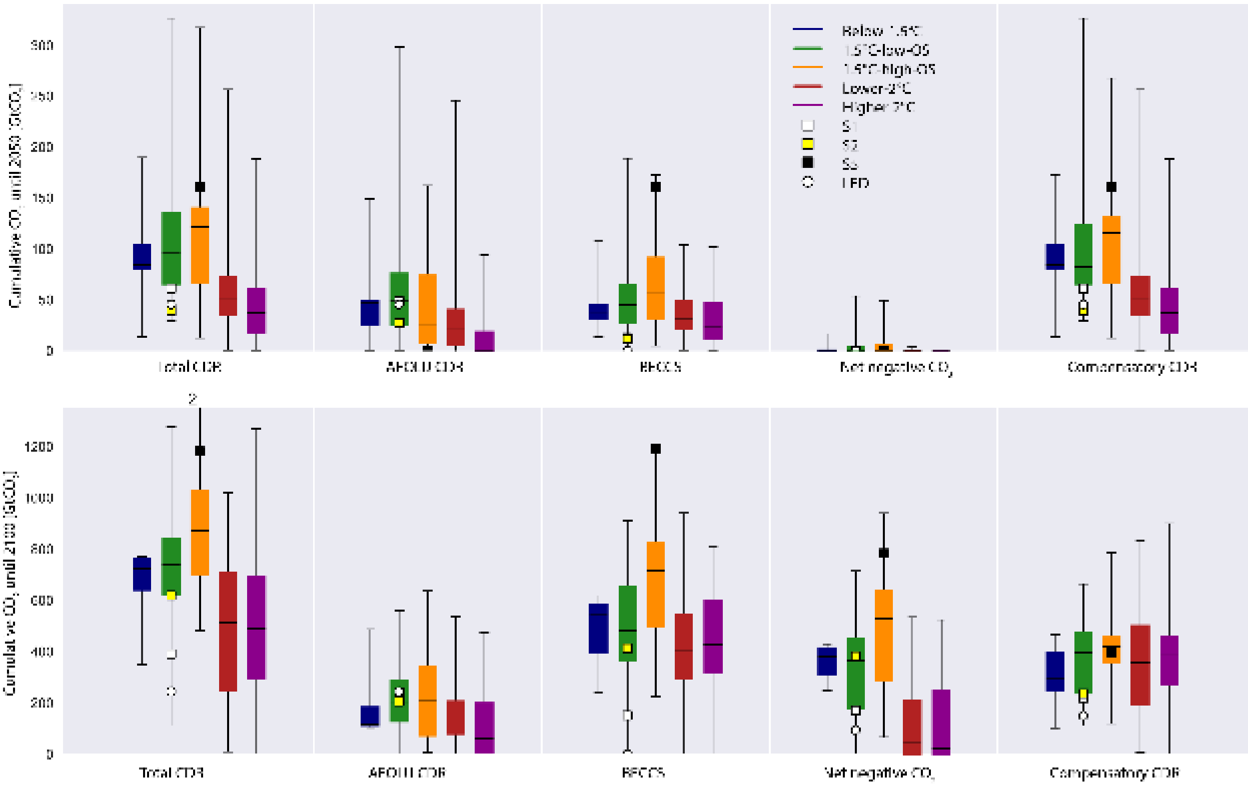


Figure 2.9: Cumulative CDR deployment in 1.5°C-consistent pathways in the literature as reported in the database collected for this assessment. Total CDR comprises all forms of CDR, including AFOLU CDR and BECCS, and in a few pathways other CDR measures like DACCS. It does not include CCS combined with fossil fuels (which is not a CDR technology as it does not result in active removal of CO_2 from the atmosphere). AFOLU CDR has not been reported directly and is hence represented by means of a proxy: the additional amount of net negative CO_2 emissions in the AFOLU sector compared to a baseline scenario (see text for a discussion). 'Compensate CO_2' depicts the cumulative amount of CDR that is used to neutralize concurrent residual CO_2 emissions. 'Net negative CO_2' describes the additional

[4] FOOTNOTE: The median and percentiles of the sum of two quantities is in general not equal to the sum of the medians of the two quantities.

amount of CDR that is used to produce net negative emissions, once residual CO_2 emissions are neutralized. The two quantities add up to total CDR for individual pathways (not for percentiles and medians, see Footnote 4).

As discussed in Section 2.3.2, CDR can be used in two ways: (i) to move more rapidly towards the point of carbon neutrality and maintain it afterwards to stabilize global-mean temperature rise, and (ii) to produce net negative emissions drawing down anthropogenic CO_2 in the atmosphere to enable temperature overshoot by declining global-mean temperature rise after its peak (Kriegler et al., 2018a; Obersteiner et al., 2018). Both uses are important in 1.5°C-consistent pathways (Figure 2.9). Because of the tighter remaining 1.5°C carbon budget, and because many pathways in the literature do not restrict exceeding this budget prior to 2100, the relative weight of the net negative emissions component of CDR increases compared to 2°C-consistent pathways. The amount of compensatory CDR remains roughly the same over the century. This is the net effect of stronger deployment of compensatory CDR until mid-century to accelerate the approach to carbon neutrality and less compensatory CDR in the second half of the century due to deeper mitigation of end-use sectors in 1.5°C-consistent pathways (Luderer et al., 2018). Comparing median levels, end-of-century net cumulative CO_2 emissions are roughly 600 $GtCO_2$ smaller in 1.5°C compared to 2°C-consistent pathways, with approximately two thirds coming from further reductions of gross CO_2 emissions and the remaining third from increased CDR deployment. As a result, total CDR deployment in the combined body of 1.5°C-consistent pathways is often larger than in 2°C-consistent pathways (Figure 2.9), but with marked variations in each pathway class.

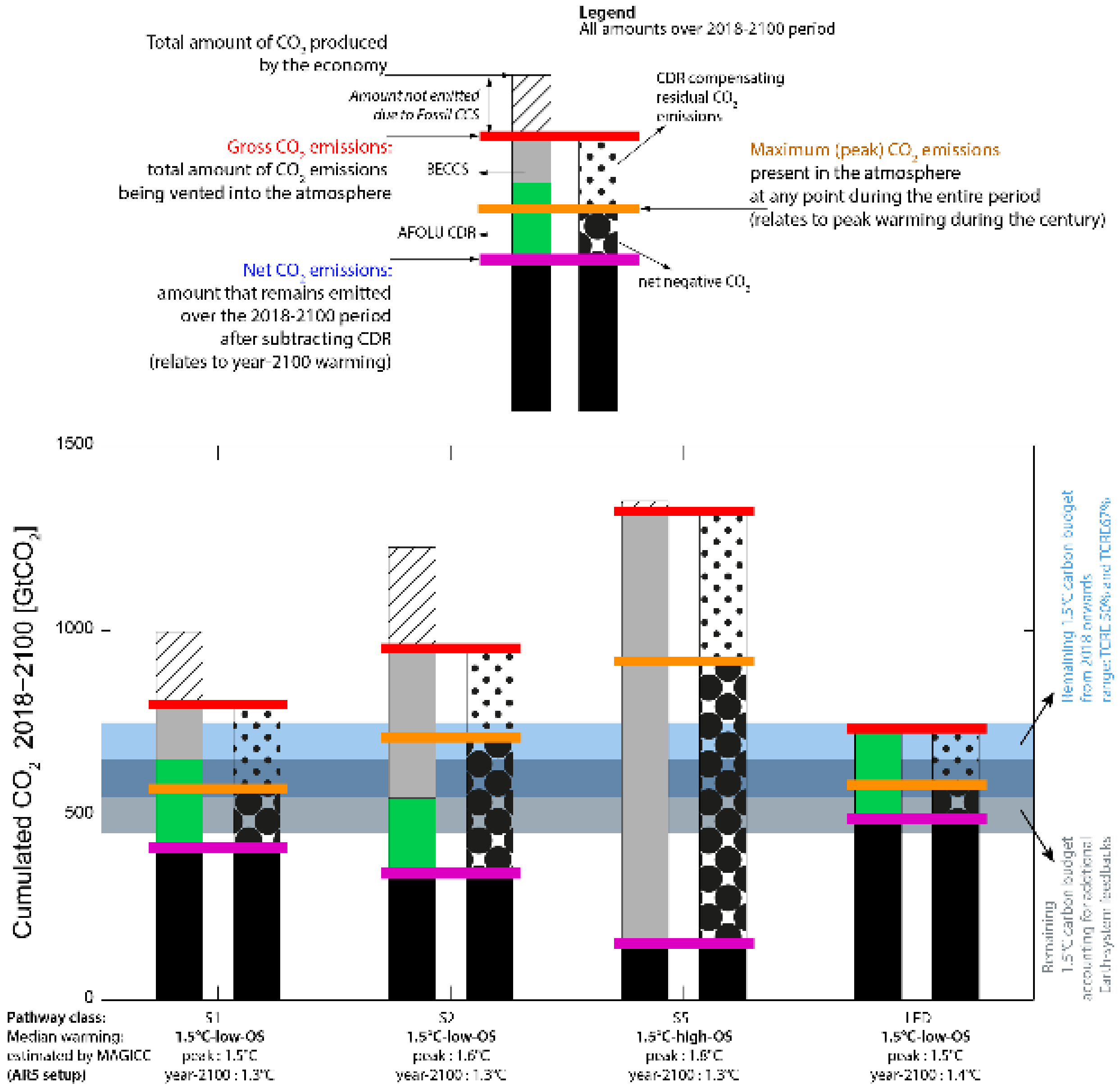


Figure 2.10: Accounting of cumulative CO_2 emissions for the four 1.5°C-consistent pathway archetypes. See top panel for explanation of the barplots. Total CDR is the difference between gross (red horizontal bar) and net (purple horizontal bar) cumulative CO_2 emissions over the period 2018–2100. Total CDR is the sum of the BECCS (grey) and AFOLU CDR (green) contributions. Cumulative net negative emissions are the difference between peak (orange horizontal bar) and net (purple) cumulative CO_2 emissions. The blue shaded area depicts the estimated range of the remaining carbon budget for a two-in-three to one-in-two chance of staying below1.5°C. The grey shaded area depicts the range when accounting for additional Earth-system feedbacks. These remaining carbon budgets have been adjusted for the difference in starting year compared to Table 2.2

Ramp-up rates of individual CDR measures in 1.5°C-consistent pathways are provided in Table 2.4. BECCS deployment is still limited in 2030, but ramped up to median levels of 3 (Below-1.5°C), 5 (1.5°C-low-OS) and 7 $GtCO_2$ yr^{-1} (1.5°C-high-OS) in 2050, and to 6 (Below-1.5°C), 12 (1.5°C-low-OS) and 15 $GtCO_2$ yr^{-1} (1.5°C-high-OS) in 2100, respectively. Net CDR in the AFOLU sector reaches slightly lower levels in 2050, and stays more constant until 2100, but data reporting limitations prevent a more quantitative assessment here. In contrast to BECCS, AFOLU CDR is more strongly deployed in non-overshoot than overshoot pathways. This indicates differences in the timing of the two CDR approaches. Afforestation is scaled up until around mid-century, when the time of carbon neutrality is reached in 1.5°C-consistent pathways, while BECCS is projected to be used predominantly in the 2nd half of the century. This reflects that afforestation is a readily available CDR technology, while BECCS is more costly and much less mature a technology. As a result, the two options contribute differently to compensating concurrent CO_2 emissions (until 2050) and to producing net negative CO_2 emissions (post-2050). BECCS deployment is particularly strong in pathways with high overshoots but could equally feature in pathways with a low temperature peak but a fast temperature decline thereafter (see Figure 2.1). Annual deployment levels until mid-century are not found to be significantly different between 2°C-consistent pathways and 1.5°C-consistent pathways with no or low overshoot. This suggests similar implementation challenges for ramping up CDR deployment at the rates projected in the pathways (Honegger and Reiner, 2018; Nemet et al., 2018). The feasibility and sustainability of upscaling CDR at these rates is assessed in Chapter 4.3.7.

Concerns have been raised that building expectations about large-scale CDR deployment in the future can lead to an actual reduction of near-term mitigation efforts (Geden, 2015; Anderson and Peters, 2016; Dooley and Kartha, 2018). The pathway literature confirms that CDR availability influences the shape of mitigation pathways critically (Krey et al., 2014a; Holz et al., 2018b; Kriegler et al., 2018b; Strefler et al., 2018b). Deeper near-term emissions reductions are required to reach the 1.5°C-2°C target range, if CDR availability is constrained. As a result, the least-cost benchmark pathways to derive GHG emissions gap estimates (UNEP, 2017) are dependent on assumptions about CDR availability. Using GHG benchmarks in climate policy makes implicit assumptions about CDR availability (Fuss et al., 2014; van Vuuren et al., 2017a). At the same time, the literature also shows that rapid and stringent mitigation as well as large-scale CDR deployment occur simultaneously in 1.5°C pathways due to the tight remaining carbon budget (Luderer et al., 2018). Thus, an emissions gap is identified even for high CDR availability (Strefler et al., 2018b), contradicting a wait-and-see approach. There are significant trade-offs between near-term action, overshoot and reliance on CDR deployment in the long-term which are assessed in Section 2.3.5.

Box 2.1: Bioenergy and BECCS deployment in integrated assessment modelling

Bioenergy can be used in various parts of the energy sector of IAMs, including for electricity, liquid fuel, biogas, and hydrogen production. It is this flexibility that makes bioenergy and bioenergy technologies valuable for the decarbonisation of energy use (Klein et al., 2014; Krey et al., 2014a; Rose et al., 2014a; Bauer et al., 2017, 2018). Most bioenergy technologies in IAMs are also available in combination with CCS (BECCS). Assumed capture rates differ between technologies, for example, about 90% for electricity and hydrogen production, and about 40-50% for liquid fuel production. Decisions about bioenergy deployment in IAMs are based on economic considerations to stay within a carbon budget that is consistent with a long-term climate goal. IAMs consider both the value of bioenergy in the energy system and the value of BECCS in removing CO_2 from the atmosphere. Typically, if bioenergy is strongly limited, BECCS technologies with high capture rates are favoured. If bioenergy is plentiful IAMs tend to choose biofuel technologies with lower capture rate, but high value for replacing fossil fuels in transport (Kriegler et al., 2013a; Bauer et al., 2018). Most bioenergy use in IAMS is combined with CCS if available (Rose et al., 2014a). If CCS is unavailable, bioenergy use remains largely unchanged or even increases due to the high value of bioenergy for the energy transformation (Bauer et al., 2018). As land impacts are tied to bioenergy use, the exclusion of BECCS from the mitigation portfolio, will not automatically remove the trade-offs with food, water and other sustainability objectives due to the continued and potentially increased use of bioenergy.

IAMs assume bioenergy to be supplied mostly from second generation biomass feedstocks such as dedicated cellulosic crops (for example Miscanthus or Poplar) as well as agricultural and forest residues. Detailed process IAMs include land-use models that capture competition for land for different uses (food, feed, fiber, bioenergy, carbon storage, biodiversity protection) under a range of dynamic factors including socio-economic drivers, productivity increases in crop and livestock systems, food demand, and land, environmental, biodiversity, and carbon policies. Assumptions about these factors can vary widely between different scenarios (Calvin et al., 2014; Popp et al., 2017; van Vuuren et al., 2018). IAMs capture a number of potential environmental impacts from bioenergy production, in particular indirect land-use change emissions from land conversion and nitrogen and water use for bioenergy production (Kraxner et al., 2013; Bodirsky et al., 2014; Bonsch et al., 2014; Obersteiner et al., 2016; Humpenöder et al., 2017). Especially the impact of bioenergy production on soil degradation is an area of active IAM development and was not comprehensively accounted for in the mitigation pathways assessed in this report (but is, for example, in (Frank et al., 2017)). Whether bioenergy has large adverse impacts on environmental and societal goals depends in large parts on the governance of land use (Haberl et al., 2013; Erb et al., 2016b; Obersteiner et al., 2016; Humpenöder et al., 2017). Here IAMs often make idealized assumptions about effective land management such as full protection of the land carbon stock by conservation measures and a global carbon price, respectively, but also variations on these assumptions have been explored (Calvin et al., 2014; Popp et al., 2014a)).

2.3.4.2 Sustainability implications of CDR deployment in 1.5°C-consistent pathways

Strong concerns about the sustainability implications of large-scale CDR deployment in deep mitigation pathways have been raised in the literature (Williamson and Bodle, 2016; Boysen et al., 2017b; Dooley and Kartha, 2018; Heck et al., 2018), and a number of important knowledge gaps have been identified (Fuss et al., 2016). An assessment of the literature on implementation constraints and sustainable development implications of CDR measures is provided in Section 4.3.7 and the Cross-chapter Box 7 in Chapter 3. Potential environmental side effects as initial context for the discussion of CDR deployment in 1.5°C-consistent pathways are provided in this section. Section 4.3.7 then contrasts CDR deployment in 1.5°C-consistent pathways with other branches of literature on limitations of CDR. Integrated modelling aims to explore a range of developments compatible with specific climate goals and often does not include the full set of broader environmental and societal concerns beyond climate change. This has given rise to the concept of sustainable development pathways (van Vuuren et al., 2015) (Cross-Chapter Box 1 in Chapter 1), and there is an increasing body of work to extend integrated modelling to cover a broader range of sustainable development goals (Section 2.6). However, only some of the available 1.5°C-consistent pathways were developed within a larger sustainable development context (Bertram et al., 2018; Grubler et al., 2018; Rogelj et al., 2018; van Vuuren et al., 2018). As discussed in Section 2.3.4.1, those pathways are characterized by low energy and/or food demand effectively limiting fossil-fuel substitution and alleviating land competition, respectively. They also include regulatory policies for deepening early action and ensuring environmental protection (Bertram et al., 2018). Overall sustainability implications of 1.5°C-consistent pathways are assessed in Section 2.5.3 and Section 5.4.

Individual CDR measures have different characteristics and therefore would carry different risks for their sustainable deployment at scale (Smith et al., 2015). Terrestrial CDR measures, BECCS and enhanced weathering of rock powder distributed on agricultural lands require land. Those land-based measures could have substantial impacts on environmental services and ecosystems (Smith and Torn, 2013; Boysen et al., 2016; Heck et al., 2016; Krause et al., 2017) (Cross-Chapter Box 7 in Chapter 3). Measures like afforestation and bioenergy with and without CCS that directly compete with other land uses could have significant impacts on agricultural and food systems (Creutzig et al., 2012, 2015; Calvin et al., 2014; Popp et al., 2014b, 2017; Kreidenweis et al., 2016; Boysen et al., 2017a; Frank et al., 2017; Humpenöder et al., 2017; Stevanović et al., 2017; Strapasson et al., 2017). BECCS using dedicated bioenergy crops could substantially increase agricultural water demand (Bonsch et al., 2014; Séférian et al., 2018) and nitrogen fertilizer use (Bodirsky et al., 2014). DACCS and BECCS rely on CCS and would require safe storage space in geological formations, including management of leakage risks (Pawar et al., 2015) and induced seismicity (Nicol et al., 2013). Some approaches like DACCS have high energy demand (Socolow et al., 2011). Most of the CDR measures currently discussed could have significant impacts on either land, energy, water, or nutrients if deployed at scale (Smith et al., 2015). However, actual trade-offs depend on a multitude factors (Haberl et al., 2011; Erb et al., 2012; Humpenöder et al., 2017), including the modalities of CDR deployment (e.g., on marginal vs. productive land) (Bauer et al., 2018), socio-economic developments (Popp et al., 2017), dietary choices (Stehfest et al., 2009; Popp et al., 2010; van Sluisveld et al., 2016; Weindl et al., 2017; van Vuuren et al., 2018), yield increases, livestock productivity and other advances in agricultural technology (Havlik et al., 2013; Valin et al., 2013; Havlík et al., 2014; Weindl et al., 2015; Erb et al., 2016b), land policies (Schmitz et al., 2012; Calvin et al., 2014; Popp et al., 2014a) and governance of land use (Unruh, 2011; Buck, 2016; Honegger and Reiner, 2018).

Figure 2.11 shows the land requirements for BECCS and afforestation in the selected 1.5°C-consistent pathway archetypes, including the LED (Grubler et al., 2018) and S1 pathways (Fujimori, 2017; Rogelj et al., 2018) following a sustainable development paradigm. As discussed, these land-use patterns are heavily influenced by assumptions about, inter alia, future population levels, crop yields, livestock production systems, and food and livestock demand, which all vary between the pathways (Popp et al., 2017) (Section 2.3.1.1). In pathways that allow for large-scale afforestation in addition to BECCS, land demand for afforestation can be larger than for BECCS (Humpenöder et al., 2014). This follows from the assumption in the modelled pathways that, unlike bioenergy crops, forests are not harvested to allow unabated carbon storage on the same patch of land. If wood harvest and subsequent processing or burial are taken into account, this finding can change. There are also synergies between the various uses of land, which are not reflected in the depicted pathways. Trees can grow on agricultural land (Zomer et al., 2016) and harvested wood can be used with BECCS and pyrolysis systems (Werner et al., 2018). The pathways show a very substantial land demand for the two CDR measures combined, up to the magnitude of the current global cropland area. This is achieved in IAMs in particular by a conversion of pasture land freed by intensification of livestock production systems, pasture intensification and/or demand changes (Weindl et al., 2017), and to more limited extent cropland for food production, as well as expansion into natural land. However, pursuing such large scale changes in land use would pose significant food supply, environmental and governance challenges, concerning both land management and tenure (Unruh, 2011; Erb et al., 2012, 2016b; Haberl et al., 2013; Haberl, 2015; Buck, 2016), particularly if synergies between land uses, the relevance of dietary changes for reducing land demand, and co-benefits with other sustainable development objectives are not fully recognized. A general discussion of the land-use transformation in 1.5°C-consistent pathways is provided in Section 2.4.4.

An important consideration for CDR which moves carbon from the atmosphere to the geological, oceanic or terrestrial carbon pools is the permanence of carbon stored in these different pools (Matthews and Caldeira, 2008; NRC, 2015; Fuss et al., 2016; Jones et al., 2016) (see also Section 4.3.7 for a discussion). Terrestrial carbon can be returned to the atmosphere on decadal timescales by a variety of mechanisms such as soil degradation, forest pest outbreaks and forest fires, and therefore requires careful consideration of policy frameworks to manage carbon storage, e.g., in forests (Gren and Aklilu, 2016). There are similar concerns about outgassing of CO_2 from ocean storage (Herzog et al., 2003), unless it is transformed to a substance that does not easily exchange with the atmosphere, e.g., ocean alkalinity or buried marine biomass (Rau, 2011). Understanding of the assessment and management of the potential risk of CO_2 release from geological storage of CO_2 has improved since the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005) with experience and the development of management practices in geological storage projects, including risk management to prevent sustentative leakage (Pawar et al., 2015). Estimates of leakage risk have been updated to include scenarios of unregulated drilling and limited wellbore integrity (Choi et al., 2013), finding ca. 70% of stored CO_2 still retained after 10,000 years in these circumstances (Alcalde et al., 2018). The literature on the potential environmental impacts from the leakage of CO_2 – and approaches to minimize these impacts should a leak occur – has also grown and is reviewed by Jones et al. (2015). To the extent non-permanence of terrestrial and geological carbon storage is driven by socio-economic and political factors, it has parallels to questions of fossil-fuel reservoirs remaining in the ground (Scott et al., 2015).

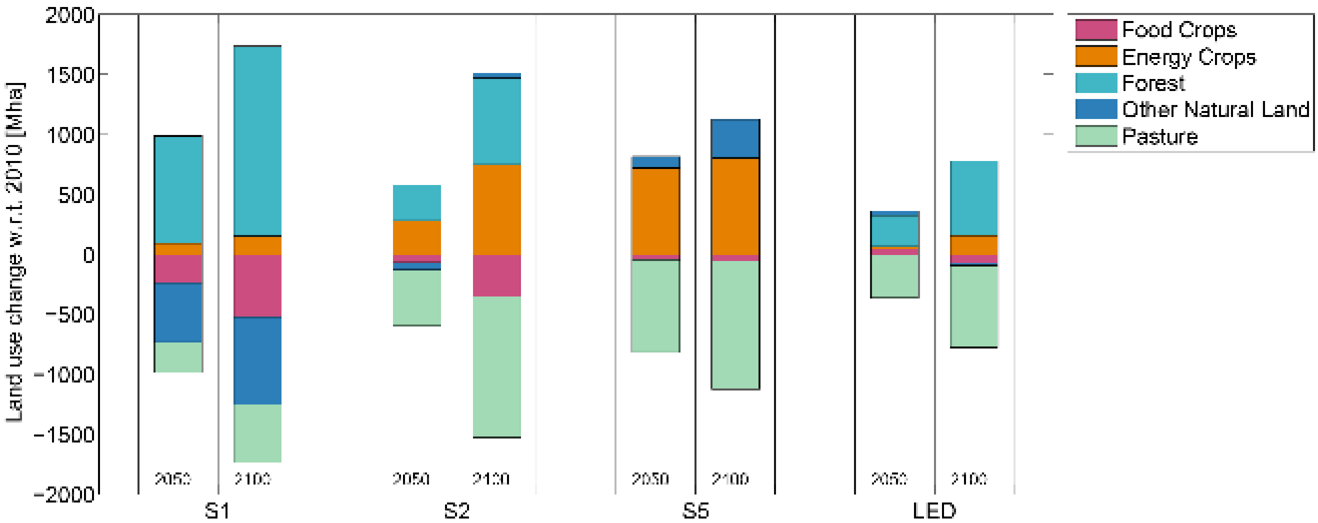


Figure 2.11: Land-use changes in 2050 and 2100 in the illustrative 1.5°C-consistent pathway archetypes (Fricko et al., 2017; Fujimori, 2017; Kriegler et al., 2017; Grubler et al., 2018; Rogelj et al., 2018).

2.3.5 Implications of near-term action in 1.5°C-consistent pathways

Less CO_2 emission reductions in the near term imply steeper and deeper reductions afterwards (Riahi et al., 2015; Luderer et al., 2016a). This is a direct consequence of the quasi-linear relationship between the total cumulative amount of CO_2 emitted into the atmosphere and global mean temperature rise (Matthews et al., 2009; Zickfeld et al., 2009; Collins et al., 2013; Knutti and Rogelj, 2015). Besides this clear geophysical trade-off over time, delaying GHG emissions reductions over the coming years also leads to economic and institutional lock-in into carbon-intensive infrastructure, that is, the continued investment in and use of carbon-intensive technologies that are difficult or costly to phase-out once deployed (Unruh and Carrillo-Hermosilla, 2006; Jakob et al., 2014; Erickson et al., 2015; Steckel et al., 2015; Seto et al., 2016; Michaelowa et al., 2018). Studies show that to meet stringent climate targets despite near-term delays in emissions reductions, models prematurely retire carbon-intensive infrastructure, in particular coal without CCS (Bertram et al., 2015a; Johnson et al., 2015). The AR5 reports that delaying mitigation action leads to substantially higher rates of emissions reductions afterwards, a larger reliance on CDR technologies in the long term, and higher transitional and long-term economic impacts (Clarke et al., 2014). The literature mainly focuses on delayed action until 2030 in the context of meeting a 2°C goal (den Elzen et al., 2010; van Vuuren and Riahi, 2011; Kriegler et al., 2013b; Luderer et al., 2013, 2016a; Rogelj et al., 2013b; Riahi et al., 2015; OECD/IEA and IRENA, 2017). However, because of the smaller carbon budget consistent with limiting warming to 1.5°C and the absence of a clearly declining long-term trend in global emissions to date, these general insights apply equally or even more so to the more stringent mitigation context of 1.5°C-consistent pathways. This is further supported by estimates of committed emissions due to fossil fuel-based infrastructure (Seto et al., 2016; Edenhofer et al., 2018).

All available 1.5°C pathways that explore consistent mitigation action from 2020 onwards peak global Kyoto-GHG emissions in the next decade and already decline Kyoto-GHG emissions to below 2010 levels by 2030. The near-term emissions development in these pathways can be compared with estimated emissions in 2030 implied by the Nationally Determined Contributions (NDCs) submitted by Parties to the Paris Agreement (Figure 2.12). Altogether, these NDCs are assessed to result in global Kyoto-GHG emissions on the order of 50–58 $GtCO_2e\ yr^{-1}$ in 2030 (for example, den Elzen et al., 2016; Fujimori et al., 2016; UNFCCC, 2016; Rogelj et al., 2017; Rose et al., 2017b; Benveniste et al., 2018; Vrontisi et al., 2018), see Cross-Chapter Box 11 in Chapter 4 for detailed assessment). In contrast, 1.5°C-consistent pathways available to this assessment show an interquartile range of about 26–38 (median 31) $GtCO_2e\ yr^{-1}$ in 2030, reducing to 26–31 (median 28) $GtCO_2e\ yr^{-1}$ if only pathways with low overshoot are taken into account[5], and still lower if pathways without overshoot are considered (Table 2.4, Section 2.3.3). Published estimates of the emissions gap between conditional NDCs and 1.5°C-consistent pathways in 2030 range from 16 (14–22) $GtCO_2e\ yr^{-1}$ (UNEP, 2017) for a greater than one-in-to chance of limiting warming below 1.5°C in 2100 to 25 (19–29) $GtCO_2e\ yr^{-1}$ (Vrontisi et al., 2018) for a greater than two-in-three chance of meeting the 1.5°C limit.

The later emissions peak and decline, the more CO_2 will have accumulated in the atmosphere. Peak cumulated CO_2 emissions and consequently also peak temperatures increase with 2030 emissions levels (Figure 2.12). Current NDCs (Cross-Chapter Box 11 in Chapter 4) are estimated to lead to CO_2 emissions of about 400–560 $GtCO_2$ from 2018 to 2030 (Rogelj et al., 2016a). Available 1.5°C- and 2°C-consistent pathways with 2030 emissions in the range estimated for the NDCs rely on an assumed swift and widespread deployment of CDR after 2030, and show peak cumulative CO_2 emissions from 2018 of about 800–1000 $GtCO_2$, above the remaining carbon budget for a one-in-two chance of remaining below 1.5°C. These emissions reflect that no pathway is able to project a phase out of CO_2 emissions starting from year-2030 NDC levels of about 40 $GtCO_2\ yr^{-1}$ (Fawcett et al., 2015; Rogelj et al., 2016a) to net zero in less than ca. 15 years. Based on the implied emissions until 2030, the high challenges of the assumed post-2030 transition, and the assessment of carbon budgets in Section 2.2.2, global warming is assessed to exceed 1.5°C if emissions stay at the levels implied by the NDCs until 2030 (Figure 2.12). The chances of remaining below 1.5°C in these circumstances remain conditional upon geophysical properties that are uncertain, but these

[5] FOOTNOTE: Note that aggregated Kyoto-GHG emissions implied by the NDCs from Cross-Chapter Box 4.3 and Kyoto-GHG ranges from the pathway classes in Chapter 2 are only approximately comparable, because this chapter applies GWP-100 values from the IPCC Fourth Assessment Report while the NDC Cross-Chapter Box 4.3 applies GWP-100 values from the IPCC Second Assessment Report. At a global scale, switching between GWP-100 values of the Second to the Fourth IPCC Assessment Report would result in an increase in estimated aggregated Kyoto-GHG emissions of about no more than 3% in 2030 (UNFCCC, 2016).

Earth system response uncertainties would have to serendipitously align beyond current median estimates in order for current NDCs to become consistent with limiting warming to 1.5°C.

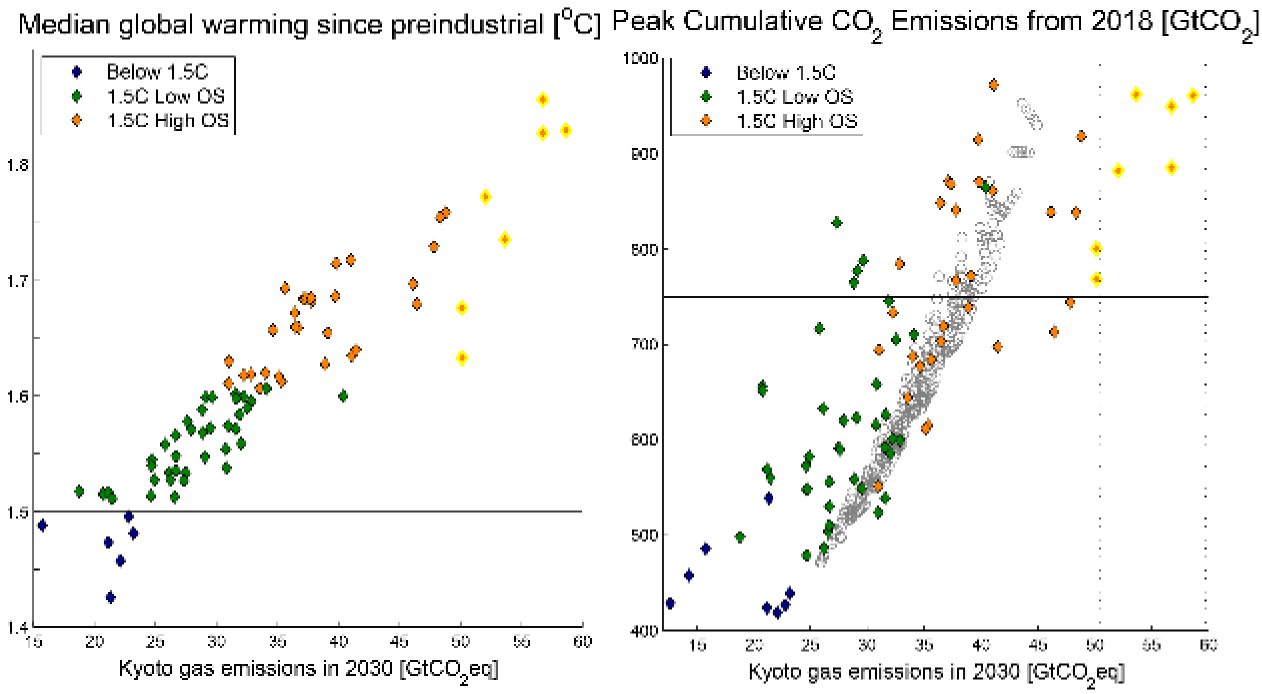


Figure 2.12: Median global warming estimated by MAGICC (left panel) and peak cumulative CO_2 emissions (right panel) in 1.5°C-consistent pathways in the SR1.5 scenario database as a function of CO_2-equivalent emissions (based on AR4 GWP-100) of Kyoto-GHGs in 2030. Pathways that were forced to go through the NDCs or a similarly high emissions point in 2030 by design are highlighted by yellow marker edges (see caption of Figure 2.13 and text for further details on the design of these pathways). The NDC range of global Kyoto-GHG emissions in 2030 assessed in Cross-Chapter Box 11 in Chapter 4 is shown by black dotted lines (adjusted to AR4 GWPs for comparison). As a second line of evidence, peak cumulative CO_2 emissions derived from a 1.5°C pathway sensitivity analysis (Kriegler et al., 2018a) are shown by grey circles in the right-hand panel. Numbers show gross fossil-fuel and industry emissions of the sensitivity cases increased by assumptions about the contributions from AFOLU (5 $GtCO_2$ yr^{-1} until 2020, followed by a linear phase out until 2040) and non-CO_2 Kyoto-GHGs (median non-CO_2 contribution from 1.5°C-consistent pathways available in the database: 10 $GtCO_2e$ yr^{-1} in 2030), and reduced by assumptions about CDR deployment until the time of net zero CO_2 emissions (limiting case for CDR deployment assumed in (Kriegler et al., 2018a) (logistic growth to 1, 4, 10 $GtCO_2$ yr^{-1} in 2030, 2040, and 2050, respectively, leading to approx. 100 $GtCO_2$ CDR by mid-century).

It is unclear whether following NDCs until 2030 would still allow global mean temperature to return to 1.5°C by 2100 after a temporary overshoot, due to the uncertainty associated with the Earth system response to net negative emissions after a peak (Section 2.2). Available IAM studies are working with reduced-form carbon cycle-climate models like MAGICC which assume a largely symmetric Earth-system response to positive and net negative CO_2 emissions. The IAM findings on returning warming to 1.5°C from NDCs after a temporary temperature overshoot are hence all conditional on this assumption. Two types of pathways with 1.5°C-consistent action starting in 2030 have been considered in the literature (Luderer et al., 2018) (Figure 2.13): pathways aiming to obtain the same end-of-century carbon budget despite higher emissions until 2030, and pathways assuming the same mitigation stringency after 2030 (approximated by using the same global price of emissions as found in least-cost pathways starting from 2020). An IAM comparison study found increasing challenges to implement pathways with the same end-of-century 1.5°C-consistent carbon budgets after following NDCs until 2030 (ADVANCE) (Luderer et al., 2018). The majority of model experiments (four out of seven) failed to produce NDC pathways that would return cumulative CO_2 emissions over the 2016–2100 period to 200 $GtCO_2$, indicating limitations to the availability and timing of CDR. The few such pathways that were identified show highly disruptive features in 2030 (including abrupt transitions from moderate to very large emissions reduction and low carbon energy deployment rates) indicating a high risk that the required post-2030 transformations are too steep and abrupt to be achieved by the mitigation measures in the models (*high confidence*). NDC pathways aiming for a cumulative 2016–2100 CO_2 emissions budget of 800 $GtCO_2$ were more readily obtained (Luderer et al., 2018), and some were classified as 1.5°C-high-OS pathways in this assessment (Section 2.1).

NDC pathways that apply a post-2030 price of emissions after 2030 as found in least-cost pathways starting from 2020 show infrastructural carbon lock-in as a result of following NDCs instead of least-cost action until 2030. A key finding is that carbon lock-ins persist long after 2030, with the majority of additional CO_2 emissions occurring during the 2030–2050 period. Luderer et al. (2018) find 90 (80–120) $GtCO_2$ additional emissions until 2030, growing to 240 (190–260) $GtCO_2$ by 2050 and 290 (200–200) $GtCO_2$ by 2100. As a result, peak warming is about 0.2°C higher and not all of the modelled pathways return warming to 1.5°C by the end of the century. There is a four sided trade-off between (i) near-term ambition, (ii) degree of overshoot, (iii) transitional challenges during the 2030–2050 period, and (iv) the amount of CDR deployment required during the century (Figure 2.13) (Holz et al., 2018b; Strefler et al., 2018b). Transition challenges, overshoot, and CDR requirements can be significantly reduced if global emissions peak before 2030 and fall below levels in line with current NDCs by 2030. For example, Strefler et al. (2018b) find that CDR deployment levels in the second half of the century can be halved in 1.5°C-consistent pathways with similar CO_2 emissions reductions rates during the 2030–2050 period if CO_2 emissions by 2030 are reduced by an additional 30% compared to NDC levels. Kriegler et al. (2018b) investigate a global roll out of selected regulatory policies and moderate carbon pricing policies. They show that additional reductions of ca. 10 $GtCO_2e\ yr^{-1}$ can be achieved in 2030 compared to the current NDCs. Such 20% reduction of year-2030 emissions compared to current NDCs would effectively lower the disruptiveness of post-2030 action. Strengthening of short-term policies in deep mitigation pathways has hence been identified as bridging options to keep the Paris climate goals within reach (Bertram et al., 2015b; IEA, 2015a; Spencer et al., 2015; Kriegler et al., 2018b).

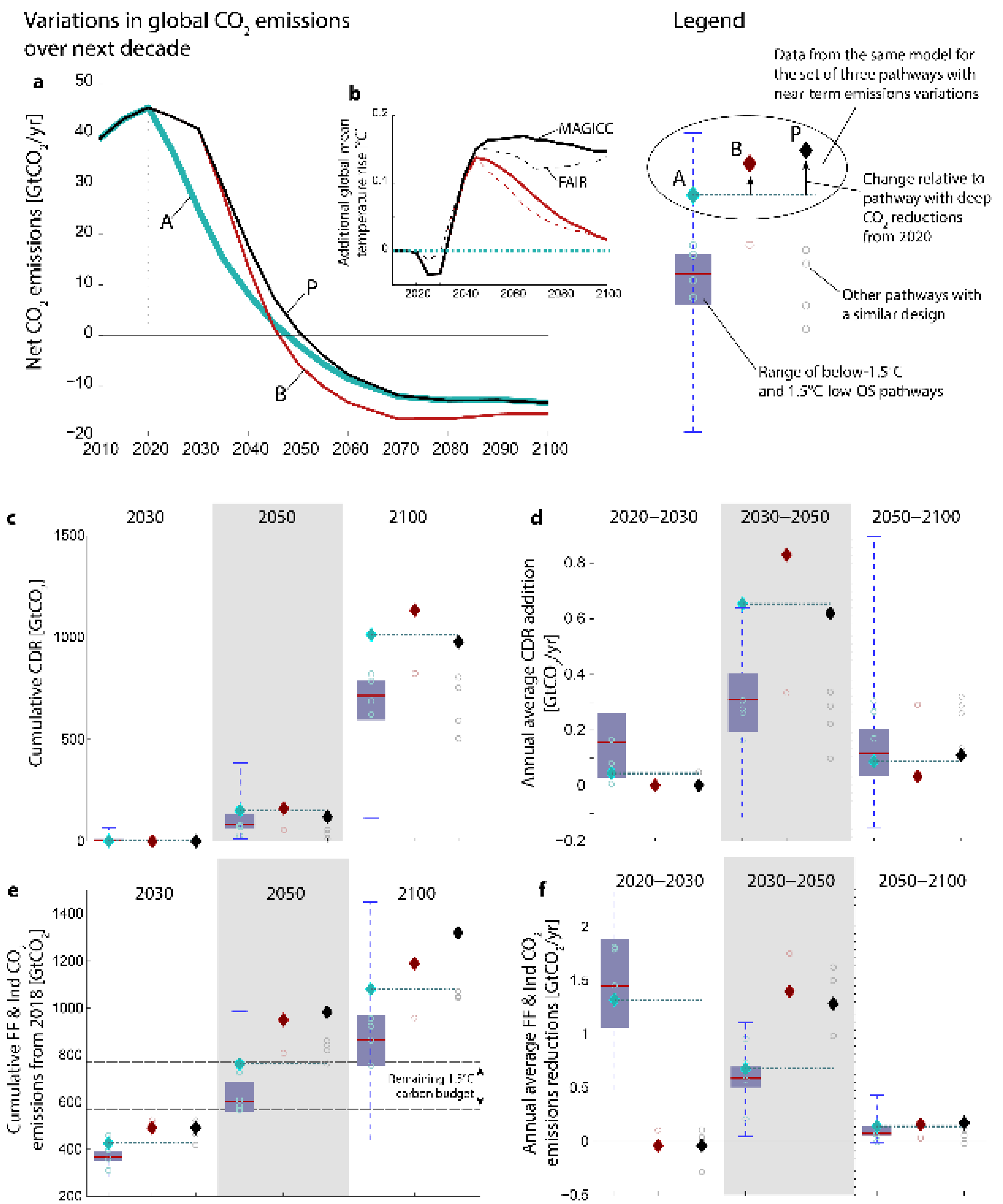


Figure 2.13: Comparison of pathways starting action for limiting warming to 1.5°C as of 2020 (A; light-blue diamonds) with pathways following the NDCs until 2030 and aiming to limit warming to 1.5°C thereafter. 1.5°C pathways following the NDCs either aim for the same cumulative CO_2 emissions by 2100 (B; red diamonds) or assume the same mitigation stringency as reflected by the price of emissions in associated least-cost 1.5°C-consistent pathways starting from 2020 (P; black diamonds)**.** Panels show the underlying emissions pathways (a), additional warming in the delay scenarios compared to 2020 action case (b), cumulated CDR (c), CDR ramp-up rates (d), cumulated gross CO_2 emissions from fossil-fuel combustion and industrial (FFI) processes over the 2018–2100 period (e), and gross FFI CO_2 emissions reductions rates (f). Scenario pairs / triplets (circles and diamonds) with 2020 and 2030 action variants were calculated by six (out of seven) models in the ADVANCE study symbols (Luderer et al., 2018) and five of them (passing near-term plausibility checks) are shown by symbols. Only two of five models could identify pathways with post-2030 action leading to a 2016–2100 carbon budget of ca. 200 $GtCO_2$ (red). The range of all 1.5°C-consistent pathways with no and low overshoot is shown by the boxplots.

2.4 Disentangling the whole-system transformation

Mitigation pathways map out prospective transformations of the energy, land and economic systems over this century (Clarke et al., 2014). There is a diversity of potential pathways consistent with 1.5°C, yet they share some key characteristics summarized in Table 2.5. To explore characteristics of 1.5°C pathways in greater detail, this section focuses on changes in energy supply and demand, and changes in the AFOLU sector.

Table 2.5: Overview of key characteristics of 1.5°C pathways.

1.5°C pathway characteristic	Supporting information	Reference
Rapid and profound near-term decarbonisation of energy supply	Strong upscaling of renewables and sustainable biomass and reduction of unabated (no CCS) fossil fuels, along with the rapid deployment of CCS lead to a zero-emission energy supply system by mid-century.	Section 2.4.1 Section 2.4.2
Greater mitigation efforts on the demand side	All end-use sectors show marked demand reductions beyond the reductions projected for 2°C pathways. Demand reductions from IAMs for 2030 and 2050 lie within the potential assessed by detailed sectorial bottom-up assessments.	Section 2.4.3
Switching from fossil fuels to electricity in end-use sectors	Both in the transport and the residential sector, electricity covers marked larger shares of total demand by mid-century.	Section 2.4.3.2 Section 2.4.3.3
Comprehensive emission reductions are implemented in the coming decade	Virtually all 1.5°C-consistent pathways decline net annual CO_2 emissions between 2020 and 2030, reaching carbon neutrality around mid-century. Below-1.5°C and 1.5°C-low-OS show maximum net CO2 emissions in 2030 of 18 and 28 $GtCO_2\ yr^{-1}$, respectively. GHG emissions in these scenarios are not higher than 34 $GtCO_2e\ yr^{-1}$ in 2030.	Section 2.3.4
Additional reductions, on top of reductions from both CO2 and non-CO2 required for 2°C, are mainly from CO2	Both CO_2 and the non-CO_2 GHGs and aerosols are strongly reduced by 2030 and until 2050 in 1.5°C pathways. The greatest difference to 2°C pathways, however, lies in additional reductions of CO_2, as the non-CO_2 mitigation potential that is currently included in integrated pathways is mostly already fully deployed for reaching a 2°C pathway.	Section 2.3.1.2
Considerable shifts in investment patterns	Low-carbon investments in the energy supply side (energy production and refineries) are projected to average 1.6-3.8 trillion 2010USD yr^{-1} globally to 2050. Investments in fossil fuels decline, with investments in unabated coal halted by 2030 in most available 1.5°C-consistent projections, while the literature is less conclusive for investments in unabated gas and oil. Energy demand investments are a critical factor for which total estimates are uncertain.	Section 2.5.2
Options are available to align 1.5°C pathways with sustainable development	Synergies can be maximized, and risks of trade-offs limited or avoided through an informed choice of mitigation strategies. Particularly pathways that focus on a lowering of demand show many synergies and few trade-offs.	Section 2.5.3
CDR at scale before mid-century	By 2050, 1.5°C pathways project deployment of BECCS at a scale of 3–7 $GtCO_2yr^{-1}$ (range of medians across 1.5°C pathway classes), depending on the level of energy demand reductions and mitigation in other sectors. Some 1.5°C pathways are available that do not use BECCS, but only focus terrestrial CDR in the AFOLU sector.	Section 2.3.3, 2.3.4.1

2.4.1 Energy System Transformation

The energy system links energy supply (Section 2.4.2) with energy demand (Section 2.4.3) through final energy carriers including electricity and liquid, solid or gaseous fuels that are tailored to their end-uses. To chart energy-system transformations in mitigation pathways, four macro-level decarbonisation indicators associated with final energy are useful: limits to the increase of final energy demand, reductions in the carbon intensity of electricity, increases in the share of final energy provided by electricity, and reductions in the carbon intensity of final energy other than electricity (referred to in this section as the carbon intensity of the residual fuel mix). Figure 2.14 shows changes of these four indicators for the pathways in the scenario database (Section 2.1.3 and Annex 2.A.3) for 1.5°C and 2°C pathways (Table 2.1).

Pathways in both the 1.5°C and 2°C classes (Figure 2.14) generally show rapid transitions until mid-century with a sustained but slower evolution thereafter. Both show an increasing share of electricity accompanied by a rapid decline in the carbon intensity of electricity. Both also show a generally slower decline in the carbon intensity of the residual fuel mix, which arises from the decarbonisation of liquids, gases and solids provided to industry, residential and commercial activities, and the transport sector.

The largest differences between 1.5°C and 2°C pathways are seen in the first half of the century (Figure 2.14), where 1.5°C pathways generally show lower energy demand, a faster electrification of energy end-use, and a faster decarbonisation of the carbon intensity of electricity and the residual fuel mix. There are very few pathways in the Below-1.5°C class (Figure 2.14). Those scenarios that are available, however, show a faster decline in the carbon intensity of electricity generation and residual fuel mix by 2030 than most pathways that are projected to temporarily overshoot 1.5°C and return by 2100 (or 2°C pathways), and also appear to distinguish themselves already by 2030 by reductions in final energy demand and an increased electricity share (Figure 2.14).

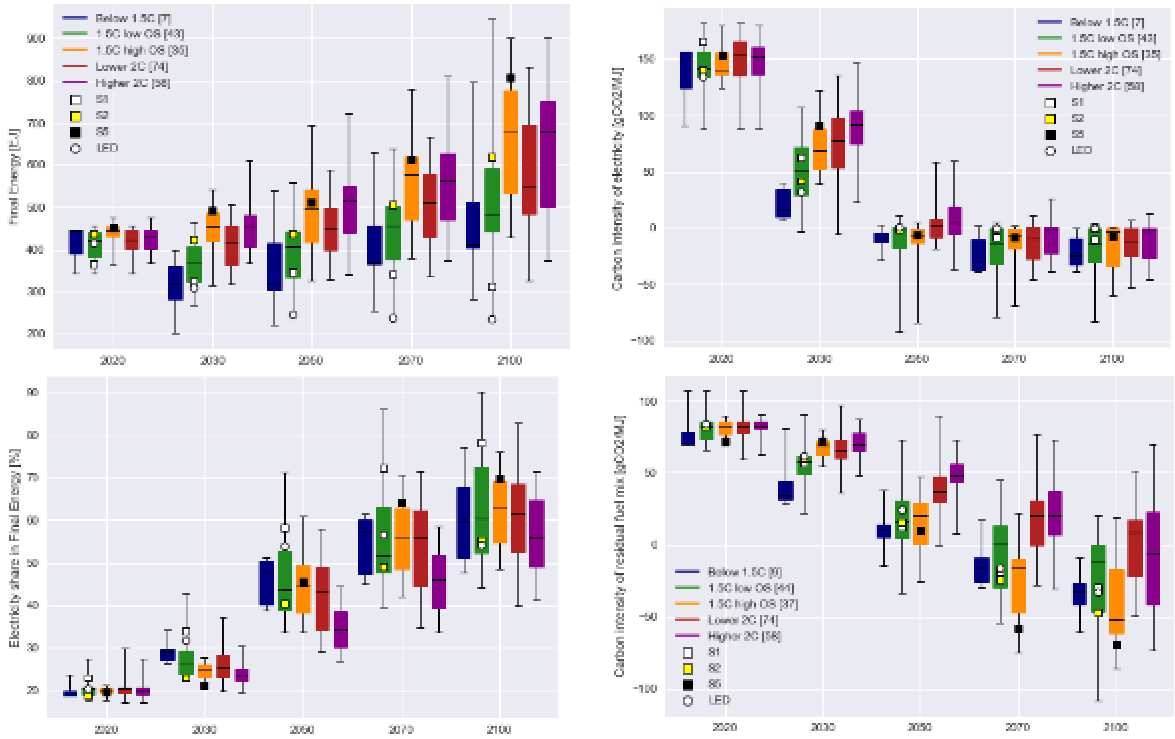


Figure 2.14: Decomposition of transformation pathways into energy demand (top left), carbon intensity of electricity (top right), the electricity share in final energy (bottom left), and the carbon intensity of the residual (non-electricity) fuel mix (bottom right). Boxplots show median, interquartile range and full range of pathways. Pathway temperature classes (Table 2.1) and illustrative pathway archetypes are indicated in the legend. Values following the class labels give the number of available pathways in each class.

2.4.2 Energy supply

Several energy supply characteristics are evident in 1.5°C pathways assessed in this section: i) growth in the share of energy derived from low carbon-emitting sources (including renewables, nuclear, and fossil fuel with CCS) and a decline in the overall share of fossil fuels without CCS (Section 2.4.2.1), ii) rapid decline in the carbon intensity of electricity generation simultaneous with further electrification of energy end-use (Section 2.4.2.2), and iii) the growth in the use of CCS applied to fossil and biomass carbon in most 1.5°C pathways (Section 2.4.2.3).

2.4.2.1 Evolution of primary energy contributions over time

By mid-century, the majority of primary energy comes from non-fossil-fuels (i.e., renewables and nuclear energy) in most 1.5°C pathways (Table 2.6). Figure 2.15 shows the evolution of primary energy supply over this century across 1.5°C pathways, and in detail for the four illustrative pathway archetypes highlighted in this chapter. Note that this section reports primary energy using the direct equivalent method on a lower heating values basis (Bruckner et al., 2014).

Renewable energy (including biomass, hydro, solar, wind, and geothermal) increases across all 1.5°C pathways with the renewable energy share of primary energy reaching 28–88% in 2050 (Table 2.6) with an interquartile range of 49–67%. The magnitude and split between bioenergy, wind, solar, and hydro differ between pathways, as can be seen in the illustrative pathway archetypes in Figure 2.15. Bioenergy is a major supplier of primary energy, contributing to both electricity and other forms of final energy such as liquid fuels for transportation (Bauer et al., 2018). In 1.5°C pathways, there is a significant growth in bioenergy used in combination with CCS for pathways where it is included (Figure 2.15).

Nuclear power increases its share in most 1.5°C pathways by 2050, but in some pathways both the absolute capacity and share of power from nuclear generators declines (Table 2.15). There are large differences in nuclear power between models and across pathways (Kim et al., 2014; Rogelj et al., 2018). One of the reasons for this variation is that the future deployment of nuclear can be constrained by societal preferences assumed in narratives underlying the pathways (O'Neill et al., 2017; van Vuuren et al., 2017b). Some 1.5°C pathways no longer see a role for nuclear fission by the end of the century, while others project over 200 EJ yr^{-1} of nuclear power in 2100 (Figure 2.15).

The share of primary energy provided by total fossil fuels decreases from 2020 to 2050 in all 1.5°C pathways, however, trends for oil, gas and coal differ (Table 2.6). By 2050, the share of primary energy from coal decreases to 0–13% across 1.5°C pathways with an interquartile range of 1–7%. From 2020 to 2050 the primary energy supplied by oil changes by –93 to +6% (interquartile range –75 to –32%); natural gas changes by –88 to +99% (interquartile range –60 to –13%), with varying levels of CCS. Pathways with higher use of coal and gas tend to deploy CCS to control their carbon emissions (see Section 2.4.2.3). As the energy transition is accelerated by several decades in 1.5°C pathways compared to 2°C pathways, residual fossil-fuel use (i.e., fossil fuels not used for electricity generation) without CCS is generally lower in 2050 than in 2°C pathways, while combined hydro, solar, and wind power deployment is generally higher than in 2°C pathways (Figure 2.15).

In addition to the 1.5°C pathways included in the scenario database (Annex 2.A.3), there are other analyses in the literature including, for example, sector-based analyses of energy demand and supply options. Even though not necessarily developed in the context of the 1.5°C target, they explore in greater detail some options for deep reductions in GHG emissions. For example, there are analyses of transition to up to 100% renewable energy by 2050 (Creutzig et al., 2017; Jacobson et al., 2017), which describe what is entailed for a renewable energy share largely from solar and wind (and electrification) that is above the range of 1.5°C pathways available in the database, although there have been challenges to the assumptions used in high renewable analyses (e.g., Clack et al., 2017). There are also analyses that result in a large role for nuclear energy in mitigation of GHGs (Hong et al., 2015; Berger et al., 2017a, 2017b; Xiao and Jiang, 2017). BECCS could also contribute a larger share, but faces challenges related to its land use and impact on food supply (Burns and Nicholson, 2017) (assessed in greater detail in Sections 2.3.4.2, 4.3.7 and 5.4). These analyses could, provided their assumptions prove plausible, expand the range of 1.5°C pathways.

In summary, the share of primary energy from renewables increases while that from coal decreases across 1.5°C pathways (*high confidence*). This statement is true for all 1.5°C pathways in the scenario database and associated literature (Annex 2.A.3), and is consistent with the additional studies mentioned above, an increase in energy supply from lower-carbon-intensity energy supply, and a decrease in energy supply from higher-carbon-intensity energy supply.

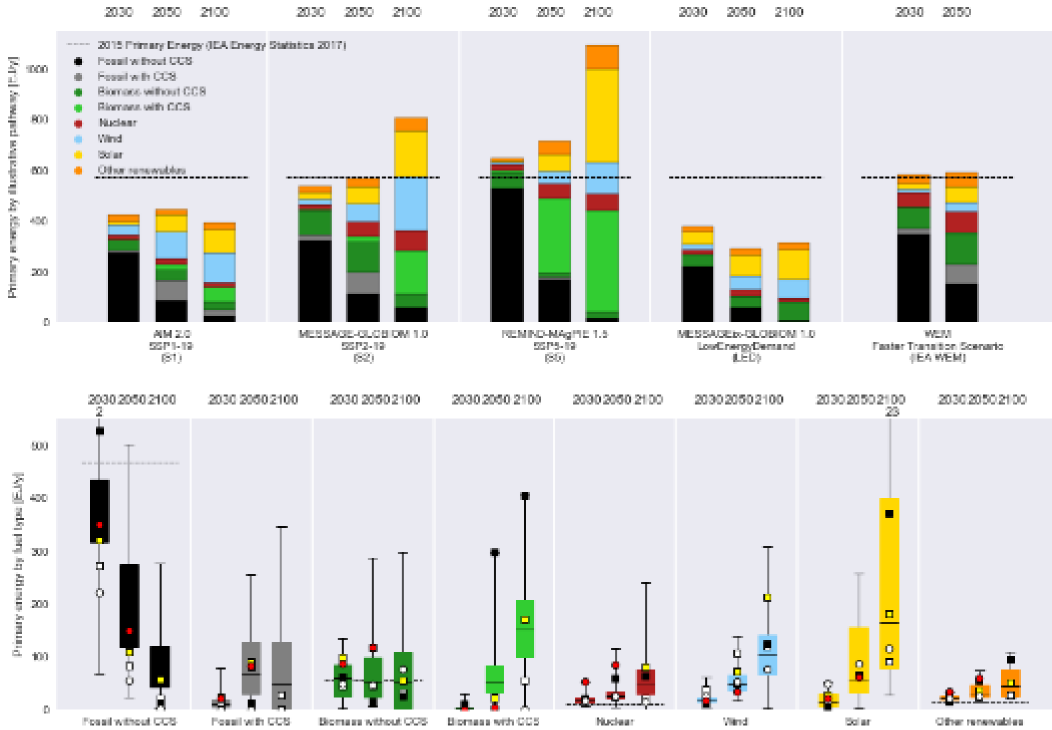


Figure 2.15: Primary energy supply for the four illustrative pathway archetypes plus the IEA's Faster Transition Scenario (OECD/IEA and IRENA, 2017) (top panel), and their relative location in the ranges for 1.5°C and 2°C pathway classes (lower panel). The category 'Other renewables' includes primary energy sources not covered by the other categories, for example, hydro and geothermal energy. The number of pathways that have higher primary energy than the scale in the bottom panel are indicated by the numbers above the whiskers. Black horizontal dashed lines indicates the level of primary energy supply in 2015 (IEA, 2017e). Boxplots in the lower panel show the minimum-maximum range (whiskers), interquartile range (box), and median (vertical thin black line). Symbols in the lower panel show the four pathway archetypes S1 (white square), S2 (yellow square), S5 (black square), LED (white disc), as well as the IEA's Faster Transition Scenario (red disc).

Table 2.6: Global primary energy supply of 1.5°C pathways from the scenario database (Annex 2.A.3). Values given for the median (maximum, minimum) across the full range of 85 available 1.5°C pathways. Growth Factor = [(primary energy supply in 2050)/(primary energy supply in 2020) – 1].

	Primary energy supply [EJ]			Share of primary energy [%]		Growth Factor
	2020	2030	2050	2020	2050	2020-2050
total primary	582.12 (636.98, 483.22)	502.81 (749.05, 237.37)	580.78 (1012.50, 289.02)			0.03 (0.59, -0.51)
renewables	87.70 (101.60, 60.16)	139.48 (203.90, 87.75)	293.80 (584.78, 176.77)	15.03 (20.39, 10.60)	60.80 (87.89, 28.47)	2.62 (6.71, 0.91)
biomass	61.35 (73.03, 40.54)	75.28 (113.02, 44.42)	154.13 (311.72, 40.36)	10.27 (14.23, 7.14)	26.38 (54.10, 10.29)	1.71 (5.56, -0.42)
non-biomass	26.35 (36.58, 17.60)	61.60 (114.41, 25.79)	157.37 (409.94, 53.79)	4.40 (7.19, 2.84)	28.60 (61.61, 9.87)	4.63 (13.46, 1.38)
nuclear	10.93 (18.55, 8.52)	16.22 (41.73, 6.80)	24.48 (115.80, 3.09)	1.97 (3.37, 1.45)	4.22 (13.60, 0.43)	1.34 (7.22, -0.64)
fossil	493.44 (638.04, 376.30)	347.62 (605.68, 70.14)	199.63 (608.39, 43.87)	83.56 (114.75, 77.73)	33.58 (74.63, 7.70)	-0.58 (0.12, -0.91)
coal	147.09 (193.55, 83.23)	49.46 (176.99, 5.97)	23.84 (134.69, 0.36)	25.72 (30.82, 17.19)	4.99 (13.30, 0.05)	-0.85 (-0.30, -1.00)
gas	135.58 (169.50, 105.01)	127.99 (208.55, 17.30)	88.97 (265.66, 14.92)	23.28 (28.39, 18.09)	13.46 (34.83, 2.80)	-0.37 (0.99, -0.88)
oil	195.02 (245.15, 151.02)	175.69 (319.80, 38.94)	93.48 (208.04, 15.07)	33.79 (42.24, 28.07)	16.22 (27.30, 2.89)	-0.54 (0.06, -0.93)

Table 2.7: Global electricity generation of 1.5°C pathways from the scenarios database (Annex 2.A.3). Values given for the median (maximum, minimum) values across the full range across 89 available 1.5°C pathways. Growth Factor = [(primary energy supply in 2050)/(primary energy supply in 2020) – 1].

	Electricty generation [EJ]			Share of electricity generation [%]		Growth Factor
	2020	2030	2050	2020	2050	2020-2050
total electricity	100.09 (113.98, 83.53)	120.01 (177.51, 81.28)	224.78 (363.10, 126.96)			1.31 (2.55, 0.28)
renewables	26.38 (41.80, 18.26)	59.50 (111.70, 30.06)	153.72 (324.26, 84.69)	27.95 (41.84, 17.38)	77.52 (96.65, 35.58)	5.08 (10.88, 2.37)
biomass	1.52 (7.00, 0.66)	3.55 (11.96, 0.79)	16.32 (40.32, 0.21)	1.55 (7.30, 0.63)	8.02 (30.28, 0.08)	6.53 (38.14, -0.93)
non-biomass	24.48 (35.72, 17.60)	55.68 (101.90, 25.79)	136.40 (323.91, 53.79)	25.00 (40.43, 16.75)	66.75 (96.46, 27.51)	4.75 (10.64, 1.38)
nuclear	10.84 (18.55, 8.52)	15.49 (41.73, 6.80)	22.64 (115.80, 3.09)	10.91 (18.34, 8.62)	8.87 (39.61, 1.02)	1.21 (7.22, -0.64)
fossil	61.35 (76.76, 39.48)	38.41 (87.54, 2.25)	14.10 (118.12, 0.00)	61.55 (71.03, 47.26)	8.05 (33.19, 0.00)	-0.76 (0.54, -1.00)
coal	32.37 (46.20, 14.40)	10.41 (43.12, 0.00)	1.29 (46.72, 0.00)	32.39 (40.88, 17.23)	0.59 (12.87, 0.00)	-0.96 (0.01, -1.00)
gas	24.70 (41.20, 13.44)	25.00 (51.99, 2.01)	11.92 (67.94, 0.00)	24.71 (39.20, 11.80)	6.78 (32.59, 0.00)	-0.52 (1.63, -1.00)
oil	1.82 (13.36, 1.12)	0.92 (7.56, 0.24)	0.08 (8.78, 0.00)	2.04 (11.73, 1.01)	0.04 (3.80, 0.00)	-0.97 (0.98, -1.00)

2.4.2.2 Evolution of electricity supply over time

Electricity supplies an increasing share of final energy, reaching 34 to 71% in 2050, across 1.5°C pathways (Figure 2.14), extending the historical increases in electricity share seen over the past decades (Bruckner et al., 2014). From 2020 to 2050, the quantity of electricity supplied in most 1.5°C pathways more than doubles (Table 2.7). By 2050, the carbon intensity of electricity has fallen rapidly to -92 to +11 gCO_2/MJ electricity across 1.5°C pathways from a value of around 140 gCO_2/MJ (range: 88–181 gCO_2/MJ) in 2020 (Figure 2.14). A negative contribution to carbon intensity is provided by BECCS in most pathways (Figure 2.16).

By 2050, the share of electricity supplied by renewables increases from 23% in 2015 (IEA, 2017b) to 36–97% across 1.5°C pathways. Wind, solar, and biomass together make a major contribution in 2050, although the share for each spans a wide range across 1.5°C pathways (Figure 2.16). Fossil fuels on the other hand have a decreasing role in electricity supply with their share falling to 0–33% by 2050 (Table 2.7).

In summary, 1.5°C pathways include a rapid decline in the carbon intensity of electricity and an increase in electrification of energy end use (*high confidence*). This is the case across all 1.5°C pathways and their associated literature (Annex 2.A.3), with pathway trends that extend those seen in past decades, and results that are consistent with additional analyses (see Section 2.4.2.2).

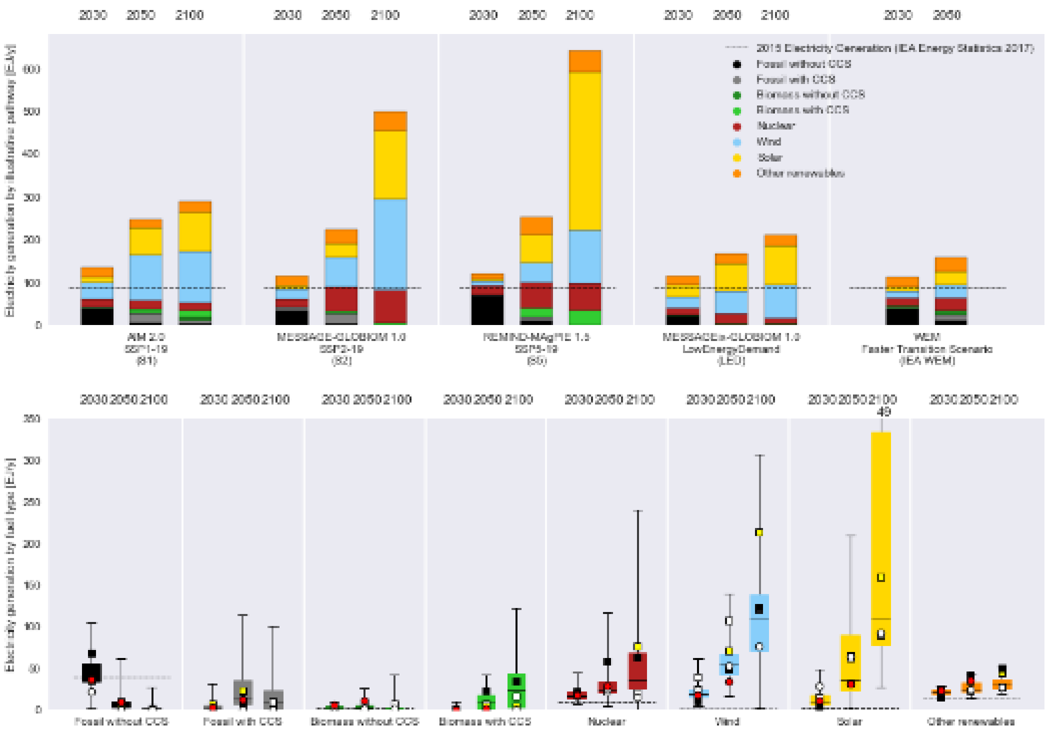


Figure 2.16: Electricity generation for the four illustrative pathway archetypes plus the IEA's Faster Transition Scenario (OECD/IEA and IRENA, 2017) (top panel), and their relative location in the ranges for 1.5°C and 2°C scenario classes (lower panel). The category 'Other renewables' includes electricity generation not covered by the other categories, for example, hydro and geothermal. The number of pathways that have higher primary energy than the scale in the bottom panel are indicated by the numbers above the whiskers. Black horizontal dashed lines indicate the level of primary energy supply in 2015 (IEA, 2017e). Boxplots in the lower panel show the minimum-maximum range (whiskers), interquartile range (box), and median (vertical thin black line). Symbols in the lower panel show the four pathway archetypes S1 (white square), S2 (yellow square), S5 (black square), LED (white disc), as well as the IEA's Faster Transition Scenario (red disc).

2.4.2.3 Deployment of Carbon Capture and Storage

Studies have shown the importance of CCS for deep mitigation pathways (Krey et al., 2014a; Kriegler et al., 2014b), based on its multiple roles to limit fossil-fuel emissions in electricity generation, liquids production, and industry applications along with the projected ability to remove CO_2 from the atmosphere when combined with bioenergy. This remains a valid finding for those 1.5°C and 2°C pathways that do not radically reduce energy demand nor offer carbon-neutral alternatives to liquids and gases that do not rely on bioenergy.

There is a wide range of CCS that is deployed across 1.5°C pathways (Figure 2.17). A few 1.5°C pathways with very low energy demand do not include CCS at all (Grubler et al., 2018). For example, the LED pathway has no CCS, whereas other pathways like the S5 pathway rely on a large amount of BECCS to get to net-zero carbon emissions. The cumulative fossil and biomass CO_2 stored through 2050 ranges from zero to 460 $GtCO_2$ across 1.5°C pathways, with zero up to 190 $GtCO_2$ from biomass captured and stored. Some pathways have very low fossil-fuel use overall, and consequently little CCS applied to fossil fuels. In 1.5°C pathways where the 2050 coal use remains above 20 EJ yr^{-1} in 2050, 33–100% is combined with CCS. While deployment of CCS for natural gas and coal vary widely across pathways, there is greater natural gas primary energy connected to CCS than coal primary energy connected to CCS in many pathways (Figure 2.17).

CCS combined with fossil-fuel use remains limited in some 1.5°C pathways (Rogelj et al., 2018) as the limited 1.5°C carbon budget penalizes CCS if it is assumed to have incomplete capture rates or if fossil fuels are assumed to continue to have significant lifecycle GHG emissions (Pehl et al., 2017). However, high capture rates are technically achievable now at higher cost, although effort to date have focussed on cost reduction of capture (IEAGHG, 2006; DOE/NETL, 2013).

The quantity of CO_2 stored via CCS over this century in 1.5°C pathways ranges from zero to 1,900 $GtCO_2$, (Figure 2.17). The IPCC Special Report on on Carbon Dioxide Capture and Storage (IPCC, 2005) found that that, worldwide, it is *likely* that there is a technical potential of at least about 2,000 $GtCO_2$ of storage capacity in geological formations. Furthermore the IPCC (2005) recognised that there could be a much larger potential for geological storage in saline formations, but the upper limit estimates are uncertain due to lack of information and an agreed methodology. Since IPCC (2005), understanding has improved and there have been detailed regional surveys of storage capacity (Vangkilde-Pedersen et al., 2009; Ogawa et al., 2011; Wei et al., 2013; Bentham et al., 2014; Riis and Halland, 2014; Warwick et al., 2014; NETL, 2015) and improvement and standardisation of methodologies (e.g., Bachu et al. 2007a, b). Dooley (2013) synthesised published literature on both the global geological storage resource as well as the potential demand for geologic storage in mitigation pathways, and found that the cumulative demand for CO_2 storage was small compared to a practical storage capacity estimate (as defined by Bachu et al., 2007a) of 3,900 $GtCO_2$ worldwide. Differences, however, remain in estimates of storage capacity due to, e.g. the potential storage limitations of subsurface pressure build-up (Szulczewski et al., 2014) and assumptions on practices that could manage such issues (Bachu, 2015). Kearns et al. (2017) constructed estimates of global storage capacity of 8,000 to 55,000 $GtCO_2$ (accounting for differences in detailed regional and local estimates), which is sufficient at a global level for this century, but found that at a regional level, robust demand for CO_2 storage exceeds their lower estimate of regional storage available for some regions. However, storage capacity is not solely determined by the geological setting, and Bachu (2015) describes storage engineering practices that could further extend storage capacity estimates. In summary, the storage capacity of all of these global estimates is larger than the cumulative CO_2 stored via CCS of 1.5°C pathways over this century.

There is uncertainty in the future deployment of CCS given the limited pace of current deployment, the evolution of CCS technology that would be associated with deployment, and the current lack of incentives for large-scale implementation of CCS (Bruckner et al., 2014; Clarke et al., 2014; Riahi et al., 2017). Given the importance of CCS in most mitigation pathways and its current slow pace of improvement, the large-scale deployment of CCS as an option depends on the further development of the technology in the near term. Chapter 4 discusses how progress on CCS might be accelerated.

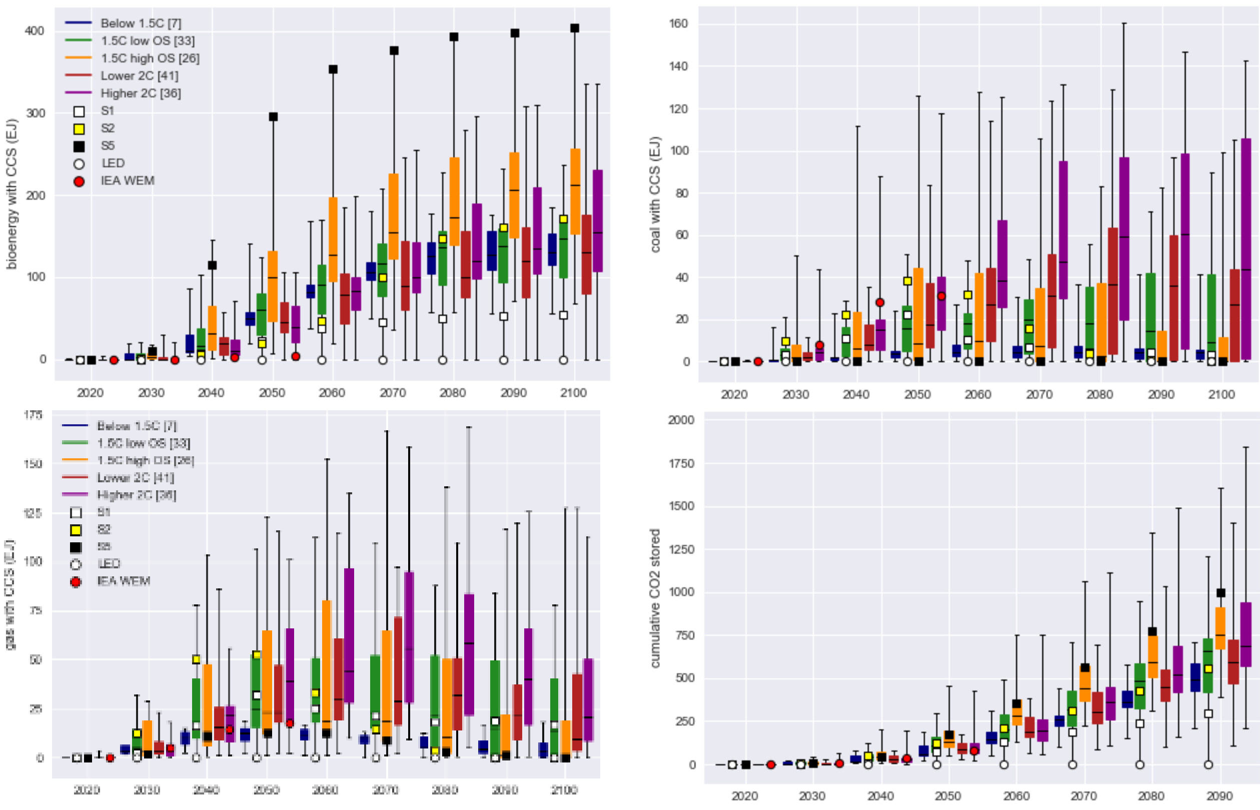


Figure 2.17: CCS deployment in 1.5°C and 2°C pathways for biomass, coal and natural gas (EJ of primary energy) and the cumulative quantity of fossil (including from, e.g., cement production) and biomass CO_2 stored via CCS (lower right in $GtCO_2$ stored). Boxplots show median, interquartile range and full range of pathways in each temperature class. Pathway temperature classes (Table 2.1), illustrative pathway archetypes, and the IEA's Faster Transition Scenario (IEA WEM) (OECD/IEA and IRENA, 2017) are indicated in the legend.

2.4.3 Energy end-use sectors

Since the power sector is almost decarbonized by mid-century in both 1.5°C and 2°C pathways, major differences come from CO_2 emission reductions in end-use sectors. Energy-demand reductions are key and common features in 1.5˚C-consistent pathways, which can be achieved by efficiency improvements and various specific demand-reduction measures. Another important feature is end-use decarbonisation including by electrification, although the potential and challenges in each end-use sector vary significantly.

In the following sections, the potential and challenges of CO_2 emission reductions towards 1.5°C and 2°C-consistent pathways are discussed for each end-use energy sector (industry, buildings, and transport sectors). For this purpose, two types of pathways are analysed and compared: IAM (integrated assessment modelling) studies and sectoral (detailed) studies. IAM data are extracted from the database that was compiled for this assessment (see Annex 2.A.3), and the sectoral data are taken from a recent series of publications; 'Energy Technology Perspectives' (ETP) (IEA, 2014, 2015b, 2016a, 2017a), the IEA/IRENA report (OECD/IEA and IRENA, 2017), and the Shell Sky report (Shell International B.V., 2018). The IAM pathways are categorized according to their temperature rise in 2100 and the overshoot of temperature during the century (see Table 2.1 in Section 2.1). Since the number of Below-1.5°C pathways is small, the following analyses focus only on the featured of the 1.5°C-low-OS and 1.5°C-high-OS pathways (hereafter denoted together as 1.5°C overshoot pathways or IAM-1.5DS-OS) and 2°C-consistent pathways (IAM-2DS). In order to show the diversity of IAM pathways, we again show specific data from the four illustrative pathways archetypes used throughout this chapter (see Sections 2.1 and 2.3).

IEA ETP-B2DS ('Beyond 2 Degrees') and ETP-2DS are pathways with a 50% chance of limiting temperature rise below 1.75°C and 2°C by 2100, respectively (IEA, 2017a). The IEA-66%2DS pathway keeps global-mean temperature rise below 2°C not just in 2100 but also over the course of the 21st century with a 66% chance of being below 2°C by 2100 (OECD/IEA and IRENA, 2017). The comparison of CO_2 emission trajectories between ETP-B2DS and IAM-1.5DS-OS show that these are consistent up to 2060 (Figure 2.18). IEA scenarios assume that only a very low level of BECCS is deployed to help offset emissions in difficult-to-decarbonize sectors, and that global energy-related CO_2 emissions cannot turn net-negative at any time and stay zero from 2060 to 2100 (IEA, 2017a). Therefore, although its temperature rise in 2100 is below 1.75°C rather than below 1.5°C, this scenario can give information related to 1.5°C-consistent overshoot pathway up to 2050. The trajectory of IEA-66%2DS (also referred to in other publications as IEA's 'Faster Transition Scenario') lies between IAM-1.5DS-OS and IAM-2DS pathway ranges, and IEA-2DS stays in the range of 2°C-consistent IAM pathways. The Shell-Sky scenario aims to hold the temperature rise to well-below 2°C, but it is a delayed action pathway relative to others, as can be seen in Figure 2.18.

Energy-demand reduction measures are key to reduce CO_2 emissions from end-use sectors for low-carbon pathways. The up-stream energy reductions can be several times to an order of magnitude larger than the initial end-use demand reduction. There are interdependencies among the end-use sectors and also between energy-supply and end-use sectors, which raise the importance of a wide, systematic approach. As shown in Figure 2.19, global final-energy consumption grows by 30% and 10% from 2010 to 2050 for 2°C-consistent and 1.5°C overshoot pathways from IAMs, respectively, while much higher growth of 75% is projected for reference scenarios. The ranges within a specific pathway class are due to a variety of factors as introduced in Section 2.3.1, as well as differences between modelling frameworks. The important energy efficiency improvements and energy conservation that facilitate many of the 1.5°C pathways raise the issue of potential rebound effects (Saunders, 2015), which, while promoting development, can make the achievement of low-energy demand futures more difficult than modelling studies anticipate (see Sections 2.5 and 2.6).

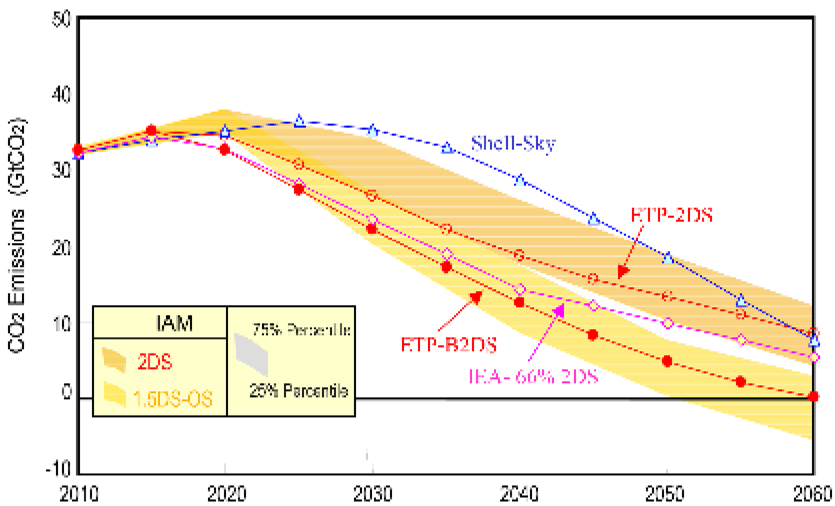


Figure 2.18: Comparison of CO_2 emission trajectories of sectoral pathways (IEA ETP-B2DS, ETP-2DS, IEA-66%2DS, Shell-Sky) with the ranges of IAM pathway (2DS are 2°C-consistent pathways and 1.5DS-OS are1.5°C-consistent overshoot pathways). The CO_2 emissions shown here are the energy-related emissions including industrial process emissions.

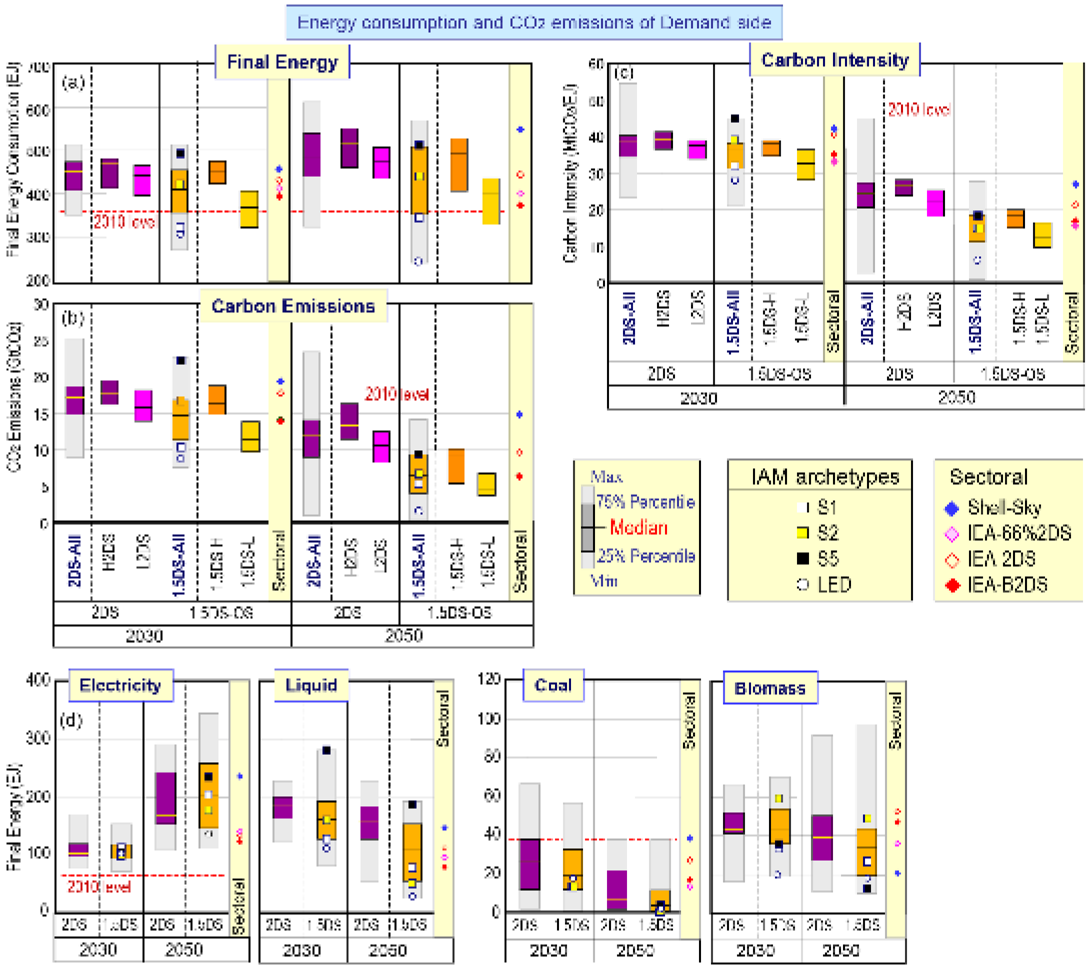


Figure 2.19: (a) Global final energy, (b) direct CO_2 emissions from the all energy demand sectors, (c) carbon intensity, and (d) structure of final energy (electricity, liquid fuel, coal, and biomass). The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS: Higher-2°C, L2DS: Lower-2°C, 1.5DS-H: 1.5°C-high-OS, 1.5DS-L: 1.5°C-low-OS, 1.5DS = 1.5DS-OS: 1.5°C-consistent pathways with overshoot. Section 2.1 for descriptions.

Final-energy demand is driven by demand in energy services for mobility, residential and commercial activities (buildings), and manufacturing. This heavily depends on assumptions about socio-economic futures as represented by the SSPs (Bauer et al., 2017) (see Sections 2.1, 2.3 and 2.5). The structure of this demand drives the composition of final energy use in terms of energy carriers (electricity, liquids, gases, solids, hydrogen etc.).

Figure 2.19 shows the structure of global final energy demand in 2030 and 2050, indicating the trend toward electrification and fossil fuel usage reduction. This trend is more significant in 1.5°C pathways than 2°C pathways. Electrification continues throughout the second half of the century leading to a 3.5 to 6-fold increase in electricity demand (interquartile range; median 4.5) by the end of the century relative to today (Grubler et al., 2018; Luderer et al., 2018). Since the electricity sector is completely decarbonised by mid-century in 1.5°C pathways (see Figure 2.20), electrification is the primary means to decarbonize energy end-use sectors.

The CO_2 emissions[6] of end-use sectors and carbon intensity are shown in Figure 2.20. The projections of IAMs and IEA studies show rather different trends, especially in the carbon intensity. These differences come from various factors, including the deployment of CCS, the level of fuel switching and efficiency

[6] FOOTNOTE: This section reports "direct" CO_2 emissions as reported for pathways in the database for the report. As shown below, the emissions from electricity are nearly zero around 2050, so the impact of indirect emissions on the whole emission contributions of each sector is very small in 2050.

improvements, and the effect of structural and behavioural changes. IAM projections are generally optimistic for the industry sectors, but not for buildings and transport sectors. Although GDP increases by a factor of 3.4 from 2010 to 2050, the total energy consumption of end-use sectors grows by only about 30% and 20% in 1.5°C overshoot and 2°C-consistent pathways, respectively. However, CO_2 emissions would need to be reduced further to achieve the stringent temperature limits. Fig. 2.20 shows that the reduction in CO_2 emissions of end-use sectors is larger and more rapid in 1.5°C overshoot than 2°C-consistent pathways, while emissions from the power sector are already almost zero in 2050 in both sets of pathways indicating that supply-side emissions reductions are almost fully exploited already in 2°C-consistent pathways (see Figure 2.20) (Rogelj et al., 2015b, 2018; Luderer et al., 2016b). The emission reductions in end-use sectors is largely made possible due to efficiency improvements, demand reduction measures and electrification, but its level differs among end-use sectors. While the carbon intensity of industry and the buildings sector decreases to a very low level of around 10 $gCO_2\ MJ^{-1}$, the carbon intensity of transport becomes the highest of any sector by 2040 due to its higher reliance on oil-based fuels. In the following subsections, the potential and challenges of CO_2 emission reduction in each end-use sector are discussed in detail.

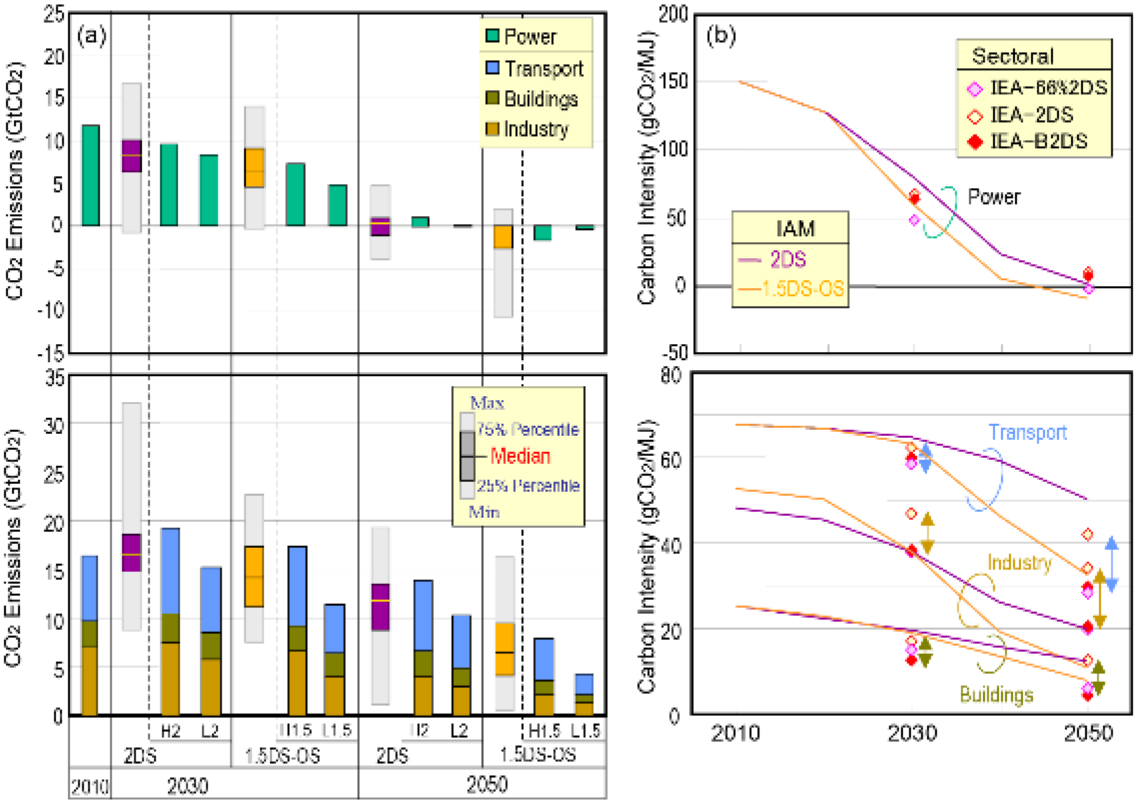


Figure 2.20: Comparison of (a) direct CO_2 emissions and (b) carbon intensity of the power and energy end-use sectors (industry, buildings, and transport sectors) between IAMs and sectoral studies (IEA-ETP and IEA/IRENA). Diamond markers in panel (b) show data for IEA-ETP scenarios (2DS and B2DS), and IEA/IRENA scenario (66%2DS). Note: for the data of IAM studies, there is rather large variation of projections for each indicator. Please see the details in the following figures in each end-use sector section.

2.4.3.1 Industry

The industry sector is the largest end-use sector both in terms of final-energy demand and GHG emissions. Its direct CO_2 emissions currently account for about 25% of total energy-related and process CO_2 emissions, and have increased with an average annual rate of 3.4% between 2000 and 2014, significantly faster than total CO_2 emissions (Hoesly et al., 2018). In addition to emissions from the combustion of fossil fuels, non-energy uses of fossil fuels in the petro-chemical industry and metal smelting, as well as non-fossil fuel process emissions (e.g., from cement production) contribute a small amount (~5%) to the sector's CO_2 emissions inventory. Material industries are particularly energy and emissions intensive: steel, non-ferrous metals, chemicals, non-metallic minerals, and pulp and paper alone accounted for close to 66% of final-energy demand, and 72% of direct industry sector emissions in 2014 (IEA, 2017a). In terms of end-uses, the bulk of energy in manufacturing industries is required for process heating and steam generation, while most electricity (but smaller shares of total final energy) is used for mechanical work (Banerjee et al., 2012; IEA, 2017a).

As shown in Figure 2.21, a major share of the additional emission reductions required for 1.5°C-overshoot pathways beyond those in 2°C-consistent pathways comes from industry. Final energy, CO_2 emissions, and carbon intensity are consistent in IAM and sectoral studies, but in IAM-1.5°C-overshoot pathways the share of electricity is higher than IEA-B2DS (40% vs. 25%) and hydrogen is also considered to have a share of about 5% vs. 0%. In 2050, final energy is increased by 30% and 5% compared with the 2010 level (red dotted line) for 1.5°C-overshoot and 2°C-consistent pathways, respectively, but CO_2 emissions are decreased by 80% and 50% and carbon intensity by 80% and 60%, respectively. This additional decarbonisation is brought by switching to low carbon fuels and CCS deployment.

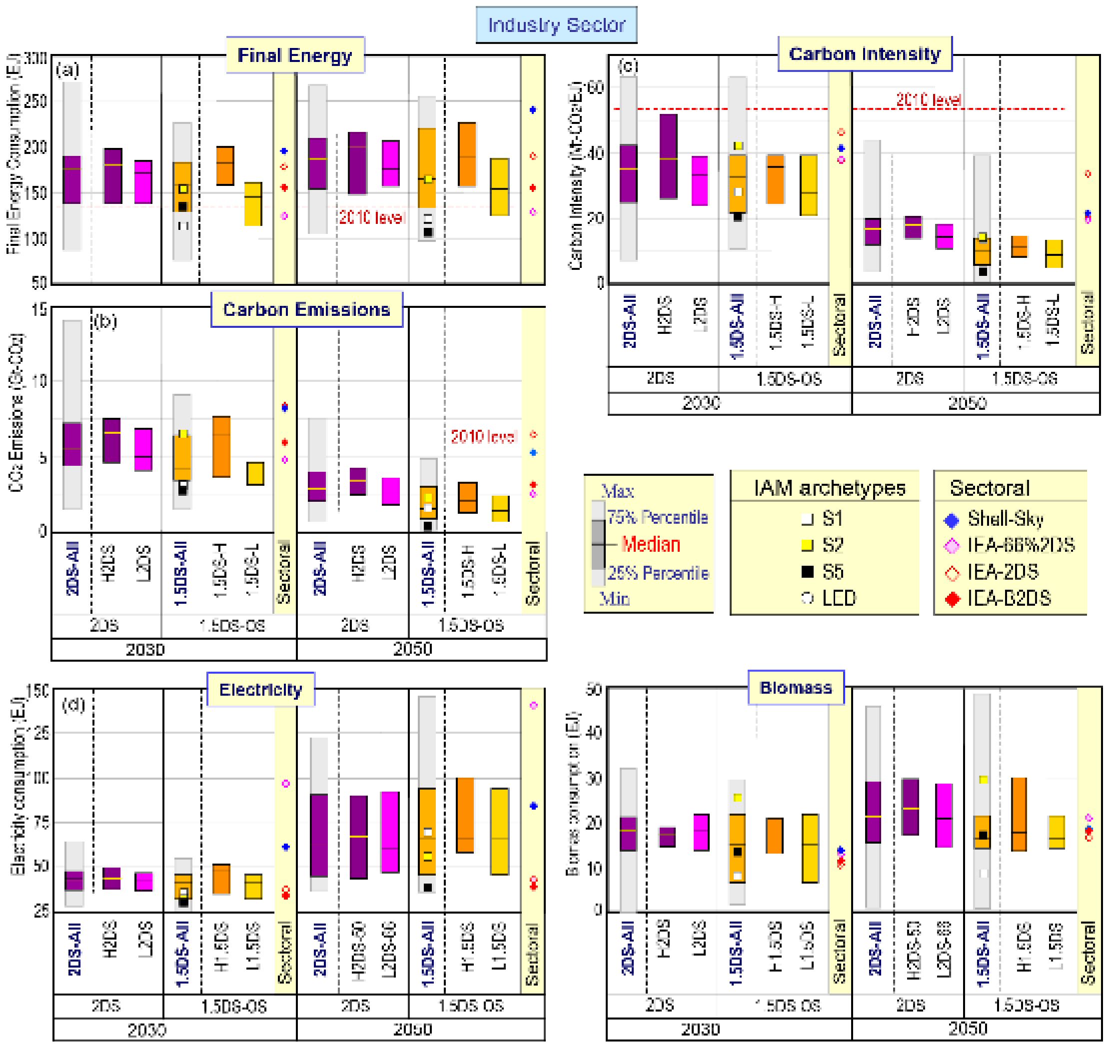


Figure 2.21: Comparison of (a) final energy, (b) direct CO_2 emissions, (c) carbon intensity, (d) electricity and biomass consumption in the industry sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS: Higher-2°C, L2DS: Lower-2°C, 1.5DS-H: 1.5°C-high-OS, 1.5DS-L: 1.5°C-low-OS, 1.5DS = 1.5DS-OS: 1.5°C-consistent pathways with overshoot. Section 2.1 for descriptions.

Broadly speaking, the industry sector's mitigation measures can be categorized in terms of the following five strategies: (i) reductions in the demand, (ii) energy efficiency, (iii) increased electrification of energy demand, (iv) reducing the carbon content of non-electric fuels, and (v) deploying innovative processes and application of CCS. IEA ETP estimates the relative contribution of different measures for CO_2 emission reduction in their B2DS scenario compared with their reference scenario in 2050 as follows: energy efficiency 42%, innovative process and CCS 37%, switching to low carbon fuels and feed-stocks 13% and material efficiency (include efficient production and use to contribute to demand reduction) 8%. The remainder of this section delves more deeply into the potential mitigation contributions of these strategies as well as their limitations.

Reduction in the use of industrial materials, while delivering similar services, or improving the quality of products could help to reduce energy demand and overall system-level CO_2 emissions. Strategies include using materials more intensively, extension of product lifetimes, increasing recycling, and increasing inter-industry material synergies, such as clinker substitution in cement production (Allwood et al., 2013; IEA, 2017a). Related to material efficiency, use of fossil-fuel feed-stocks could shift to lower-carbon feed-stocks such as oil to natural gas and biomass and end-uses could shift to more sustainable materials such as biomass-based materials, reducing the demand for energy-intensive materials (IEA, 2017a).

Reaping energy efficiency potentials hinges critically on advanced management practices in industrial facilities such as energy management systems, as well as targeted policies to accelerate adoption of best available technology (see Section 2.5). Although excess energy, usually as waste heat, is inevitable, recovering and reusing this waste heat under economically and technically viable conditions benefits the overall energy system. Furthermore, demand-side management strategies could modulate the level of industrial activity in line with the availability of resources in the power system. This could imply a shift away from peak demand and as power supply decarbonizes, this demand-shaping potential could shift some load to times with high portions of low-carbon electricity generation (IEA, 2017a).

In the industry sector, energy demand increases more than 40% between 2010 and 2050 in baseline scenarios. However, in the 1.5°C-overshoot and 2°C-consistent pathways from IAMs, the increase is only 30% and 5%, respectively (Figure 2.21). These energy demand reductions encompass both efficiency improvements in production as well as reductions in material demand, as most IAMs do not discern these two factors.

CO_2 emissions from industry increase by 30% in 2050 compared to 2010 in baseline scenarios. By contrast, these emissions are reduced by 80% and 50% relative to 2010 levels in 1.5°C-overshoot and 2°C-consistent pathways from IAMs, respectively (Figure 2.21). By mid-century, CO_2 emissions per unit electricity are projected to decrease to near zero in both sets of pathways (see Figure 2.20). An accelerated electrification of the industry sector thus becomes an increasingly powerful mitigation option. In the IAM pathways, the share of electricity increases up to 30% by 2050 in 1.5°C-overshoot pathways (Figure 2.21) from 20% in 2010. Some industrial fuel uses are substantially more difficult to electrify than others, and electrification would have other effects on the process, including impacts on plant design, cost and available process integration options (IEA, 2017a)[7].

In 1.5°C-overshoot pathways, the carbon intensity of non-electric fuels consumed by industry decreases to 16 gCO_2 MJ^{-1} by 2050, compared to 25 gCO_2 MJ^{-1} in 2°C-consistent pathways. Considerable carbon intensity reductions are already achieved by 2030, largely via a rapid phase-out of coal. Biomass becomes an increasingly important energy carrier in the industry sector in deep-decarbonisation pathways, but primarily in the longer term (in 2050, biomass accounts for only 10% of final energy consumption even in 1.5°C-overshoot pathways). In addition, hydrogen plays a considerable role as a substitute for fossil-based non-electric energy demands in some pathways.

Without major deployment of new sustainability-oriented low-carbon industrial processes, the 1.5°C-overshoot target is difficult to achieve. Bringing such technologies and processes to commercial deployment requires significant investment in research and development. Some examples of innovative low-carbon process routes include: new steelmaking processes such as upgraded smelt reduction and upgraded direct reduced iron, inert anodes for aluminium smelting, and full oxy-fuelling kilns for clinker production in cement manufacturing (IEA, 2017a).

[7] FOOTNOTE: Electrification can be linked with the heating and drying process by electric boilers and electro-thermal processes, and also low-temperature heat demand by heat pumps. In iron and steel industry, hydrogen produced by electrolysis can be used as a reduction agent of iron instead of coke. Excess resources, such as black liquor will provide the opportunity to increase the systematic efficiency to use for electricity generation.

CCS plays a major role in decarbonizing the industry sector in the context of 1.5°C and 2°C pathways, especially in industries with higher process emissions, such as cement, iron and steel industries. In 1.5°C-overshoot pathways, CCS in industry reaches 3 $GtCO_2$ yr^{-1} by 2050, albeit with strong variations across pathways. Given project long-lead times and the need for technological innovation, early scale-up of industry CCS is essential to achieve the stringent temperature target. Development and demonstration of such projects has been slow, however. Currently, only two large-scale industrial CCS projects outside of oil and gas processing are in operation (Global CCS Institute, 2016). The estimated current cost[8] of CO_2 avoided (in 2015-US$) ranges from $20-27 tCO_2^{-1} for gas processing and bio-ethanol production, and $60-138 tCO_2^{-1} for fossil fuel-fired power generation up to $104-188 tCO_2^{-1} for cement production (Irlam, 2017).

2.4.3.2 Buildings

In 2014, the buildings sector accounted for 31% of total global final-energy use, 54% of final-electricity demand, and 8% of energy-related CO_2 emissions (excluding indirect emission due to electricity). When upstream electricity generation is taken into account, buildings were responsible for 23% of global energy-related CO_2 emissions, with one-third of those from direct fossil fuel consumption (IEA, 2017a).

Past growth of energy consumption has been mainly driven by population and economic growth, with improved access to electricity, and higher use of electrical appliances and space cooling resulting from increasing living standards, especially in developing countries (Lucon et al., 2014). These trends will continue in the future and in 2050, energy consumption is projected to increase by 20% (50%) compared to 2010 in IAM-1.5°C-overshoot (2°C-consistent) pathways (Figure 2.22). However, sectoral studies (IEA-ETP scenarios) show different trends. Energy consumption in 2050 decreases compared to 2010 in ETP-B2DS, and the reduction rate of CO_2 emissions is higher than in IAM pathways (Figure 2.22). Mitigation options are often more widely covered in sectoral studies (Lucon et al., 2014), leading to greater reductions in energy consumption and CO_2 emissions.

Emissions reductions are driven by a clear tempering of energy demand and a strong electrification of the buildings sector. The share of electricity in 2050 is 60% in 1.5°C-overshoot pathways, compared with 50% in 2°C-consistent pathways (Figure 2.22). Electrification contributes to the reduction of direct CO_2 emissions by replacing carbon-intensive fuels, like oil and coal. Furthermore, when combined with a rapid decarbonisation of the power system (see Section 2.4.1) it also enables further reduction of indirect CO_2 emissions from electricity. Sectoral bottom-up models in general estimate lower electrification potentials for the buildings sector in comparison to global IAMs (see Figure 2.22). Besides CO_2 emissions, increasing global demand for air conditioning in buildings may also lead to increased emissions of HFCs in this sector over the next few decades. Although these gases are currently a relatively small proportion of annual GHG emissions, their use in the air conditioning sector is expected to grow rapidly over the next few decades if alternatives are not adopted. However, their projected future impact can be significantly mitigated through better servicing and maintenance of equipment and switching of cooling gases (Shah et al., 2015; Purohit and Höglund-Isaksson, 2017).

IEA-ETP (IEA, 2017a) analysed the relative importance of various technology measures toward the reduction of energy and CO_2 emissions in the buildings sector. The largest energy savings potential is in heating and cooling demand largely due to building envelope improvements and high efficiency and renewable equipment. In the ETP-B2DS, energy demand for space heating and cooling is 33% lower in 2050 than the reference scenario and these reductions account for 54% of total reductions from the reference scenario. Energy savings from shifts to high-performance lighting, appliances, and water heating equipment account for a further 24% of the total reduction. The long-term, strategic shift away from fossil-fuel use in buildings, alongside the rapid uptake of energy efficient, integrated and renewable energy technologies (with clean power generation), leads to a drastic reduction of CO_2 emissions. In ETP-B2DS, the direct CO_2 emissions are 79% lower than the reference scenario in 2050 and the remaining emissions come mainly from the continued use of natural gas.

[8] FOOTNOTE: These are first-of-a-kind (FOAK) cost data.

The buildings sector is characterized by very long-living infrastructure and immediate steps are hence important to avoid lock-in of inefficient carbon and energy-intensive buildings. This applies both to new buildings in developing countries where substantial new construction is expected in the near future and to retrofits of existing building stock in developed regions. This represents both a significant risk and opportunity for mitigation[9]. A recent study highlights the benefits of deploying the most advanced renovation technologies, which would avoid lock-in into less efficient measures (Güneralp et al., 2017). Aside from the effect of building envelope measures, adoption of energy-efficient technologies such as heat pumps and more recently light-emitting diodes is also important for the reduction of energy and CO_2 emissions (IEA, 2017a). Consumer choices, behaviour and building operation can also significantly affect energy consumption (see Section 4.3).

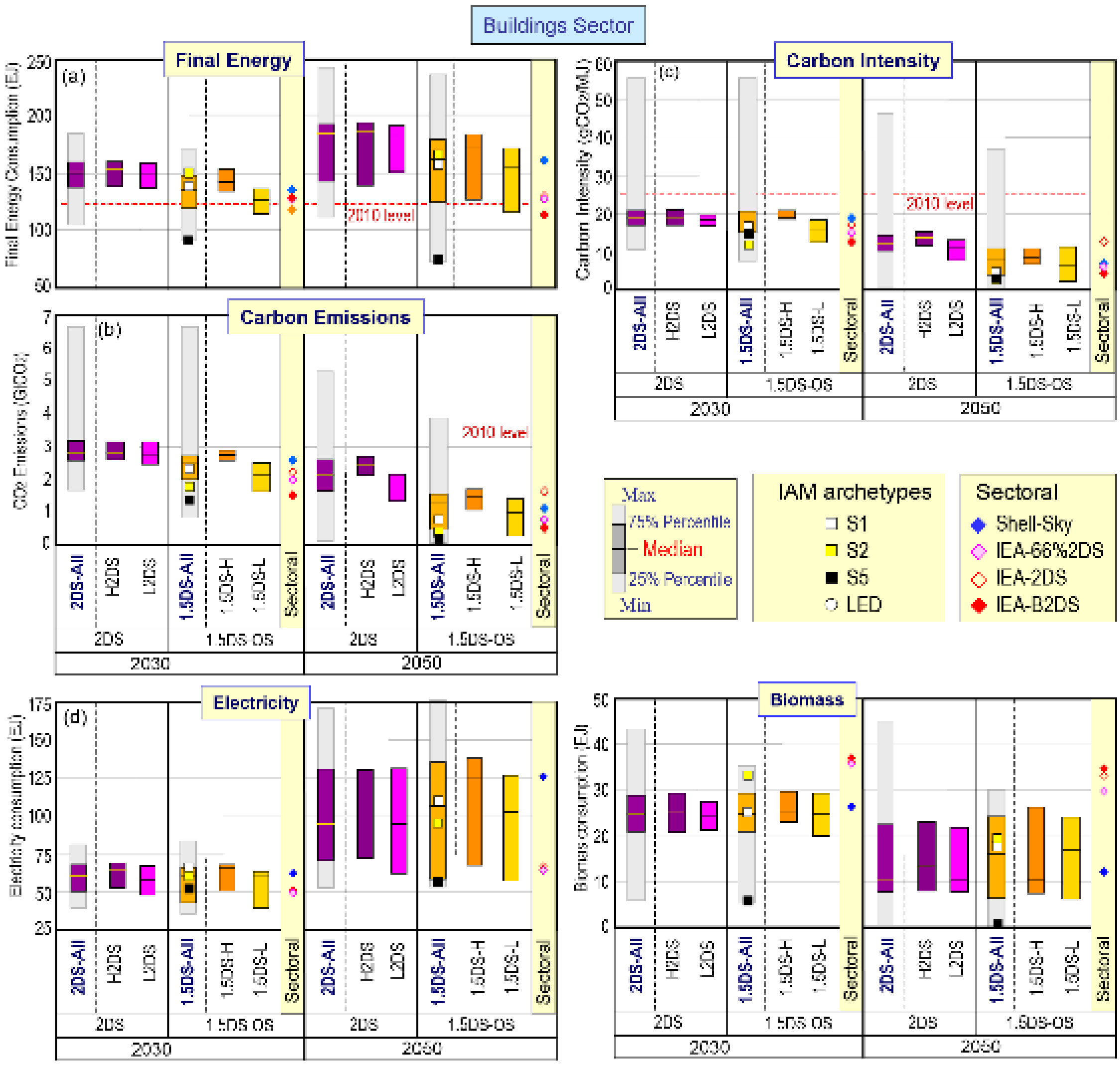


Figure 2.22: Comparison of (a) final energy, (b) direct CO_2 emissions, (c) carbon intensity, (d) electricity and biomass consumption in the buildings sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS: Higher-2°C, L2DS: Lower-2°C, 1.5DS-H: 1.5°C-high-OS, 1.5DS-L: 1.5°C-low-OS, 1.5DS = 1.5DS-OS: 1.5°C-consistent pathways with overshoot. Section 2.1 for descriptions.

[9] FOOTNOTE: In this section, we only discuss the direct emissions from the sector, but the selection of building materials have a significant impact on the reduction of energy and emissions during the production, such as shift from the steel and concrete to wood-based materials.

2.4.3.3 Transport

Transport accounted for 28% of global final-energy demand and 23% of global energy-related CO_2 emissions in 2014. Emissions increased by 2.5% annually between 2010 and 2015, and over the past half century the sector has witnessed faster emissions growth than any other. The transport sector is the least diversified energy end-use sector; the sector consumed 65% of global oil final-energy demand, with 92% of transport final-energy demand consisting of oil products (IEA, 2017a), suggesting major challenges for deep decarbonisation.

Final energy, CO_2 emissions, and carbon intensity for the transport sector are shown in Figure 2.23. The projections of IAMs are more pessimistic than IEA-ETP scenarios, though both clearly project deep cuts in energy consumption and CO_2 emissions by 2050. For example, 1.5°C-overshoot pathways from IAMs project a reduction of 15% in energy consumption between 2015 and 2050, while ETP-B2DS projects a reduction of 30% (Figure 2.23). Furthermore, IAM pathways are generally more pessimistic in the projections of CO_2 emissions and carbon intensity reductions. In AR5 (Clarke et al., 2014; Sims et al., 2014), similar comparisons between IAMs and sectoral studies were performed and these were in good agreement with each other. Since the AR5, two important changes can be identified; rapid growth of electric vehicle sales in passenger cars, and more attention towards structural changes in this sector. The former contributes to reduction of CO_2 emissions and the latter reduction of energy consumption.

Deep emissions reductions in the transport sector would be achieved by several means. Technology focused measures such as energy efficiency and fuel-switching are two of these. Structural changes that avoid or shift transport activity are also important. While the former solutions (technologies) always tend to figure into deep decarbonisation pathways in a major way, this is not always the case with the latter, especially in IAM pathways. Comparing different types of global transport models, Yeh et al. (2016) find that sectoral (intensive) studies generally envision greater mitigation potential from structural changes in transport activity and modal choice. Though, even there, it is primarily the switching of passengers and freight from less- to more-efficient travel modes (e.g., cars, trucks and airplanes to buses and trains) that is the main strategy; other actions, such as increasing vehicle load factors (occupancy rates) and outright reductions in travel demand (e.g., as a result of integrated transport, land-use and urban planning), figure much less prominently. Whether these dynamics accurately reflect the actual mitigation potential of structural changes in transport activity and modal choice is a point of investigation. According to the recent IEA-ETP scenarios, the share of avoid (reduction of mobility demand) and shift (shifting to more efficient modes) measures in the reduction of CO_2 emissions from the reference to B2DS scenarios in 2050 amounts to 20% (IEA, 2017a).

The potential and strategies to reduce energy consumption and CO_2 emissions differ significantly among transport modes. In ETP-B2DS, the shares of energy consumption and CO_2 emissions in 2050 for each mode are rather different (see Table 2.8), indicating the challenge of decarbonizing heavy-duty vehicles (HDV, trucks), aviation, and shipping. The reduction of CO_2 emissions in the whole sector from the reference scenario to ETP-B2DS is 60% in 2050, with varying contributions per mode (Table 2.8). Since there is no silver bullet for this deep decarbonisation, every possible measure would be required to achieve this stringent emissions outcome. The contribution of various measures for the CO_2 emission reduction from the reference scenario to the IEA-B2DS in 2050 can be decomposed to efficiency improvement (29%), biofuels (36%), electrification (15%), and avoid/shift (20%) (IEA, 2017a). It is noted that the share of electrification becomes larger compared with older studies, reflected by the recent growth of electric vehicle sales worldwide. Another new trend is the allocation of biofuels to each mode of transport. In IEA-B2DS, the total amount of biofuels consumed in the transport sector is 24EJ[10] in 2060, and allocated to LDV (light-duty vehicles, 17%), HDV (35%), aviation (28%), and shipping (21%), that is, more biofuels is allocated to the difficult-to-decarbonize modes (see Table 2.8).

[10] FOOTNOTE: This is estimated for the biofuels produced in a "sustainable manner" from non-food crop feed-stocks, which are capable of delivering significant lifecycle GHG emissions savings compared with fossil fuel alternatives, and which do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts.

Table 2.8: Transport sector indicators by mode in 2050 (IEA, 2017a). Share of Energy consumption, biofuel consumption, CO_2 emissions, and reduction of energy consumption and CO_2 emissions from 2014. (CO_2 emissions are Well-to-Wheel emissions, including the emission during the fuel production.), LDV: Light Duty Vehicle, HDV: Heavy Duty Vehicle

	Share of each mode (%)			Reduction from 2014 (%)	
	Energy	Biofuel	CO_2	Energy	CO_2
LDV	36	17	30	51	81
HDV	33	35	36	8	56
Rail	6		-1	-136	107
Aviation	12	28	14	14	56
Shipping	17	21	21	26	29

In road transport, incremental vehicle improvements (including engines) are relevant, especially in the short to medium term. Hybrid electric vehicles (HEVs) are also instrumental to enabling the transition from ICEs (internal combustion engine vehicles) to electric vehicles, especially plug-in hybrid electric vehicles (PHEVs). Electrification is a powerful measure to decarbonize short-distance vehicles (passenger cars and two and three wheelers) and the rail sector. In road freight transport (trucks), systemic improvements (e.g., in supply chains, logistics, and routing) would be effective measures with efficiency improvement of vehicles. Shipping and aviation are more challenging to decarbonize, while their demand growth is projected to be higher than other transport modes. Both modes would need to pursue highly ambitious efficiency improvements and use of low-carbon fuels. In the near and medium term, this would be advanced biofuels while in the long term it could be hydrogen as direct use for shipping or an intermediate product for synthetic fuels for both modes (IEA, 2017a).

The share of low-carbon fuels in the total transport fuel mix increases to 10% (16%) by 2030 and to 40% (58%) by 2050 in 1.5°C-overshoot pathways from IAMs. The IEA-B2DS scenario is on the more ambitious side, especially in the share of electricity. Hence, there is wide variation among scenarios, including the IAM pathways, regarding changes in the transport fuel mix over the first half of the century. As seen in Figure 2.23, the projections of energy consumption, CO_2 emissions, and carbon intensity are quite different between IAM and ETP scenarios. These differences can be explained by more weight on efficiency improvements and avoid/shift decreasing energy consumption, and the higher share of biofuels and electricity accelerating the speed of decarbonisation in ETP scenarios. Although biofuel consumption and electric vehicle sales have increased significantly in recent years, the growth rates projected in these pathways would be unprecedented and far higher than has been experienced to date.

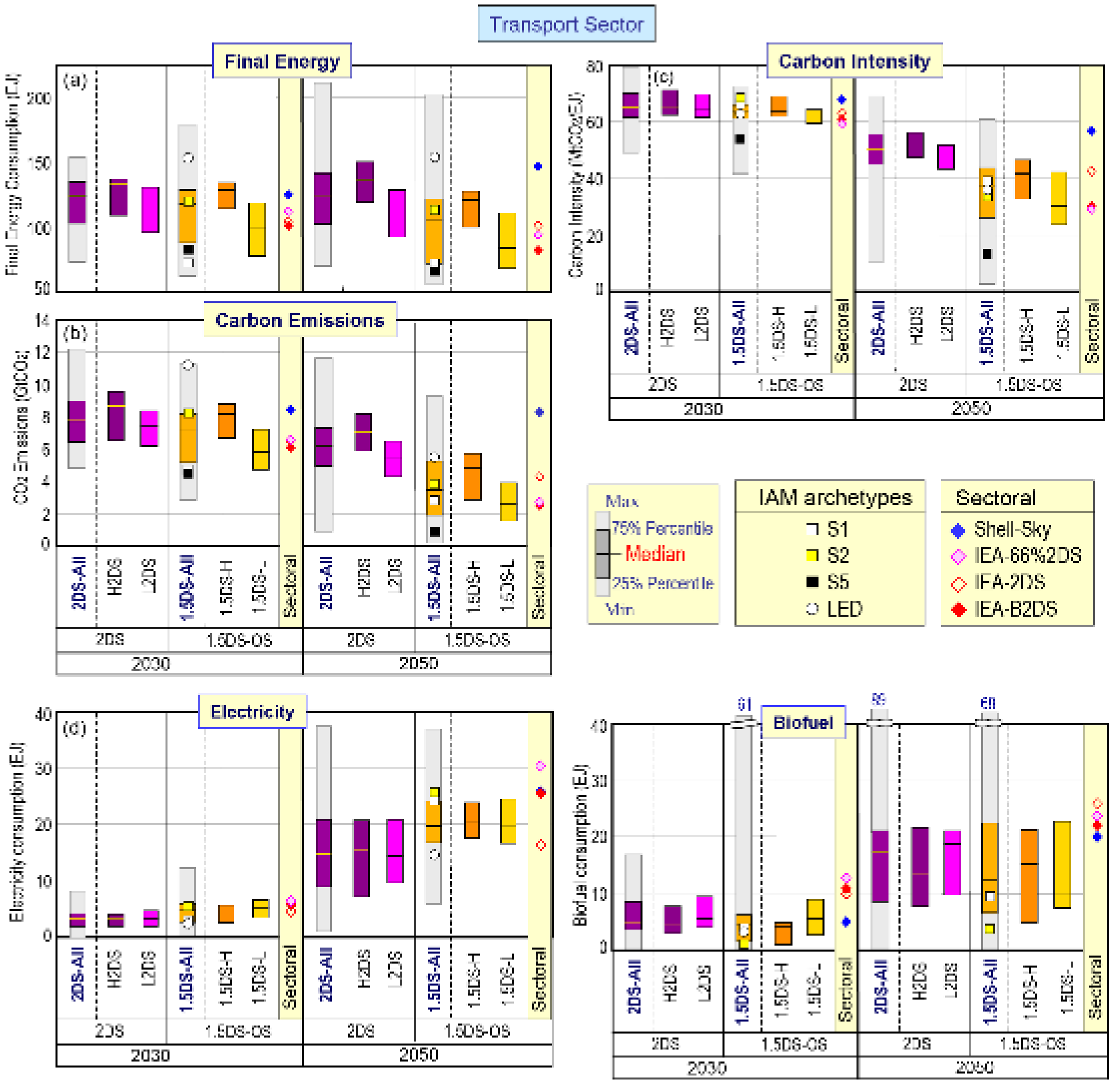


Figure 2.23: Comparison of (a) final energy, (b) direct CO_2 emissions, (c) carbon intensity, (d) electricity and biofuel consumption in the transport sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS: Higher-2°C, L2DS: Lower-2°C, 1.5DS-H: 1.5°C-high-OS, 1.5DS-L: 1.5°C-low-OS, 1.5DS = 1.5DS-OS: 1.5°C-consistent pathways with overshoot. Section 2.1 for descriptions.

1.5°C pathways require an acceleration of the mitigation solutions already featured in 2°C-consistent pathways (e.g., more efficient vehicle technologies operating on lower-carbon fuels), as well as those having received lesser attention in most global transport decarbonisation pathways up to now (e.g., mode-shifting and travel demand management). Current-generation, global pathways generally do not include these newer transport sector developments, whereby technological solutions are related to shifts in traveller's behaviour.

2.4.4 *Land-use transitions and changes in the agricultural sector*

The agricultural and land system described together under the umbrella of the AFOLU (Agriculture, Forestry, and Other Land Use) sector plays an important role in 1.5°C pathways (Clarke et al., 2014; Smith and Bustamante, 2014; Popp et al., 2017). On the one hand, its emissions need to be limited over the course of this century to be in line with pathways limiting warming to 1.5°C (see Sections 2.2-3). On the other hand, the AFOLU system is responsible for food and feed production, for wood production for pulp and construction, for the production of biomass that is used for energy, CDR or other uses, and for the supply of non-provisioning (ecosystem) services (Smith and Bustamante, 2014). Meeting all demands together requires changes in land use, as well as in agricultural and forestry practices, for which a multitude of potential options have been identified (Smith and Bustamante, 2014; Popp et al., 2017) (see also Annex 2.A.2 and Chapter 4, Section 4.3.1, 4.3.2 and 4.3.7).

This section assesses the transformation of the AFOLU system, mainly making use of pathways from IAMs (see Section 2.1) that are based on quantifications of the SSPs and that report distinct land-use evolutions in line with limiting warming to 1.5°C (Calvin et al., 2017; Fricko et al., 2017; Fujimori, 2017; Kriegler et al., 2017; Popp et al., 2017; Riahi et al., 2017; van Vuuren et al., 2017b; Doelman et al., 2018; Rogelj et al., 2018). The SSPs were designed to vary mitigation challenges (O'Neill et al., 2014) (Cross-Chapter Box 1.1), including for the AFOLU sector (Popp et al., 2017; Riahi et al., 2017). The SSP pathway ensemble hence allows for a structured exploration of AFOLU transitions in the context of climate change mitigation in line with 1.5°C, taking into account technological and socio-economic aspects. Other considerations, like food security, livelihoods and biodiversity, are also of importance when identifying AFOLU strategies. These are at present only tangentially explored by the SSPs. Further assessments of AFOLU mitigation options are provided in other parts of this report and in the IPCC AR6 Special Report on Climate Change and Land (SRCCL). Chapter 4 provides an assessment of bioenergy (including feedstocks, see Section 4.3.1), livestock management (Section 4.3.1), reducing rates of deforestation and other land-based mitigation options (as mitigation and adaptation option, see Section 4.3.2), and BECCS, Afforestation and Reforestation options (including the bottom-up literature of their sustainable potential, mitigation cost and side effects, Section 4.3.7). Chapter 3 discusses impacts land-based CDR (Cross-Chapter Box 7 in Chapter 3). Chapter 5 assesses the sustainable development implications of AFOLU mitigation, including impacts on biodiversity (Section 5.4). Finally, the SRCCL will undertake a more comprehensive assessment of land and climate change aspects. For the sake of complementarity, this section focusses on the magnitude and pace of land transitions in 1.5°C pathways, as well as on the implications of different AFOLU mitigation strategies for different land types. The interactions with other societal objectives and potential limitations of identified AFOLU measures link to these large-scale evolutions, but these are assessed elsewhere (see above).

Land-use changes until mid-century occur in the large majority of SSP pathways, both under stringent and in absence of mitigation (Figure 2.24). In the latter case, changes are mainly due to socio-economic drivers like growing demands for food, feed and wood products. General transition trends can be identified for many land types in 1.5°C pathways, which differ from those in baseline scenarios and depend on the interplay with mitigation in other sectors (Figure 2.24) (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Mitigation that demands land mainly occurs at the expense of agricultural land for food and feed production. Additionally, some biomass is projected to be grown on marginal land or supplied from residues and waste, but at lower shares. Land for second generation energy crops (such as miscanthus or poplar) expands by 2030 and 2050 in all available pathways that assume a cost-effective achievement of a 1.5°C temperature goal in 2100 (Figure 2.24), but the scale depends strongly on underlying socioeconomic assumptions (see later discussion of land pathway archetypes). Reducing rates of deforestation restricts agricultural expansion and forest cover can expand strongly in 1.5°C and 2°C pathways alike compared to its extent in no-climate policy baselines due to reduced deforestation, afforestation and reforestation measures. However, the extent to which forest cover expands varies highly across models in the literature, with some models projecting forest cover to stay virtually constant or decline slightly. This is due to whether afforestation and reforestation is included as a mitigation technology in these pathways and interactions with other sectors.

As a consequence of other land use changes, pasture land is generally projected to be reduced compared to both baselines in which no climate change mitigation action is undertaken and 2°C-consistent pathways. Furthermore, cropland for food and feed production decreases in most 1.5°C pathways, both compared to a no-climate baseline and relative to 2010. These reductions in agricultural land for food and feed production are facilitated by intensification on agricultural land and in livestock production systems (Popp et al., 2017), as well as changes in consumption patterns (Frank et al., 2017; Fujimori, 2017) (see also 4.3.2 for an assessment of these mitigation options). For example, in a scenario based on rapid technological progress (Kriegler et al., 2017), global average cereal crop yields in 2100 are assumed to be above 5 tDM/ha.yr in mitigation scenarios aiming at limiting end-of-century radiative forcing to 4.5 or 2.6 W/m^2, compared to 4 tDM/ha.yr in the SSP5 baseline to ensure the same food production. Similar improvements are present in 1.5°C variants of such scenarios. Historically, cereal crop yields are estimated at 1 tDM/ha.yr and ca. 3 tDM/ha.yr in 1965 and 2010, respectively (calculations based on FAOSTAT, 2017). For aggregate energy crops, models assume 4.2-8.9 tDM/ha.yr in 2010, increasing to about 6.9-17.4 tDM/ha.yr in 2050, which fall within the range found in the bottom-up literature yet depend on crop, climatic zone, land quality, and plot size (Searle and Malins, 2014).

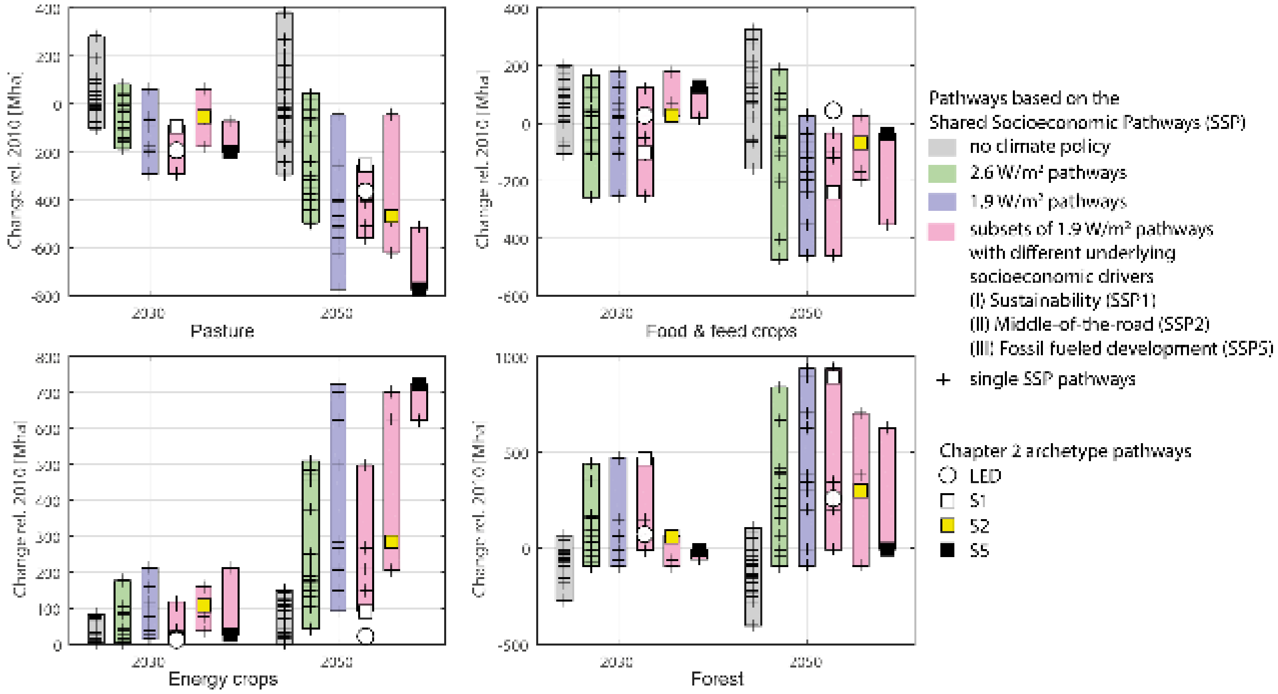


Figure 2.24: Overview of land-use change transitions in 2030 and 2050, relative to 2010 based on pathways based on the Shared Socioeconomic Pathways (SSP) (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Grey: no-climate-policy baseline; green: 2.6 W/m^2 pathways; blue: 1.9 W/m^2 pathways. Pink: 1.9 W/m^2 pathways grouped per underlying socioeconomic assumption (from left to right: SSP1 sustainability, SSP2 middle-of-the-road, SSP5 fossil-fuelled development). Ranges show the minimum-maximum range across the SSPs. Single pathways are shown with plus signs. Illustrative archetype pathways are highlighted with distinct icons. Each panel shows the changes for a different land type. 1.9 and 2.6 W/m^2 are taken as proxies for 1.5°C and 2°C pathways, respectively. 2.6 W/m^2 pathways are mostly consistent with the Lower-2°C and Higher-2°C pathway classes. 1.9 W/m^2 pathways are consistent with the 1.5°C-low-OS (mostly SSP1 and SSP2) and 1.5°C-high-OS (SSP5) pathway classes. In 2010, pasture was estimated to cover about 3-3.5 10^3 Mha, food and feed crops about 1.5-1.6 10^3 Mha, energy crops about 0-14 Mha and forest about 3.7-4.2 10^3 Mha, across the models that reported SSP pathways (Popp et al., 2017).

The pace of projected land transitions over the coming decades can differ strongly between 1.5°C and baseline scenarios without climate change mitigation and from historical trends (Table 2.9). However, there is uncertainty in the sign and magnitude of these future land-use changes (Prestele et al., 2016; Popp et al., 2017; Doelman et al., 2018). The pace of projected cropland changes overlaps with historical trends over the past four decades, but in several cases also goes well beyond this range. By the 2030-2050 period, the projected reductions in pasture and potentially strong increases in forest cover imply a reversed dynamic compared to historical and baseline trends. For forest increases, this suggests that distinct policy and government measures would be needed to achieve this, particularly in a context of projected increased bioenergy use.

Table 2.9: Annual pace of land-use change in baseline, 2°C and 1.5°C pathways. All values in Mha/yr. 2.6 W/m^2 pathways are mostly consistent with the Lower-2°C and Higher-2°C pathway classes. 1.9 W/m^2 pathways are broadly consistent with the 1.5°C-low-OS (mostly SSP1 and SSP2) and 1.5°C-high-OS (SSP5) pathway classes. Baseline projections reflect land-use developments projected by integrated assessment models under the assumptions of the Shared Socioeconomic Pathways (SSP) in absence of climate policies (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Values give the full range across SSP scenarios. According to the Food and Agriculture Organization of the United Nations (FAOSTAT, 2017), 4.9 billion hectares (approximately 40% of the land surface) was under agricultural use in 2005, either as cropland (1.5 billion hectares) or pasture (3.4 billion hectares). FAO data in the table are equally from FAOSTAT (2017).

Annual pace of land-use change [Mha yr^{-1}] Land type	**Pathway**	**Time window**		**Historical**	
		2010-2030	**2030-2050**	**1970-1990**	**1990-2010**
Pasture	1.9 W m^{-2}	[-14.6/3.0]	[-28.7/-5.2]	8.7	0.9
	2.6 W m^{-2}	[-9.3/4.1]	[-21.6/0.4]	Permanent meadows and pastures (FAO)	Permanent meadows and pastures (FAO)
	Baseline	[-5.1/14.1]	[-9.6/9.0]		
Cropland for food, feed and material	1.9 W m^{-2}	[-12.7/9.0]	[-18.5/0.1]		
	2.6 W m^{-2}	[-12.9/8.3]	[-16.8/2.3]		
	Baseline	[-5.3/9.9]	[-2.7/6.7]		
Cropland for energy	1.9 W m^{-2}	[0.7/10.5]	[3.9/34.8]		
	2.6 W m^{-2}	[0.2/8.8]	[2.0/22.9]		
	Baseline	[0.2/4.2]	[-0.2/6.1]		
Total cropland	1.9 W m^{-2}	[-6.8/12.8]	[-5.8/26.7]	4.6	0.9
(Sum of cropland for food	2.6 W m^{-2}	[-8.4/9.3]	[-7.1/17.8]	Arable land and Permanent crops	Arable land and Permanent crops
and feed & energy)	Baseline	[-3.0/11.3]	[0.6/11.0]		
Forest	1.9 W m^{-2}	[-4.8/23.7]	[0.0/34.3]	N.A.	-5.6
	2.6 W m^{-2}	[-4.7/22.2]	[-2.4/31.7]	Forest (FAO)	Forest (FAO)
	Baseline	[-13.6/3.3]	[-6.5/4.3]		

Changes of the AFOLU sector are driven by three main factors: demand changes, efficiency of production, and policy assumptions (Smith et al., 2013; Popp et al., 2017). Demand for agricultural products and other land-based commodities is influenced by consumption patterns (including dietary preferences and food waste affecting demand for food and feed) (Smith et al., 2013; van Vuuren et al., 2018), demand for forest products for pulp and construction (including less wood waste), and demand for biomass for energy production (Lambin and Meyfroidt, 2011; Smith and Bustamante, 2014). Efficiency of agricultural and forestry production relates to improvements in agricultural and forestry practices (including product cascades, by-products as well as more waste- and residue-based biomass for energy production), agricultural and forestry yield increases as well as intensification of livestock production systems leading to higher feed efficiency and changes in feed composition (Havlík et al., 2014; Weindl et al., 2015). Policy assumptions relate to the level of land protection, the treatment of food waste, policy choices about the timing of mitigation action (early vs late), the choice and preference of land-based mitigation options (for example, the inclusion of afforestation and reforestation as mitigation options), interactions with other sectors (Popp et al., 2017) and trade (Schmitz et al., 2012; Wiebe et al., 2015).

A global study (Stevanović et al., 2017) reported similar GHG reduction potentials for production (agricultural production measures in combination with reduced deforestation) and consumption side (diet change in combination with lower shares of food waste) measures of in the order of 40% in 2100[11] (compared to a baseline scenario without land-based mitigation). Lower consumption of livestock products by 2050 could also substantially reduce deforestation and cumulative carbon losses (Weindl et al., 2017). On

[11] FOOTNOTE: Land-based mitigation options on the supply and the demand side are assessed in 4.3.2 and CDR options with a land component in 4.3.7. Chapter 5 (Section 5.4) assesses the implications of land-based mitigation for related SDGs, e.g., food security.

the supply side, minor productivity growth in extensive livestock production systems is projected to lead to substantial CO_2 emission abatement, but the emission saving potential of productivity gains in intensive systems is limited, mainly due to trade-offs with soil carbon stocks (Weindl et al., 2017). In addition, even within existing livestock production systems, a transition from extensive to more productive systems bears substantial GHG abatement potential, while improving food availability (Gerber et al., 2013; Havlík et al., 2014). Many studies highlight the capability of agricultural intensification for reducing GHG emissions in the AFOLU sector or even enhancing terrestrial carbon stocks (Valin et al., 2013; Popp et al., 2014a; Wise et al., 2014). Also the importance of immediate and global land-use regulations for a comprehensive reduction of land-related GHG emissions (especially related to deforestation) has been shown by several studies (Calvin et al., 2017; Fricko et al., 2017; Fujimori, 2017). Ultimately, there are also interactions between these three factors and the wider society and economy, for example, if CDR technologies that are not land based are deployed (like direct air capture – DACCS, see Chapter 4, Section 4.3.7) or if other sectors over- or underachieve their projected mitigation contributions (Clarke et al., 2014). Variations in these drivers can lead to drastically different land-use implications (Popp et al., 2014b) (Figure 2.24).

Stringent mitigation pathways inform general GHG dynamics in the AFOLU sector. First, CO_2 emissions from deforestation can be abated at relatively low carbon prices if displacement effects in other regions (Calvin et al., 2017) or other land-use types with high carbon density (Calvin et al., 2014; Popp et al., 2014a; Kriegler et al., 2017) can be avoided. However, efficiency and costs of reducing rates of deforestation strongly depend on governance performance, institutions and macroeconomic factors (Wang et al., 2016). Secondly, besides CO_2 reductions, the land system can play an important role for overall CDR efforts (Rogelj et al., 2018) via BECCS, afforestation and reforestation, or a combination of options. The AFOLU sector also provides further potential for active terrestrial carbon sequestration, e.g., via land restoration, improved management of forest and agricultural land (Griscom et al., 2017), or biochar applications (Smith, 2016) (see also Section 4.3.7). These options have so far not been extensively integrated in the mitigation pathway literature (see Annex 2.A.2), but in theory their availability would impact the deployment of other CDR technologies, like BECCS (Section 2.3.4) (Strefler et al., 2018a). These interactions will be discussed further in the SRCCL.

Residual agricultural non-CO_2 emissions of CH_4 and N_2O play an important role for temperature stabilisation pathways and their relative importance increases in stringent mitigation pathways in which CO_2 is reduced to net zero emissions globally (Gernaat et al., 2015; Popp et al., 2017; Stevanović et al., 2017; Rogelj et al., 2018), for example, through their impact on the remaining carbon budget (Section 2.2). Although agricultural non-CO_2 emissions show marked reduction potentials in 2°C-consistent pathways, complete elimination of these emission sources does not occur in IAMs based on the evolution of agricultural practice assumed in integrated models (Figure 2.25) (Gernaat et al., 2015). CH_4 emissions in 1.5°C pathways are reduced through improved agricultural management (e.g., improved management of water in rice production, manure and herds, and better livestock quality through breeding and improved feeding practices) as well as dietary shifts away from emissions-intensive livestock products. Similarly, N_2O emissions decrease due to improved N-efficiency and manure management (Frank et al., 2018). However, high levels of bioenergy production can also result in increased N_2O emissions (Kriegler et al., 2017) highlighting the importance of appropriate management approaches (Davis et al., 2013). Residual agricultural emissions can be further reduced by limiting demand for GHG-intensive foods through shifts to healthier and more sustainable diets (Tilman and Clark, 2014; Erb et al., 2016b; Springmann et al., 2016) and reductions in food waste (Bajželj et al., 2014; Muller et al., 2017; Popp et al., 2017) (see also Chapter 4, and SRCCL). Finally, several mitigation measures that could affect these agricultural non-CO_2 emissions are not, or only to a limited degree, considered in the current integrated pathway literature (see Annex 2.A.2). Such measures (like plant-based and synthetic proteins, methane inhibitors and vaccines in livestock, alternate wetting and drying in paddy rice, or nitrification inhibitors) are very diverse and differ in their development or deployment stages. Their potentials have not been explicitly assessed here.

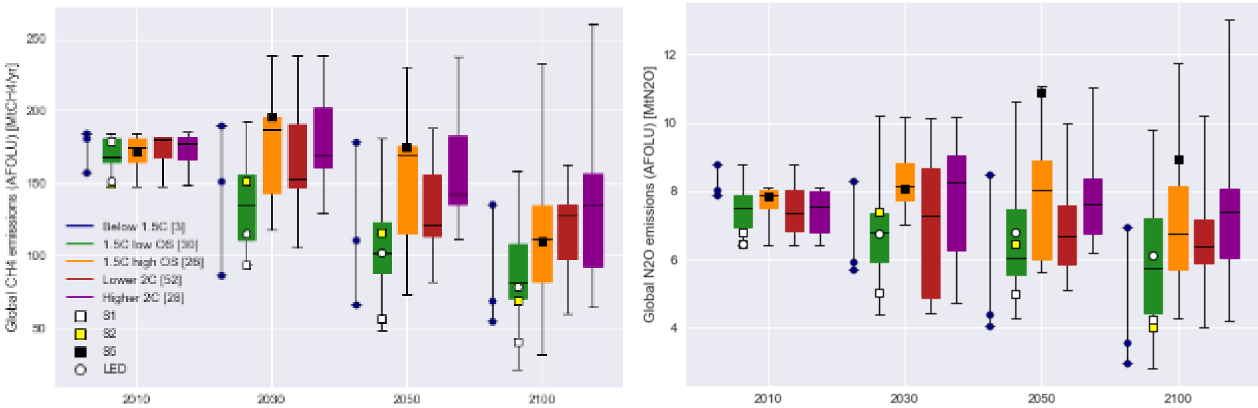


Figure 2.25: Agricultural emissions in transformation pathways. Global agricultural CH_4 (left) and N_2O (right) emissions. Boxplots show median, interquartile range and full range. Classes are defined in Section 2.1.

Pathways consistent with 1.5°C rely on one or more of the three strategies highlighted above (demand changes, efficiency gains, and policy assumptions), and can apply these in different configurations. For example, among the four illustrative archetypes used in this chapter (Section 2.1) the LED and S1 pathways focus on generally low resource and energy consumption (including healthy diets with low animal-calorie shares and low food waste) as well as significant agricultural intensification in combination with high levels of nature protection. Under such assumptions, comparably small amounts of land are needed for land demanding mitigation activities such as BECCS and afforestation and reforestation, leaving the land footprint for energy crops in 2050 virtually the same compared to 2010 levels for the LED pathway. In contrast, future land-use developments can look very differently under the resource- and energy-intensive S5 pathway that includes unhealthy diets with high animal shares and high shares of food waste (Tilman and Clark, 2014; Springmann et al., 2016) combined with a strong orientation towards technology solutions to compensate for high reliance on fossil-fuel resources and associated high levels of GHG emissions in the baseline. In such pathways, climate change mitigation strategies strongly depend on the availability of CDR through BECCS (Humpenöder et al., 2014). As a consequence, the S5 pathway sources significant amounts of biomass through bioenergy crop expansion in combination with agricultural intensification. Also, further policy assumptions can strongly affect land-use developments, highlighting the importance for land use of making appropriate policy choices. For example, within the SSP set, some pathways rely strongly on a policy to incentivise afforestation and reforestation for CDR together with BECCS, which results in an expansion of forest area and a corresponding increase in terrestrial carbon stock. Finally, the variety of pathways illustrates how policy choices in the AFOLU and other sectors strongly affect land-use developments and associated sustainable development interactions (Section 5.4) in 1.5°C pathways.

The choice of strategy or mitigation portfolio impacts the GHG dynamics of the land system and other sectors (see Section 2.3), as well as the synergies and trade-offs with other environmental and societal objectives (see Section 2.5.3 and Section 5.4). For example, AFOLU developments in 1.5°C pathways range from strategies that differ almost an order of magnitude in their projected land requirements for bioenergy (Figure 2.24), and some strategies would allow an increase in forest cover over the 21st century compared to strategies under which forest cover remains approximately constant. High agricultural yields and application of intensified animal husbandry, implementation of best-available technologies for reducing non-CO_2 emissions, or lifestyle changes including a less-meat-intensive diet and less CO_2-intensive transport modes, have been identified to allow for such a forest expansion and reduced footprints from bioenergy without compromising food security (Frank et al., 2017; Doelman et al., 2018; van Vuuren et al., 2018).

The IAMs used in the pathways underlying this assessment (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018) do not include all potential land-based mitigation options and side-effects, and their results are hence subject to uncertainty. For example, recent research has highlighted the potential impact of forest management practices on land carbon content (Erb et al., 2016a; Naudts et al., 2016) and the uncertainty surrounding future crop yields (Haberl et al., 2013; Searle and Malins, 2014), and water availability (Liu et al., 2014). These aspects are included in IAMs in varying degrees, but were not assessed in this report. Furthermore, land-use modules of some IAMs can depict spatially resolved climate damages to agriculture (Nelson et al., 2014), but this option was not used in the SSP quantifications (Riahi et al., 2017). Damages (e.g., due to ozone exposure or varying indirect fertilization due to atmospheric N and Fe deposition (e.g., Shindell et al., 2012; Mahowald et al., 2017) are also not included. Finally, this assessment did not look into the literature of agricultural sector models which could provide important additional detail and granularity to the here presented discussion[12]. This limits their ability to capture the full mitigation potentials and benefits between scenarios. An in-depth assessment of these aspects lies outside the scope of this Special Report. However, their existence affects the confidence assessment of the AFOLU transition in 1.5°C pathways.

Despite the limitations of current modelling approaches, there is *high agreement* and *robust evidence* across models and studies that the AFOLU sector plays an important role in stringent mitigation pathways. The findings from these multiple lines of evidence also result in *high confidence* that AFOLU mitigation strategies can vary significantly based on preferences and policy choices, facilitating the exploration of strategies that can achieve multiple societal objectives simultaneously (see also Section 2.5.3). At the same time, given the many uncertainties and limitations, only *low to medium confidence* can be attributed by this assessment to the more extreme AFOLU developments found in the pathway literature, and *low to medium confidence* to the level of residual non-CO_2 emissions.

[12] FOOTNOTE: For example, the GLEAM (http://www.fao.org/gleam/en/) model from the UN Food and Agricultural Organisation (FAO).

2.5 Challenges, opportunities and co-impacts of transformative mitigation pathways

This section examines aspects other than climate outcomes of 1.5°C mitigation pathways. Focus is given to challenges and opportunities related to policy regimes, price of carbon and co-impacts, including sustainable development issues, which can be derived from the existing integrated pathway literature. Attention is also given to uncertainties and critical assumptions underpinning mitigation pathways. The challenges and opportunities identified in this section are further elaborated Chapter 4 (e.g., policy choice and implementation) and Chapter 5 (e.g., sustainable development). The assessment indicates unprecedented policy and geopolitical challenges.

2.5.1 Policy frameworks and enabling conditions

Moving from a 2°C to a 1.5°C pathway implies bold integrated policies that enable higher socio-technical transition speeds, larger deployment scales, and the phase-out of existing systems that may lock in emissions for decades (Geels et al., 2017; Kuramochi et al., 2017; Rockström et al., 2017; Vogt-Schilb and Hallegatte, 2017; Kriegler et al., 2018b; Michaelowa et al., 2018) (*high confidence*). This requires higher levels of transformative policy regimes in the near term, which allow deep decarbonisation pathways to emerge and a net zero carbon energy-economy system to emerge in the 2040–2060 period (Rogelj et al., 2015b; Bataille et al., 2016b). This enables accelerated levels of technological deployment and innovation (Geels et al., 2017; IEA, 2017a; Grubler et al., 2018) and assumes more profound behavioural, economic and political transformation (Sections 2.3, 2.4 and 4.4). Despite inherent levels of uncertainty attached to modelling studies (e.g., related to climate and carbon-cycle response), studies stress the urgency for transformative policy efforts to reduce emissions in the short term (Riahi et al., 2015; Kuramochi et al., 2017; Rogelj et al., 2018).

The available literature indicates that mitigation pathways in line with 1.5°C-consistent pathways would require stringent and integrated policy interventions (*very high confidence*). Higher policy ambition often takes the form of stringent economy-wide emission targets (and resulting peak-and-decline of emissions), larger coverage of NDCs to more gases and sectors (e.g., land-use, international aviation), much lower energy and carbon intensity rates than historically seen, carbon prices much higher than the ones observed in real markets, increased climate finance, global coordinated policy action, and implementation of additional initiatives (e.g., by non-state actors) (Sections 2.3, 2.4 and 2.5.2). The diversity (beyond carbon pricing) and effectiveness of policy portfolios are of prime importance, particularly in the short-term (Mundaca and Markandya, 2016; Kuramochi et al., 2017; OECD, 2017; Kriegler et al., 2018b; Michaelowa et al., 2018). For instance, deep decarbonisation pathways in line with a 2˚C target (covering 74% of global energy-system emissions) include a mix of stringent regulation (e.g., building codes, minimum performance standards), carbon pricing mechanisms and R&D (research and development) innovation policies (Bataille et al., 2016a). Carbon pricing, direct regulation and public investment to enable innovation are critical for deep decarbonisation pathways (Grubb et al., 2014). Effective planning (including compact city measures) and integrated regulatory frameworks are also key drivers in the IEA-ETP B2DS study for the transport sector (IEA, 2017a). Effective urban planning can reduce GHG emissions from urban transport between 20% and 50% (Creutzig, 2016). Comprehensive policy frameworks would be needed if the decarbonisation of the power system is pursued while increasing end-use electrification (including transport) (IEA, 2017a). Technology policies (e.g., feed-in-tariffs), financing instruments, carbon pricing and system integration management driving the rapid adoption of renewable energy technologies are critical for the decarbonisation of electricity generation (Bruckner et al., 2014; Luderer et al., 2014; Creutzig et al., 2017; Pietzcker et al., 2017). Likewise, low-carbon and resilient investments are facilitated by a mix of coherent policies including fiscal and structural reforms (e.g., labour markets), public procurement, carbon pricing, stringent standards, information schemes, technology policies, fossil-fuel subsidy removal, climate risk disclosure, and land-use and transport planning (OECD, 2017). Pathways in which CDR options are restricted emphasise the strengthening of near-term policy mixes (Luderer et al., 2013; Kriegler et al., 2018b). Together with the decarbonisation of the supply side, ambitious policies targeting fuel switching and energy efficiency improvements on the demand side play a major role across mitigation pathways (Clarke et al., 2014; Kriegler et al., 2014b; Riahi et al., 2015; Kuramochi et al., 2017; Brown and Li, 2018; Rogelj et al., 2018; Wachsmuth and Duscha, 2018).

The combined evidence suggests that aggressive policies addressing energy efficiency are central in keeping 1.5°C within reach and lowering energy system and mitigation costs (Luderer et al., 2013; Rogelj et al., 2013b, 2015b; Grubler et al., 2018) (*high confidence*). Demand-side policies that increase energy efficiency or limit energy demand at a higher rate than historically observed are critical enabling factors reducing mitigation costs for stringent mitigation pathways across the board (Luderer et al., 2013; Rogelj et al., 2013b, 2015b; Clarke et al., 2014; Bertram et al., 2015a; Bataille et al., 2016b). Ambitious sector-specific mitigation policies in industry, transportation and residential sectors are needed in the short run for emissions to peak in 2030 (Méjean et al., 2018). Stringent demand-side policies (e.g., tightened efficiency standards for buildings and appliances) driving the expansion, efficiency and provision of high-quality energy services are essential to meet a 1.5˚C mitigation target while avoiding the need of CDR (Grubler et al., 2018). A 1.5˚C pathway for the transport sector is possible using a mix of additional and stringent policy actions preventing (or reducing) the need for transport, encouraging shifts towards efficient modes of transport, and improving vehicle-fuel efficiency (Ghota et al., 2018). Stringent demand-side policies also reduce the need for CCS (Wachsmuth and Duscha, 2018). Even in the presence of weak-near term policy frameworks, increased energy efficiency lowers mitigation costs noticeably compared to pathways with reference energy intensity (Bertram et al., 2015a). Horizontal issues in the literature relate to the rebound effect, the potential overestimation of the effectiveness of energy efficiency policy, and policies to counteract the rebound (Saunders, 2015; van den Bergh, 2017; Grubler et al., 2018) (Sections 2.4 and 4.4).

SSP-based modelling studies underline that socio-economic and climate policy assumptions strongly influence mitigation pathway characteristics and the economics of achieving a specific climate target (Bauer et al., 2017; Guivarch and Rogelj, 2017; Riahi et al., 2017; Rogelj et al., 2018) (*very high confidence*). SSP assumptions related to economic growth and energy intensity are critical determinants of projected CO_2 emissions (Marangoni et al., 2017). A multi-model inter-comparison study found that mitigation challenges in line with a 1.5˚C target vary substantially across SSPs and policy assumptions (Rogelj et al., 2018). Under SSP1-SPA1 (sustainability) and SSP2-SPA2 (middle-of-the-road), the majority of IAMs were capable of producing 1.5˚C pathways. On the contrary, none of the IAMs contained in the SR1.5 database could produce a 1.5°C pathway under SSP3-SPA3 assumptions. Preventing elements include, for instance, climate policy fragmentation, limited control of land-use emissions, heavy reliance on fossil fuels, unsustainable consumption and marked inequalities (Rogelj et al., 2018). Dietary aspects of the SSPs are also critical: climate-friendly diets were contained in 'sustainability' (SSP1) and meat-intensive diets in SSP3 and SSP5 (Popp et al., 2017). CDR requirements are reduced under 'sustainability' related assumptions (Strefler et al., 2018b). These are major policy-related factors for why SSP1-SPA1 translates into relatively low mitigation challenges whereas SSP3-SPA3 and SSP5-SPA5 entail futures that pose the highest socio-technical and economic challenges. SSPs/SPAs assumptions indicate that policy-driven pathways that encompass accelerated change away from fossil fuels, large-scale deployment of low-carbon energy supplies, improved energy efficiency and sustainable consumption lifestyles reduce the risks of climate targets becoming unreachable (Clarke et al., 2014; Riahi et al., 2015, 2017; Marangoni et al., 2017; Rogelj et al., 2017, 2018; Strefler et al., 2018b).

Policy assumptions that lead to weak or delayed mitigation action from what would be possible in a fully cooperative world, strongly influence the achievability of mitigation targets (Luderer et al., 2013; Rogelj et al., 2013; OECD, 2017; Holz et al., 2018a; Strefler et al., 2018b) (*high confidence*). Such regimes also include current NDCs (Fawcett et al., 2015; Aldy et al., 2016; Rogelj et al., 2016a, 2017; Hof et al., 2017; van Soest et al., 2017), which have been reported to make achieving a 2°C pathway unattainable without CDR (Strefler et al., 2018b). Not strengthening NDCs make it very challenging to keep 1.5°C within reach (see Section 2.3 and Cross-Chapter Box 11 in Chapter 4). One multi-model inter-comparison study (Luderer et al., 2016b, 2018) explored the effects on 1.5°C pathways assuming the implementation of current NDCs until 2030 and stringent reductions thereafter. It finds that delays in globally coordinated actions leads to various models reaching no 1.5°C-consistent pathways during the 21st century. Transnational emission reduction initiatives (TERIs) outside the UNFCCC have also been assessed and found to overlap (70–80%) with NDCs and be inadequate to bridge the gap between NDCs and a 2˚C pathway (Roelfsema et al., 2018). Weak and fragmented short-term policy efforts use up a large share of the long-term carbon budget before 2030–2050 (Bertram et al., 2015a; van Vuuren et al., 2016) and increase the need for the full portfolio of mitigation measures, including CDR (Clarke et al., 2014; Riahi et al., 2015; Xu and Ramanathan, 2017). Furthermore, fragmented policy scenarios also exhibit 'carbon leakage' via energy and capital markets (Arroyo-Currás et al., 2015; Kriegler et al., 2015b). A lack of integrated policy portfolios can increase the risks of trade-offs between mitigation approaches and sustainable development objectives (see Sections 2.5.3 and 5.4). However, more detailed analysis is needed about realistic (less disruptive) policy trajectories until 2030 that can strengthen near-term mitigation action and meaningfully decrease post-2030 challenges (see Section 4.4).

Whereas the policy frameworks and enabling conditions identified above pertain to the 'idealised' dimension of mitigation pathways, aspects related to 1.5°C mitigation pathways in practice are of prime importance. For example, issues related to second-best stringency levels, international cooperation, public acceptance, distributional consequences, multi-level governance, non-state actions, compliance levels, capacity building, rebound effects, linkages across highly heterogeneous policies, sustained behavioural change, finance and intra- and inter-generational issues need to be considered (Somanthan et al., 2014; Bataille et al., 2016a; Mundaca and Markandya, 2016; Baranzini et al., 2017; van den Bergh, 2017; Vogt-Schilb and Hallegatte, 2017; Chan et al., 2018; Holz et al., 2018a; Klinsky and Winkler, 2018; Michaelowa et al., 2018; Patterson et al., 2018) (see Section 4.4). Furthermore, policies interact with a wide portfolio of pre-existing policy instruments that address multiple areas (e.g., technology markets, economic growth, poverty alleviation, climate adaptation) and deal with various market failures (e.g., information asymmetries) and behavioural aspects (e.g., heuristics) that prevent or hinder mitigation actions (Kolstad et al., 2014; Mehling and Tvinnereim, 2018). The socio-technical transition literature points to multiple complexities in real-world settings that prevent reaching 'idealised' policy conditions but at the same time can still accelerate transformative change through other co-evolutionary processes of technology and society (Geels et al., 2017; Rockström et al., 2017). Such co-processes are complex and go beyond the role of policy (including carbon pricing) and comprise the role of citizens, businesses, stakeholder groups or governments, as well as the interplay of institutional and socio-political dimensions (Michaelowa et al., 2018; Veland et al., 2018). It is argued that large system transformations, similar to those in 1.5°C pathways, require prioritizing an evolutionary and behavioural framework in economic theory rather than an optimization or equilibrium framework as is common in current IAMs (Grubb et al., 2014; Patt, 2017). Accumulated know-how, accelerated innovation and public investment play a key role in (rapid) transitions (Geels et al., 2017; Michaelowa et al., 2018) (see Sections 4.2 and 4.4).

In summary, the emerging literature supports the AR5 on the need for integrated, robust and stringent policy frameworks targeting both the supply and demand-side of energy-economy systems (*high confidence*). Continuous ex-ante policy assessments provide learning opportunities for both policy makers and stakeholders.

[START CROSS CHAPTER BOX 5 HERE]

Cross-Chapter Box 5: Economics of 1.5°C Pathways and the Social Cost of Carbon

Luis Mundaca (Sweden/Chile), Mustafa Babiker (Sudan), Johannes Emmerling (Germany/Italy), Sabine Fuss (Germany), Jean-Charles Hourcade (France), Elmar Kriegler (Germany), Anil Markandya (UK/Spain), Joyashree Roy (India), Drew Shindell (USA)

Two approaches have been commonly used to assess alternative emissions pathways: **cost-effectiveness analysis (CEA)** and **cost-benefit analysis (CBA)**. **CEA** aims at identifying emissions pathways minimising the total mitigation costs of achieving a given warming or GHG limit (Clarke et al., 2014). **CBA** has the goal to identify the optimal emissions trajectory minimising the discounted flows of abatement expenditures and monetised climate change damages (Boardman, 2006; Stern, 2007). A third concept, the **Social Cost of Carbon (SCC)** measures the total net damages of an extra metric ton of CO_2 emissions due to the associated climate change (Nordhaus, 2014; Pizer et al., 2014; Rose et al., 2017a). Negative and positive impacts are monetised, discounted and the net value is expressed as an equivalent loss of consumption today. The SCC can be evaluated for any emissions pathway under policy consideration (Rose, 2012; NASEM, 2016, 2017).

Along the optimal trajectory determined by CBA, the SCC equals the discounted value of the marginal abatement cost of a metric ton of CO_2 emissions. Equating the present value of future damages and marginal abatement costs includes a number of critical value judgments in the formulation of the social welfare function (SWF), particularly in how non-market damages and the distribution of damages across countries and individuals and between current and future generations are valued (Kolstad et al., 2014). For example, since climate damages accrue to a larger extent in the farther future and can persist for many years, assumptions and approaches to determine the social discount rate (normative 'prescriptive' vs. positive 'descriptive') and social welfare function (e.g., discounted utilitarian SWF vs. undiscounted prioritarian SWF) can heavily influence CBA outcomes and associated estimates of SCC (Kolstad et al., 2014; Pizer et al., 2014; Adler and Treich, 2015; Adler et al., 2017; NASEM, 2017; Nordhaus, 2017; Rose et al., 2017a).

In CEA, the marginal abatement cost of carbon is determined by the climate goal under consideration. It equals the shadow price of carbon associated with the goal which in turn can be interpreted as the willingness to pay for imposing the goal as a political constraint. Emissions prices are usually expressed in carbon (equivalent) prices using the GWP-100 metric as the exchange rate for pricing emissions of non-CO_2 GHGs controlled under internationally climate agreements (like CH_4, N_2O and fluorinated gases, see Cross-Chapter Box 1.2)[13]. Since policy goals like the goals of limiting warming to 1.5°C or well below 2°C do not directly result from a money metric trade-off between mitigation and damages, associated shadow prices can differ from the SCC in a CBA. In CEA, value judgments are to a large extent concentrated in the choice of climate goal and related implications, while more explicit assumptions about social values are required to perform CBA. For example, assumptions about the social discount rate no longer affect the overall abatement levels now set by the climate goal, but the choice and timing of investments in individual measures to reach these levels.

Although CBA-based and CEA-based assessment are both subject to large uncertainty about socio-techno-economic trends, policy developments and climate response, the range of estimates for the SCC along an optimal trajectory determined by CBA is far higher than for estimates of the shadow price of carbon in CEA-based approaches. In CBA, the value judgments about inter- and intra-generational equity combined with uncertainties in the climate damage functions assumed, including their empirical basis, are important (Pindyck, 2013; Stern, 2013; Revesz et al., 2014). In a CEA-based approach, the value judgments about the aggregate welfare function matter less and uncertainty about climate response and impacts can be tied into various climate targets and related emissions budgets (Clarke et al., 2014).

The CEA- and CBA-based carbon cost estimates are derived with a different set of tools. They are all summarised as integrated assessment models (IAMs) but in fact are of very different nature (Weyant, 2017). Detailed process IAMs such as AIM (Fujimori, 2017), GCAM (Thomson et al., 2011; Calvin et al., 2017), IMAGE (van Vuuren et al., 2011b, 2017b), MESSAGE-GLOBIOM (Riahi et al., 2011; Havlík et al., 2014; Fricko et al., 2017), REMIND-MAgPIE (Popp et al., 2010; Luderer et al., 2013; Kriegler et al., 2017) and WITCH (Bosetti et al., 2006, 2008, 2009) include a process-based representation of energy and land systems, but in most cases lack a comprehensive representation of climate damages, and are typically used for CEA. Diagnostic analyses across CBA-IAMs indicate important dissimilarities in modelling assembly, implementation issues and behaviour (e.g., parametric uncertainty, damage responses, income sensitivity) that need to be recognised to better understand SCC estimates (Rose et al., 2017a).

CBA-IAMs such as DICE (Nordhaus and Boyer, 2000; Nordhaus, 2013, 2017), PAGE (Hope, 2006) and FUND (Tol, 1999; Anthoff and Tol, 2009) attempt to capture the full feedback from climate response to socio-economic damages in an aggregated manner, but are usually much more stylised than detailed process IAMs. In a nutshell, the methodological framework for estimating SCC involves projections of population growth, economic activity and resulting emissions; computations of atmospheric composition and global-mean temperatures as a result of emissions; estimations of physical impacts of climate changes; monetisation of impacts (positive and negative) on human welfare; and the discounting of the future monetary value of impacts to year of emission (Kolstad et al., 2014; Revesz et al., 2014; NASEM, 2017; Rose et al., 2017a). There has been a discussion in the literature to what extent CBA-IAMs underestimate the SCC due to, for example, a limited treatment or difficulties in addressing damages to human well-being, labour productivity, value of capital stock, ecosystem services and the risks of catastrophic climate change for future generations (Ackerman and Stanton, 2012; Revesz et al., 2014; Moore and Diaz, 2015; Stern, 2016). However, there has been progress in 'bottom-up' empirical analyses of climate damages (Hsiang et al., 2017), the insights of which could be integrated into these models (Dell et al., 2014). Most of the models used in Chapter 2 on 1.5°C mitigation pathways are detailed process IAMs and thus deal with CEA.

[13] FOOTNOTE: Also other metrics to compare emissions have been suggested and adopted by governments nationally (Kandlikar, 1995; Marten et al., 2015; Shindell, 2015; Interagency Working Group on Social Cost of Greenhouse Gases, 2016).

An important question is how results from CEA- and CBA-type approaches can be compared and synthesised. Such synthesis needs to be done with care, since estimates of the shadow price of carbon under the climate goal and SCC estimates from CBA might not be directly comparable due to different tools, approaches and assumptions used to derive them. Acknowledging this caveat, the SCC literature has identified a range of factors, assumptions and value judgements that support SCC values above \$100 tCO_2^{-1} that are also found as net present values of the shadow price of carbon in 1.5°C pathways. These factors include accounting for tipping points in the climate system (Lemoine and Traeger, 2014; Cai et al., 2015; Lontzek et al., 2015), a low social discount rate (Nordhaus, 2005; Stern, 2007) and inequality aversion (Schmidt et al., 2013; Dennig et al., 2015; Adler et al., 2017).

The SCC and the shadow price of carbon are not merely theoretical concepts but used in regulation (Pizer et al., 2014; Revesz et al., 2014; Stiglitz et al., 2017). As stated by the report of the High-Level Commission on Carbon Pricing (Stiglitz et al., 2017), in the real world there is a distinction to be made between the implementable and efficient explicit carbon prices and the implicit (notional) carbon prices to be retained for policy appraisal and the evaluation of public investments, as is already done in some jurisdictions such as the USA, UK and France. Since 2008, the U.S. government has used SCC estimates to assess the benefits and costs related to CO_2 emissions resulting from federal policymaking (NASEM, 2017; Rose et al., 2017a).

The use of the SCC for policy appraisals is however not straightforward in an SDG context. There are suggestions that a broader range of polluting activities than only CO_2 emissions, for example emissions of air pollutants, and a broader range of impacts than only climate change, such as impacts on air quality, health and sustainable development in general (see Chapter 5 for a detailed discussion), would need to be included in social costs (Sarofim et al., 2017; Shindell et al., 2017a). Most importantly, a consistent valuation of the SCC in a sustainable development framework would require accounting for the SDGs in the social welfare formulation (see Chapter 5).

[END CROSS CHAPTER BOX 5 HERE]

2.5.2 Economic and financial implications of 1.5°C Pathways

2.5.2.1 Price of carbon emissions

The price of carbon assessed here is fundamentally different from the concepts of optimal carbon price in a cost-benefit analysis, or the social cost of carbon (see Cross-Chapter Box 5 in this Chapter and Section 3.5.2). Under a cost-effective analysis (CEA) modelling framework, prices for carbon (mitigation costs) reflect the stringency of mitigation requirements at the margin (i.e., cost of mitigating one extra unit of emission).

Based on data available for this special report, the price of carbon varies substantially across models and scenarios, and their value increase with mitigation efforts (see Figure 2.26) (*high confidence*). For instance, undiscounted values under a Higher-2˚C pathway range from 10–200 USD_{2010} $tCO_{2\text{-eq}}{}^{-1}$ in 2030, 45–960 USD_{2010} $tCO_{2\text{-eq}}{}^{-1}$ in 2050, 120–1000 USD_{2010} $tCO_{2\text{-eq}}{}^{-1}$ in 2070 and 160–2125 USD_{2010} $tCO_{2\text{-eq}}{}^{-1}$ in 2100. On the contrary, estimates for a Below-1.5˚C pathway range from 135–5500 USD_{2010} $tCO_{2\text{-eq}}{}^{-1}$ in 2030, 245–13000 USD_{2010} $tCO_{2\text{-eq}}{}^{-1}$ in 2050, 420–17500 USD_{2010} $tCO_{2\text{-eq}}{}^{-1}$ in 2070 and 690–27000 USD_{2010} $tCO_{2\text{-eq}}{}^{-1}$ in 2100. One can also observe that values for 1.5°C-low-OS pathway are relatively higher than 1.5°C-high-OS pathway in 2030, but the difference decreases over time. This is because in 1.5°C-high-OS pathways there is relatively less mitigation activity in the first half of the century, but more in the second half. *LED* exhibits the lowest values across the illustrative pathway archetypes. As a whole, the average discounted price of emissions across 1.5˚C- and 2˚C pathways differs by a factor of four across models (assuming a 5% annual discount rate). If values from 1.5˚C-high-OS pathways (with peak warming 0.1–0.4°C higher than 1.5°C) or pathways with very large land-use sinks are kept in the 1.5˚C pathway superclass, the differential value is reduced to a limited degree, from a factor 4 to a factor 3. The increase in carbon prices between 1.5°C- and 2°C-consistent pathways is based on a direct comparison of pathway pairs from the same model and the same study in which the 1.5°C-consistent pathway assumes a significantly smaller carbon budget compared to the 2°C-consistent pathway (e.g., 600 $GtCO_2$ smaller in the CD-LINKS and ADVANCE studies). This assumption is the main driver behind the increase in the price of carbon (Luderer et al., 2018; McCollum et al., 2018).[14] Considering incomplete and uncertain information, an optimal price of carbon of the magnitude estimated in modelling studies needs to be compared with what is politically and institutionally feasible (see Section 4.4.5.2).

The wide range of values depends on numerous aspects, including methodologies, projected energy service demands, mitigation targets, fuel prices and technology availability (Clarke et al., 2014; Kriegler et al., 2015b; Rogelj et al., 2015c; Riahi et al., 2017; Stiglitz et al., 2017) (*high confidence*). The characteristics of the technology portfolio, particularly in terms of investment costs and deployment rates play a key role (Luderer et al., 2013, 2016a; Clarke et al., 2014; Bertram et al., 2015a; Riahi et al., 2015; Rogelj et al., 2015c). Models that encompass a higher degree of technology granularity and that entail more flexibility regarding mitigation response, often produce relatively lower mitigation costs than those that show less flexibility from a technology perspective (Bertram et al., 2015a; Kriegler et al., 2015a). Pathways providing high estimates often have limited flexibility of substituting fossil fuels with low-carbon technologies and the associated need to compensate fossil-fuel emissions with CDR. Emission prices are also sensitive to the non-availability of BECCS (Bauer et al., 2018). Furthermore, and due to the treatment of future price anticipation, recursive-dynamic modelling approaches (with 'myopic anticipation') exhibit higher prices in the short term but modest increases in the long term compared to optimisation modelling frameworks with 'perfect foresight' that show exponential pricing trajectories (Guivarch and Rogelj, 2017). The chosen social discount rate in CEA studies (range of 2–8% per year in the reported data, varying over time and sectors) can also affect the choice and timing of investments in mitigation measures (Clarke et al., 2014; Kriegler et al., 2015b; Weyant, 2017). However, the impacts of varying discount rates on 1.5°C (and 2˚C) mitigation strategies can only be assessed to a limited degree. The above highlights the importance of sampling bias in pathway analysis ensembles towards outcomes derived from models which are more flexible, have more mitigation options and cheaper cost assumptions and thus can provide feasible pathways in contrast to other who are unable to do so (Tavoni and Tol, 2010; Clarke et al., 2014; Bertram et al., 2015a; Kriegler et al., 2015a; Guivarch and Rogelj, 2017). All CEA-based IAM studies reveal no unique carbon pricing path (Bertram et al., 2015a; Kriegler et al., 2015b; Akimoto et al., 2017; Riahi et al., 2017).

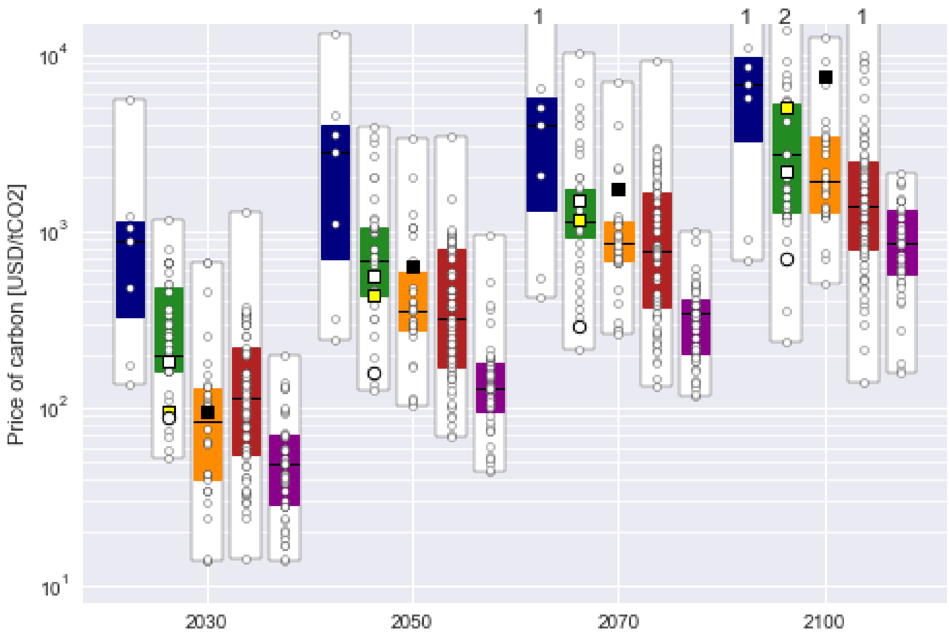
Socio-economic conditions and policy assumptions also influence the price of carbon (Bauer et al., 2017; Guivarch and Rogelj, 2017; Hof et al., 2017; Riahi et al., 2017; Rogelj et al., 2018) (*very high confidence*). A multi-model study (Riahi et al., 2017) estimated the average discounted price of carbon (2010-2100, 5% discount rate) for a 2˚C target to be nearly three times higher in the SSP5 marker than in the SSP1 marker. Another multi-model study (Rogelj et al., 2018) estimated average discounted carbon prices (2020-2100, 5%) to be 35–65% lower in SSP1 compared to SSP2 in 1.5˚C pathways. Delayed near-term mitigation policies and measures, including the limited extent of international global cooperation, increases total economic mitigation costs, and corresponding prices of carbon (Luderer et al., 2013; Clarke et al., 2014). This is because stronger efforts are required in the period after the delay to counterbalance the higher emissions in the near term. Staged accession scenarios also produce higher carbon prices than immediate action mitigation scenarios under the same stringency level of emissions (Kriegler et al., 2015b). In addition, the revenue recycling effect of carbon pricing can reduce mitigation costs by displacing distortionary taxes (Baranzini et al., 2017; OECD, 2017; McFarland et al., 2018; Sands, 2018; Siegmeier et al., 2018) and the reduction of capital tax (compared to a labour tax) can yield greater savings in welfare costs (Sands, 2018). The effect on public budgets is particularly important in the near term, however it can decline in the long term as carbon neutrality is achieved (Sands, 2018).

It has been long argued that carbon pricing (whether via a tax or cap-and-trade scheme) can theoretically achieve cost-effective emission reductions (Nordhaus, 2007; Stern, 2007; Aldy and Stavins, 2012; Goulder and Schein, 2013; Somanthan et al., 2014; Weitzman, 2014; Tol, 2017). Whereas the integrated assessment literature is mostly focused on the role of carbon pricing to reduce emissions (Clarke et al., 2014; Riahi et al., 2017; Weyant, 2017) there is an emerging body of studies (including bottom-up approaches) that focuses on the interaction and performance of various policy mixes (e.g., regulation, subsidies, standards). Assuming global implementation of a mix of regionally existing best practice policies (mostly regulatory policies in the electricity, industry, buildings, transport and agricultural sectors) and moderate carbon pricing (between 5–

[14] FOOTNOTE: Unlike AR5, which only included cost-effective scenarios for estimating discounted average carbon prices for 2015-2100 (also using a 5% discount rate) (see Clarke et al., 2014, p.450), please note that values shown in Figure 2.26 (panel b) include delays or technology constraint cases (see Sections 2.1 and 2.3).

20 USD_{2010} tCO_2^{-1} in 2025 in most world regions and average prices around 25 USD_{2010} tCO_2^{-1} in 2030), early action mitigation pathways are generated that reduce global CO_2 emissions by an additional 10 $GtCO_2e$ in 2030 compared to the NDCs (Kriegler et al., 2018b) (see Section 2.3.5). Furthermore, a mix of stringent energy efficiency policies (e.g., minimum performance standards, building codes) combined with a carbon tax (rising from 10 USD_{2010} tCO_2^{-1} in 2020 to 27 USD_{2010} tCO_2^{-1} in 2040) is more cost-effective than a carbon tax alone (from 20 to 53 USD_{2010} tCO_2^{-1}) to generate a 1.5˚C pathway for the U.S. electric sector (Brown and Li, 2018). Likewise, a policy mix encompassing a moderate carbon price (7 USD_{2010} tCO_2^{-1} in 2015) combined with a ban on new coal-based power plants and dedicated policies addressing renewable electricity generation capacity and electric vehicles reduces efficiency losses compared with an optimal carbon pricing in 2030 (Bertram et al., 2015b). One study estimates the price of carbon in high energy-intensive pathways to be 25–50% higher than in low energy-intensive pathways that assume ambitious regulatory instruments, economic incentives (in addition to a carbon price) and voluntary initiatives (Méjean et al., 2018). A bottom-up approach shows that stringent minimum performance standards (MEPS) for appliances (e.g., refrigerators) can effectively complement carbon pricing, as tightened MEPS can achieve ambitious efficiency improvements that cannot be assured by carbon prices of 100 USD_{2010} tCO_2^{-1} or higher (Sonnenschein et al., 2018). The literature indicates that the pricing of emissions is relevant but needs to be complemented with other policies to drive the required changes in line with 1.5°C-consistent cost-effective pathways (Stiglitz et al., 2017; Mehling and Tvinnereim, 2018; Méjean et al., 2018; Michaelowa et al., 2018) (*low to medium evidence, high agreement*) (see Section 4.4.5).

In summary, new analyses are consistent with the AR5 and show that the price of carbon would need to increase significantly when a higher level of stringency is pursued (*high confidence*). Values vary substantially across models, scenarios and socio-economic, technology and policy assumptions. While the price of carbon is central to prompt mitigation pathways compatible with 1.5°C-consistent pathways, a complementary mix of stringent policies is required.



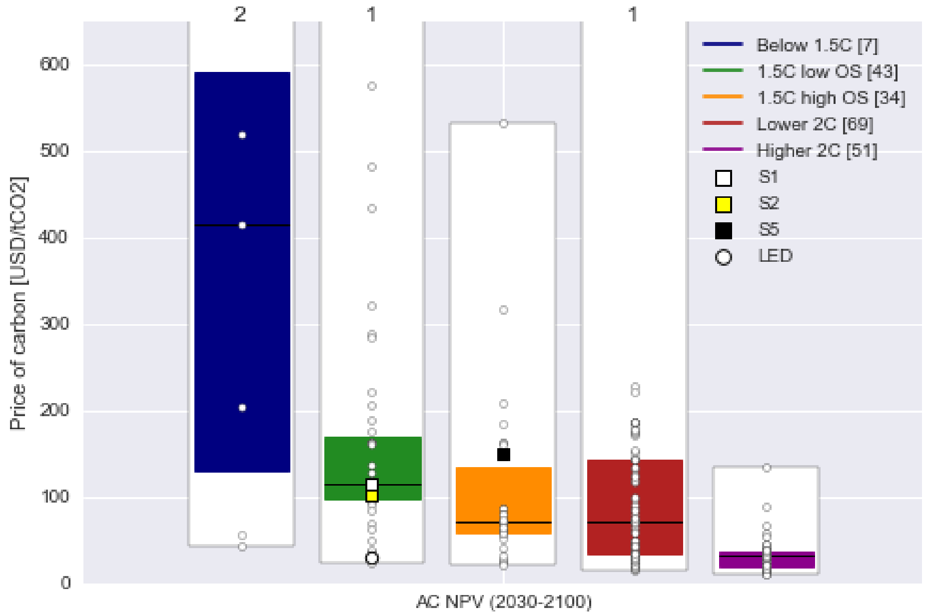


Figure 2.26: Global price of carbon emissions consistent with mitigation pathways. Panels show undiscounted price of carbon (2030-2100) (top panel) and average price of carbon (2030-2100) discounted at a 5% discount rate (lower panel). AC: Annually compounded. NPV: Net present value. Median values in floating black line. The number of pathways included in boxplots is indicated in the legend. Number of pathways outside the figure range is noted at the top.

2.5.2.2 Investments

Realising the transformations towards a 1.5°C world requires a major shift in investment patterns (McCollum et al., 2018). Literature on global climate-change mitigation investments is relatively sparse, with most detailed literature having focused on 2°C pathways (McCollum et al., 2013; Bowen et al., 2014; Gupta and Harnisch, 2014; Marangoni and Tavoni, 2014; OECD/IEA and IRENA, 2017).

Global energy-system investments in the year 2016 are estimated at approximately 1.7 trillion USD_{2010} (approximately 2.2% of global GDP and 10% of gross capital formation), of which 0.23 trillion USD_{2010} was for incremental end-use energy efficiency and the remainder for supply-side capacity installations (IEA, 2017c). There is some uncertainty surrounding this number because not all entities making investments report them publicly, and model-based estimates show an uncertainty range of about ± 15% (McCollum et al., 2018). Notwithstanding, the trend for global energy investments has been generally upward over the last two decades: increasing about threefold between 2000 and 2012, then levelling off for three years before declining in both 2015 and 2016 as a result of the oil price collapse and simultaneous capital cost reductions for renewables (IEA, 2017c).

Estimates of demand-side investments, either in total or for incremental efficiency efforts, are more uncertain, mainly due to a lack of reliable statistics and definitional issues about what exactly is counted towards a demand-side investment and what the reference should be for estimating incremental efficiency (McCollum et al., 2013). Grubler and Wilson (2014) use two working definitions (a broader and a narrower one) to provide a first-order estimate of historical end-use technology investments in total. The broad definition defines end-use technologies as the technological systems purchasable by final consumers in order to provide a useful service, for example, heating and air conditioning systems, cars, freezers, or aircraft. The narrow definition sets the boundary at the specific energy-using components or subsystems of the larger end-use technologies (e.g., compressor, car engine, heating element). Based on these two definitions, demand-side energy investments for the year 2005 were estimated about 1–3.5 trillion USD_{2010} (central estimate 1.7 trillion USD_{2010}) using the broad definition and 0.1–0.6 trillion USD_{2010} (central estimate 0.3 trillion USD_{2010}) using the narrower definition. Due to these definitional issues, demand-side investment projections are uncertain, often underreported, and difficult to compare. Global IAMs often do not fully and explicitly represent all the various measures that could improve end-use efficiency.

Research carried out by six global IAM teams found that 1.5°C-consistent climate policies would require a marked upscaling of energy system supply-side investments (resource extraction, power generation, fuel conversion, pipelines/transmission, and energy storage) between now and mid-century, reaching levels of between 1.6–3.8 trillion USD_{2010} yr^{-1} globally on average over the 2016-2050 timeframe (McCollum et al., 2018) (Figure 2.27). How these investment needs compare to those in a policy baseline scenario is uncertain: they could be higher, much higher, or lower. Investments in the policy baselines from these same models are 1.6–2.7 trillion USD_{2010} yr^{-1}. Much hinges on the reductions in energy demand growth embodied in the 1.5°C pathways, which require investing in energy efficiency. Studies suggest that annual supply-side investments by mid-century could be lowered by around 10% (McCollum et al., 2018) and in some cases up to 50% (Grubler et al., 2018) if strong policies to limit energy demand growth are successfully implemented. However, the degree to which these supply-side reductions would be partially offset by an increase in demand-side investments is unclear.

Some trends are robust across scenarios (Figure 2.27). First, pursuing 1.5°C mitigation efforts requires a major reallocation of the investment portfolio, implying a financial system aligned to mitigation challenges. The path laid out by countries' current NDCs until 2030 will not drive these structural changes; and despite increasing low-carbon investments in recent years (IEA, 2016b; Frankfurt School-UNEP Centre/BNEF, 2017), these are not yet aligned with 1.5°C. Specifically, annual investments in low-carbon energy are projected to average 0.8–2.9 trillion USD_{2010} yr^{-1} globally to 2050 in 1.5 °C pathways, overtaking fossil investments globally already by around 2025 (McCollum et al., 2018). The bulk of these investments are projected to be for clean electricity generation, particularly solar and wind power (0.09–1.0 trillion USD_{2010} yr^{-1} and 0.1–0.35 trillion USD_{2010} yr^{-1}, respectively) as well as nuclear power (0.1–0.25 trillion USD_{2010} yr^{-1}). The precise apportioning of these investments depends on model assumptions and societal preferences related to mitigation strategies and policy choices (see Sections 2.1 and 2.3). Investments for electricity transmission and distribution and storage are also scaled up in 1.5°C pathways (0.3–1.3 trillion USD_{2010} yr^{-1}), given their widespread electrification of the end-use sectors (see Section 2.4). Meanwhile, 1.5°C pathways see a reduction in annual investments for fossil-fuel extraction and unabated fossil electricity generation (to 0.3–0.85 trillion USD_{2010} yr^{-1} on average over the 2016–2050 period). Investments in unabated coal are halted by 2030 in most 1.5°C projections, while the literature is less conclusive for investments in unabated gas (McCollum et al., 2018). This illustrates how mitigation strategies vary between models, but in the real world should be considered in terms of their societal desirability (see Section 2.5.3). Furthermore, some fossil investments made over the next few years – or those made in the last few – will likely need to be retired prior to fully recovering their capital investment or before the end of their operational lifetime (Bertram et al., 2015a; Johnson et al., 2015; OECD/IEA and IRENA, 2017). How the pace of the energy transition will be affected by such dynamics, namely with respect to politics and society, is not well captured by global IAMs at present. Modelling studies have, however, shown how the reliability of institutions influences investment risks and hence climate mitigation investment decisions (Iyer et al., 2015), finding that a lack of regulatory credibility or policy commitment fails to stimulate low-carbon investments (Bosetti and Victor, 2011; Faehn and Isaksen, 2016).

Low-carbon supply-side investment needs are projected to be largest in OECD countries and those of developing Asia. The regional distribution of investments in 1.5°C pathways estimated by the multiple models in (McCollum et al., 2018) are the following (average over 2016-2050 timeframe): 0.30-1.3 trillion USD_{2010} yr^{-1}(ASIA), 0.35–0.85 trillion USD_{2010} yr^{-1} (OECD), 0.08–0.55 trillion USD_{2010} yr^{-1} (MAF), 0.07–0.25 trillion USD_{2010} yr^{-1} (LAM), and 0.05–0.15 trillion USD_{2010} yr^{-1} (REF) (regions are defined consistent with their use in AR5 WGIII, see Table A.II.8 in Krey et al., 2014b).

Until now, IAM investment analyses of 1.5 °C pathways have focused on middle-of-the-road socioeconomic and technological development futures (SSP2) (Fricko et al., 2017). Consideration of a broader range of development futures would yield different outcomes in terms of the magnitudes of the projected investment levels. Sensitivity analyses indicate that the magnitude of supply-side investments as well as the investment portfolio do not change strongly across the SSPs for a given level of climate policy stringency (McCollum et al., 2018). With only one dedicated multi-model comparison study published, there is *limited to medium evidence* available. For some features, there is *high agreement* across modelling frameworks leading, for example, to *medium to high confidence* that limiting global temperature increase to 1.5°C will require a major reallocation of the investment portfolio. Given the limited amount of sensitivity cases available compared to the default SSP2 assumptions, *medium confidence* can be assigned to the specific energy and climate mitigation investment estimates reported here.

Assumptions in modelling studies indicate a number of challenges. For instance, access to finance and mobilisation of funds are critical (Fankhauser et al., 2016; OECD, 2017). In turn, policy efforts need to be effective in re-directing financial resources (UNEP, 2015; OECD, 2017) and reduce transaction costs for bankable mitigation projects (i.e. projects that have adequate future cash-flow, collateral, etc. so lenders are willing to finance it), particularly on the demand side (Mundaca et al., 2013; Brunner and Enting, 2014; Grubler et al., 2018). Assumptions also imply that policy certainty, regulatory oversight mechanisms and fiduciary duty need to be robust and effective to safeguard credible and stable financial markets and de-risk mitigation investments in the long term (Clarke et al., 2014; Mundaca et al., 2016; EC, 2017; OECD, 2017). Importantly, the different time horizons that actors have in the competitive finance industry are typically not explicitly captured by modelling assumptions (Harmes, 2011). See Section 4.4.5 for details of climate finance in practice.

In summary and despite inherent uncertainties, the emerging literature indicates a gap between current investment patterns and those compatible with 1.5°C (or 2°C) pathways (*limited to medium evidence, high agreement*). Estimates and assumptions from modelling frameworks suggest a major shift in investment patterns and entail a financial system effectively aligned with mitigation challenges (*high confidence*).

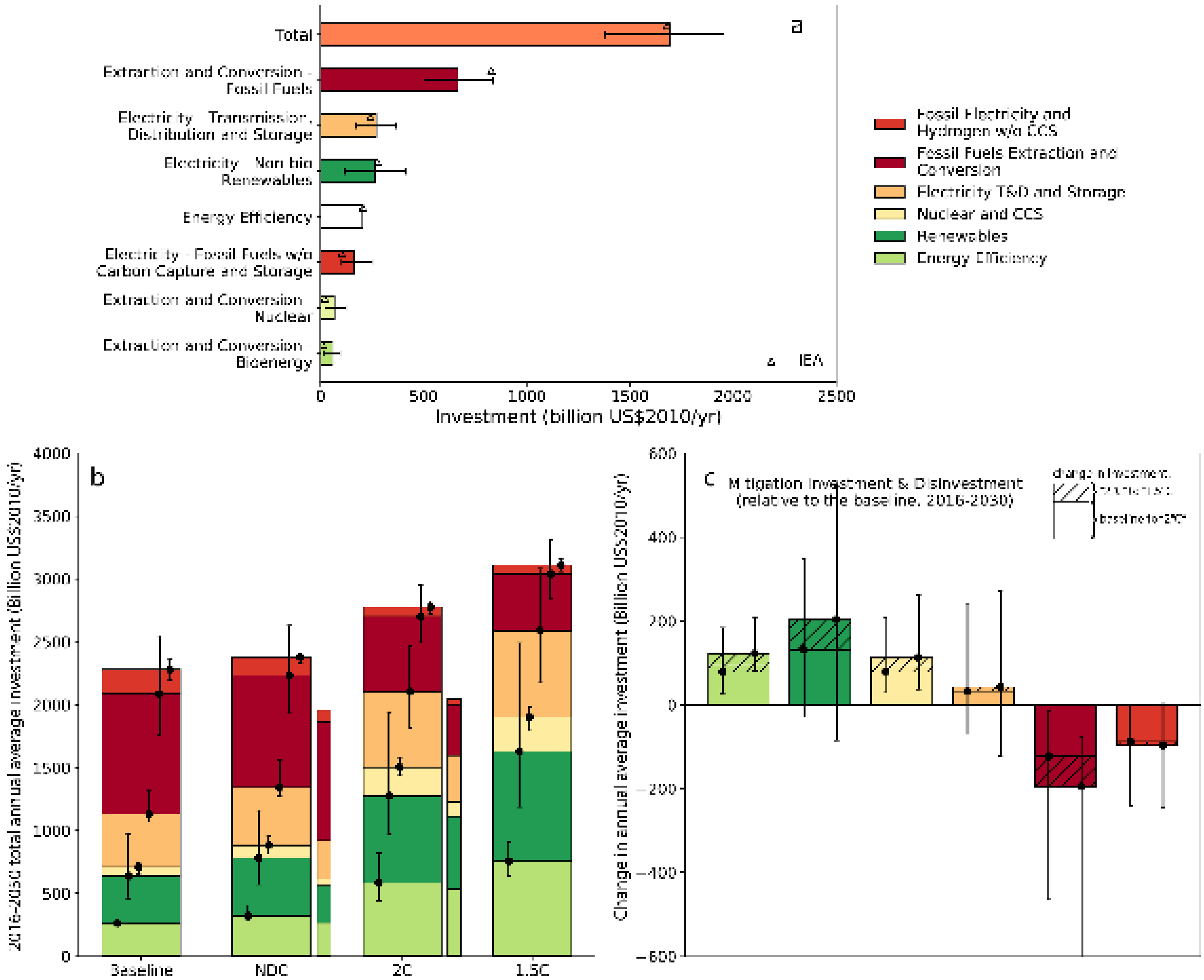


Figure 2.27: Historical and projected global energy investments. (a) Historical investment estimates across six global models from (McCollum et al., 2018) (bars = model means, whiskers full model range) compared to historical estimates from IEA (International Energy Agency (IEA) 2016) (triangles). (b) Average annual investments over the 2016–2050 period in no-climate policy 'baselines', scenarios which implement the NDCs ('NDC'), scenarios consistent with the Lower-2°C pathway class ('2°C'), and scenarios in line with the 1.5°C-low-OS pathway class ('1.5°C'). Whiskers show the range of models; wide bars show the multi-model means; narrow bars represent analogous values from individual IEA

scenarios (OECD/IEA and IRENA, 2017). (c) Average annual mitigation investments and disinvestments for the 2016–2030 periods relative to the baseline. The solid bars show the values for '2°C' pathways, while the hatched areas show the additional investments for the pathways labelled with '1.5°C'. Whiskers show the full range around the multi-model means. T&D stands for transmission and distribution, and CCS stands for carbon capture and storage. Global cumulative carbon dioxide emissions, from fossil fuels and industrial processes (FF&I) but excluding land use, over the 2016-2100 timeframe range from 880 to 1074 $GtCO_2$ (multi-model mean: 952 $GtCO_2$) in the '2°C' pathway and from 206 to 525 $GtCO_2$ (mean: 390 $GtCO_2$) in the '1.5°C' pathway.

2.5.3 Sustainable development features of 1.5°C pathways

Potential synergies and trade-offs between 1.5°C mitigation pathways and different sustainable development (SD) dimensions (see Cross-Chapter Box 4) are an emerging field of research. Section 5.4 assesses interactions between individual mitigation measures with other societal objectives, as well as the Sustainable Development Goals (SGDs) (Table 5.1). This section synthesized the Chapter 5 insights to assess how these interactions play out in integrated 1.5°C pathways, and the four illustrative pathway archetypes of this chapter in particular (see Section 2.1). Information from integrated pathways is combined with the interactions assessed in Chapter 5 and aggregated for each SDG, with a level of confidence attributed to each interaction based on the amount and agreement of the scientific evidence (see Chapter 5).

Figure 2.28 shows how the scale and combination of individual mitigation measures (i.e., their mitigation portfolios) influence the extent of synergies and trade-offs with other societal objectives. All pathways generate multiple synergies with SD dimensions and can advance several other SDGs simultaneously. Some, however, show higher risks for trade-offs. An example is increased biomass production and its potential to increase pressure on land and water resources, food production, biodiversity, and reduced air-quality when combusted inefficiently. At the same time, mitigation actions in energy-demand sectors and behavioural response options with appropriate management of rebound effects can advance multiple SDGs simultaneously, more so than energy supply-side mitigation actions (see Section 5.4, Table 5.1 and Figure 5.3 for more examples). Of the four pathway archetypes used in this chapter (*S1*, *S2*, *S5*, and *LED*), the *S1* and *LED* pathways show the largest number of synergies and least number of potential trade-offs, while for the *S5* pathway most potential trade-offs are identified. In general, pathways with emphasis on demand reductions, with policies that incentivise behavioural change, sustainable consumption patterns, healthy diets and relatively low use of CDR (or only afforestation) show relatively more synergies with individual SDGs than others.

There is *robust evidence* and *high agreement* in the pathway literature that multiple strategies can be considered to limit warming to 1.5°C (see Sections 2.1.3, 2.3 and 2.4). Together with the extensive evidence on the existence of interactions of mitigation measures with other societal objectives (Section 5.4), this results in *high confidence* that the choice of mitigation portfolio or strategy can markedly affect the achievement of other societal objectives. For instance, action on SLCFs has been suggested to facilitate the achievement of SDGs (Shindell et al., 2017b) and to reduce regional impacts, e.g., from black carbon sources on snow and ice loss in the Arctic and alpine regions (Painter et al., 2013), with particular focus on the warming sub-set of SLCFs. Reductions in both surface aerosols and ozone through methane reductions provide health and ecosystem co-benefits (Jacobson, 2002, 2010; Anenberg et al., 2012; Shindell et al., 2012; Stohl et al., 2015; Collins et al., 2018). Public health benefits of stringent mitigation pathways in line with 1.5°C-consistent pathways can be sizeable. For instance, a study examining a more rapid reduction of fossil-fuel usage to achieve 1.5°C relative to 2°C, similar to that of other recent studies (Grubler et al., 2018; van Vuuren et al., 2018), found that improved air quality would lead to more than 100 million avoided premature deaths over the 21st century (Shindell et al., 2018). These benefits are assumed to be in addition to those occurring under 2°C pathways (e.g., Silva et al., 2016), and could in monetary terms offset a large portion to all of the initial mitigation costs (West et al., 2013; Shindell et al., 2018). However, some sources of SLCFs with important impacts for public health (e.g., traditional biomass burning) are only mildly affected by climate policy in the available integrated pathways and are more strongly impacted by baseline assumptions about future societal development and preferences, and technologies instead (Rao et al., 2016, 2017).

At the same time, the literature on climate-SDG interactions is still an emergent field of research and hence there is *low to medium confidence* in the precise magnitude of the majority of these interactions. Very limited literature suggests that achieving co-benefits are not automatically assured but result from conscious and carefully coordinated policies and implementation strategies (Shukla and Chaturvedi, 2012; Clarke et al., 2014; McCollum et al., 2018). Understanding these mitigation-SDG interactions is key for selecting mitigation options that maximise synergies and minimize trade-offs towards the 1.5°C and sustainable development objectives (van Vuuren et al., 2015; Hildingsson and Johansson, 2016; Jakob and Steckel, 2016; von Stechow et al., 2016; Delponte et al., 2017).

In summary, the combined evidence indicates that the chosen mitigation portfolio can distinctly have an impact on the achievement of other societal policy objectives (*high confidence*); however, there is uncertainty regarding the specific extent of climate-SDG interactions.

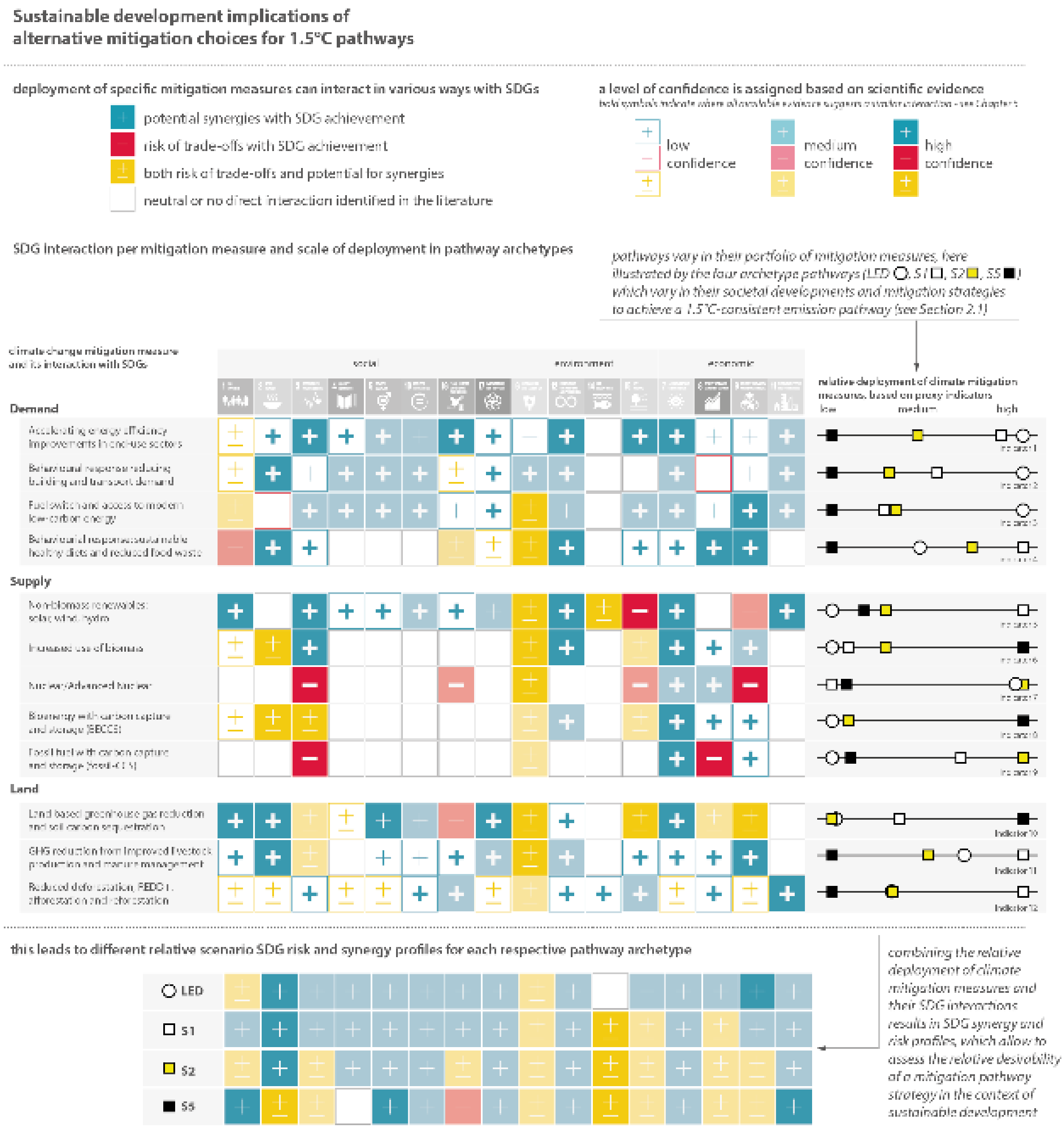


Figure 2.28: Interactions of individual mitigation measures and alternative mitigations portfolios for 1.5°C with Sustainable Development Goals (SDGs). The assessment of interactions between mitigation measures and individual SDGs is based on the assessment of Section 5.4. Proxy indicators and synthesis method are described in Annex 2.A.5.

2.6 Knowledge gaps

This section summarises the knowledge gaps articulated in earlier sections of the chapter.

2.6.1 Geophysical understanding

Knowledge gaps are associated with the carbon-cycle response, the role of non-CO_2 emissions and on the evaluation of an appropriate historic baseline.

Quantifying how the carbon cycle responds to negative emissions is an important knowledge gap for strong mitigation pathways (Section 2.2). Earth-system feedback uncertainties are important to consider for the longer-term response, particularly in how permafrost melting might affect the carbon budget (Section 2.2). Future research and ongoing observations over the next years will provide a better indication as to how the 2006-2015 base period compares with the long-term trends and might at present bias the carbon budget estimates.

The future emissions of short-lived climate forcers and their temperature response are a large source of uncertainty in 1.5°C pathways, having a greater relative uncertainty than in higher CO_2 emission pathways. Their global emissions, their sectorial and regional disaggregation and their climate response are generally less well quantified than for CO_2 (Sections 2.2 and 2.3). Emissions from the agricultural sector including land-use based mitigation options in 1.5°C pathways constitute the main source of uncertainty here and are an important gap in understanding the potential achievement of stringent mitigation scenarios (Sections 2.3 and 2.4). This also includes uncertainties surrounding the mitigation potential of the long-lived GHG nitrous oxide. (Sections 2.3 and 2.4)

There is considerable uncertainty in how future emissions of aerosol precursors will affect the effective radiative forcing from aerosol-cloud interaction. The potential future warming from mitigation of these emissions reduces remaining carbon budgets and increases peak temperatures (Section 2.2). The potential co-benefits of mitigating air pollutants and how the reduction in air pollution may affect the carbon sink are also important sources of uncertainty (Sections 2.2 and 2.5).

The pathway classification employed in this Chapter employs results from the MAGICC model with its AR5 parameter sets. The alternative representation of the relationship between emissions and effective radiative forcing and response in the FAIR model would lead to a different classification that would make 1.5°C targets more achievable (Section 2.2 and Annex 2.A.1). Such a revision would significantly alter the temperature outcomes for the pathways and, if the result is found to be robust, future research and assessments would need to adjust their classifications accordingly. Any possible high bias in the MAGICC response may be partly or entirely offset by missing Earth system feedbacks that are not represented in either climate emulator that would act to increase the temperature response (Section 2.2). For this assessment report, any possible bias in MAGICC setup applied in this and earlier reports is not established enough in the literature to change the classification approach. However, we only place *medium confidence* in the classification adopted by the chapter.

2.6.2 Integrated assessment approaches

IAMs attempt to be as broad as possible in order to explore interactions between various societal subsystems, like the economy, land, and energy system. They hence include stylised and simplified representations of these subsystems. Climate damages, avoided impacts and societal co-benefits of the modelled transformations remain largely unaccounted for and are important knowledge gaps. Furthermore, rapid technological changes and uncertainties about input data present continuous challenges.

The IAMs used in this report do not account for climate impacts (Section 2.1), and similarly, none of the Gross Domestic Product (GDP) projections in the mitigation pathway literature assessed in this chapter included the feedback of climate damages on economic growth (Section 2.3). Although some IAMs do allow for climate impact feedbacks in their modelling frameworks, particularly in their land components, such feedbacks were by design excluded in pathways developed in the context of the SSP framework. The SSP framework aims at providing an integrative framework for the assessment of climate change adaptation and mitigation. IAMs are typically developed to inform the mitigation component of this question, while the assessment of impacts is carried out by specialized impact models. However, the use of a consistent set of socio-economic drivers embodied by the SSPs allows for an integrated assessment of climate change impacts and mitigation challenges at a later stage. Further integration of these two strands of research will allow a better understanding of climate impacts on mitigation studies.

Many of the IAMs that contributed mitigation pathways to this assessment include a process-based description of the land system in addition to the energy system and several have been extended to cover air pollutants and water use. These features make them increasingly fit to explore questions beyond those that touch upon climate mitigation only. The models do not, however, fully account for all constraints that could affect realization of pathways (Section 2.1).

While the representation of renewable energy resource potentials, technology costs and system integration in IAMs has been updated since AR5, bottom-up studies find higher mitigation potentials in the industry, buildings, and transport sector in that realized by selected pathways from IAMs, indicating the possibility to strengthen sectorial decarbonisation strategies compared to the IAM 1.5°C pathways assessed in this chapter (Section 2.1).

Studies indicate that a major shift in investment patterns is required to limit global warming to 1.5°C. This assessment would benefit from a more explicit representation and understanding of the financial sector within the modelling approaches. Assumptions in modelling studies imply low-to-zero transaction costs for market agents and that regulatory oversight mechanisms and fiduciary duty need to be highly robust to guarantee stable and credible financial markets in the long term. This area can be subject to high uncertainty, however. The heterogeneity of actors (e.g., banks, insurance companies, asset managers, or credit rating agencies) and financial products also needs to be taken into account, as does the mobilisation of capital and financial flows between countries and regions (Section 2.5).

The literature on interactions between 1.5˚C mitigation pathways and SDGs is an emergent field of research (Section 2.3.5, 2.5 and Chapter 5). Whereas the choice of mitigation strategies can noticeably affect the attainment of various societal objectives, there is uncertainty regarding the extent of the majority of identified interactions. Understanding climate-SDG interactions helps the choice of mitigation options that minimize trade-offs and risks and maximise synergies towards sustainable development objectives and the 1.5°C goal (Section 2.5).

2.6.3 Carbon Dioxide Removal (CDR)

Most 1.5°C and 2°C pathways are heavily reliant on CDR at a speculatively large scale before mid-century. There are a number of knowledge gaps associated which such technologies. Chapter 4 performs a detailed assessment of CDR technologies.

There is uncertainty in the future deployment of CCS given the limited pace of current deployment, the evolution of CCS technology that would be associated with deployment, and the current lack of incentives for large-scale implementation of CCS (Section 4.2.7). Technologies other than BECCS and afforestation have yet to be comprehensively assessed in integrated assessment approaches. No proposed technology is close to deployment at scale and regulatory frameworks are not established. This limits how they can be realistically implemented within IAMs. (Section 2.3)

Evaluating the potential from BECCS is problematic due to large uncertainties in future land projections due to differences in modelling approaches in current land-use models which are at least as great as the differences attributed to climate scenario variations. (Section 2.3)

There is substantial uncertainty about the adverse effects of large-scale CDR deployment on the environment and societal sustainable development goals. It is not fully understood how land use and land management choices for large-scale BECCS will affect various ecosystem services and sustainable development, and further translate into indirect impacts on climate including GHG emissions other than CO_2. (Section 2.3, Section 2.5.3)

Frequently Asked Questions

FAQ 2.1: What kind of pathways limit warming to 1.5°C and are we on track?

Summary*: There is no definitive way to limit global temperature rise to 1.5°C above pre-industrial levels. This Special Report identifies two main conceptual pathways to illustrate different interpretations. One stabilises global temperature at, or just below, 1.5°C. Another sees global temperature temporarily exceed 1.5°C before coming back down. Countries' pledges to reduce their emissions are currently not in line with limiting global warming to 1.5°C.*

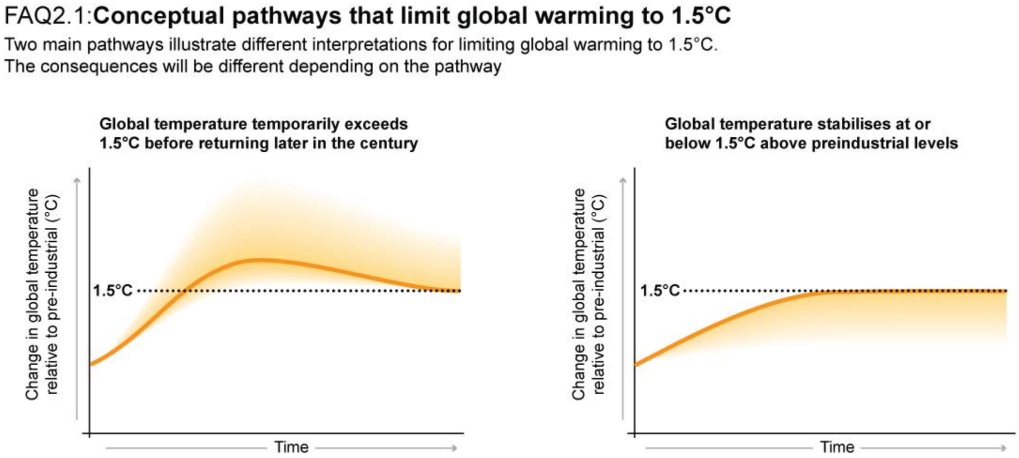
Scientists use computer models to simulate the emissions of greenhouse gases that would be consistent with different levels of warming. The different possibilities are often referred to as 'greenhouse gas emission pathways'. There is no single, definitive pathway to limiting warming to 1.5°C.

This IPCC special report identifies two main pathways that explore global warming of 1.5°C. The first involves global temperature stabilising at or below before 1.5°C above preindustrial levels. The second pathway sees warming exceed 1.5°C around mid-century, remain above 1.5°C for a maximum duration of a few decades, and return to below 1.5°C before 2100. The latter is often referred to as an 'overshoot' pathway. Any alternative situation in which global temperature continues to rise, exceeding 1.5°C permanently until the end of the 21^{st} century, is not considered to be a 1.5°C pathway.

The two types of pathway have different implications for greenhouse gas emissions, as well as for climate change impacts and for achieving sustainable development. For example, the larger and longer an 'overshoot', the greater the reliance on practices or technologies that remove CO_2 from the atmosphere, on top of reducing the sources of emissions (mitigation). Such ideas for CO_2 removal have not been proven to work at scale and, therefore, run the risk of being less practical, effective or economical than assumed. There is also the risk that the use of CO_2 removal techniques ends up competing for land and water and if these trade-offs are not appropriately managed, they can adversely affect sustainable development. Additionally, a larger and longer overshoot increases the risk for irreversible climate impacts, such as the onset of the collapse of polar ice shelves and accelerated sea level rise.

Countries that formally accept or 'ratify' the Paris Agreement submit pledges for how they intend to address climate change. Unique to each country, these pledges are known as Nationally Determined Contributions (NDCs). Different groups of researchers around the world have analysed the combined effect of adding up all the NDCs. Such analyses show that current pledges are not on track to limit global warming to 1.5°C above pre-industrial levels. If current pledges for 2030 are achieved but no more, researchers find very few (if any) ways to reduce emissions after 2030 sufficiently quickly to limit warming to 1.5°C. This, in turn, suggests that with the national pledges as they stand, warming would exceed 1.5°C, at least for a period of time, and practices and technologies that remove CO_2 from the atmosphere at a global scale would be required to return warming to 1.5°C at a later date.

A world that is consistent with holding warming to 1.5°C would see greenhouse gas emissions rapidly decline in the coming decade, with strong international cooperation and a scaling up of countries' combined ambition beyond current NDCs. In contrast, delayed action, limited international cooperation, and weak or fragmented policies that lead to stagnating or increasing greenhouse gas emissions would put the possibility of limiting global temperature rise to 1.5°C above pre-industrial levels out of reach.



FAQ2.1, Figure 1: Two main pathways for limiting global temperature rise to 1.5°C above pre-industrial levels are discussed in this Special Report. These are: stabilising global temperature at, or just below, 1.5°C (left) and global temperature temporarily exceeding 1.5°C before coming back down later in the century (right). Temperatures shown are relative to pre-industrial but pathways are illustrative only, demonstrating conceptual not quantitative characteristics.

FAQ 2.2: What do energy supply and demand have to do with limiting warming to 1.5°C?

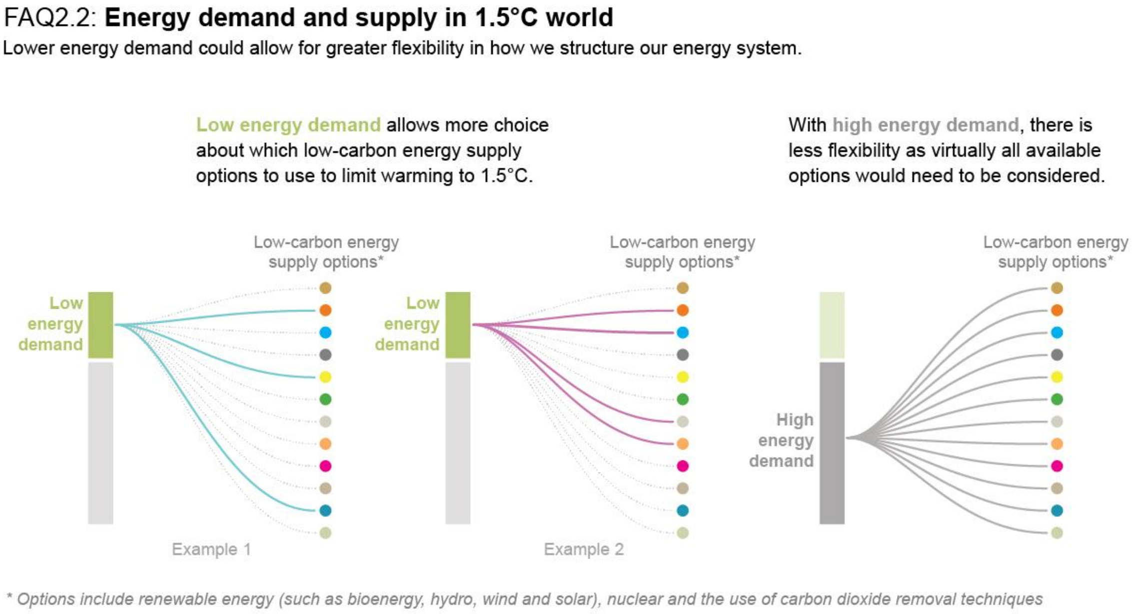
***Summary**: Limiting global warming to 1.5°C above pre-industrial levels would require major reductions in greenhouse gas emissions in all sectors. But different sectors are not independent of each other and making changes in one can have implications for another. For example, if we as a society use a lot of energy, then this could mean we have less flexibility in the choice of mitigation options available to limit warming to 1.5°C. If we use less energy, the choice of possible actions is greater. For example we could be less reliant on technologies that remove carbon dioxide (*CO_2*) from the atmosphere.*

To stabilise global temperature at any level, 'net' CO_2 emissions would need to be reduced to zero. This means the amount of CO_2 entering the atmosphere must equal the amount that is removed. Achieving a balance between CO_2 'sources' and 'sinks' is often referred to as 'net zero' emissions or 'carbon neutrality'. The implication of net zero emissions is that the concentration of CO_2 in the atmosphere would slowly decline over time until a new equilibrium is reached, as CO_2 emissions from human activity are redistributed and taken up by the oceans and the land biosphere. This would lead to a near-constant global temperature over many centuries.

Warming will not be limited to 1.5°C or 2°C unless transformations in a number of areas achieve the required greenhouse gas emissions reductions. Emissions would need to decline rapidly across all of society's main sectors, including buildings, industry, transport, energy, and agriculture, forestry and other land use (AFOLU). Actions that can reduce emissions include, for example, phasing out coal in the energy sector, increasing the amount of energy produced from renewable sources, electrifying transport, and reducing the 'carbon footprint' of the food we consume.

The above are examples of 'supply-side' actions. Broadly speaking, these are actions that can reduce greenhouse gas emissions through the use of low-carbon solutions. A different type of action can reduce how much energy human society uses, while still ensuring increasing levels of development and well-being. Known as 'demand-side' actions, this category includes improving energy efficiency in buildings and reducing consumption of energy- and greenhouse-gas intensive products through behavioural and lifestyle changes, for example. Demand and supply-side measures are not an either-or question, they work in parallel with each other. But emphasis can be given to one or the other.

Making changes in one sector can have consequences for another, as they are not independent of each other. In other words, the choices that we make now as a society in one sector can either restrict or expand our options later on. For example, a high demand for energy could mean we would need to deploy almost all known options to reduce emissions in order to limit global temperature rise to 1.5°C above pre-industrial levels, with the potential for adverse side-effects. For example, a high-demand pathway increases our reliance on practices and technologies that remove CO_2 from the atmosphere. As of yet, such techniques have not been proven to work on a large scale and, depending on how they are implemented, could compete for land and water. By leading to lower overall energy demand, effective demand-side measures could allow for greater flexibility in how we structure our energy system. However, demand-side measures are not easy to implement and barriers have prevented the most efficient practices being used in the past.



FAQ2.2, Figure 1: Having a lower energy demand increases the flexibility in choosing options for supplying energy. A larger energy demand means many more low carbon energy supply options would need to be used.

References

Ackerman, F. and E.A. Stanton, 2012: Climate Risks and Carbon Prices: Revising the Social Cost of Carbon. *Economics: The Open-Access, Open-Assessment E-Journal*, **6(2012-10)**, 1, doi:10.5018/economics-ejournal.ja.2012-10.

Adler, M.D. and N. Treich, 2015: Prioritarianism and Climate Change. *Environmental and Resource Economics*, **62(2)**, 279-308, doi:10.1007/s10640-015-9960-7.

Adler, M.D. et al., 2017: Priority for the worse-off and the social cost of carbon. *Nature Clim. Change*, **7(6)**, 443-449, doi:10.1038/nclimate3298.

Akimoto, K., F. Sano, and T. Tomoda, 2017: GHG emission pathways until 2300 for the 1.5 °C temperature rise target and the mitigation costs achieving the pathways. *Mitigation and Adaptation Strategies for Global Change*, 1-14, doi:10.1007/s11027-017-9762-z.

Alcalde, J. et al., 2018: Estimating geological CO_2 storage security to deliver on climate mitigation. *Nature Communications* (in press), doi:10.1038/s41467-018-04423-1.

Aldy, J.E. and R.N. Stavins, 2012: The Promise and Problems of Pricing Carbon. *The Journal of Environment & Development*, **21(2)**, 152-180, doi:10.1177/1070496512442508.

Aldy, J.E. et al., 2016: Economic tools to promote transparency and comparability in the Paris Agreement. *Nature Climate Change*, **6(11)**, 1000-1004, doi:10.1038/nclimate3106.

Allen, M.R. et al., 2009: Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, **458(7242)**, 1163-1166, doi:10.1038/nature08019.

Allen, M.R. et al., 2016: New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nature Climate Change*, **6(May)**, 1-5, doi:10.1038/nclimate2998.

Allen, M.R. et al., 2018: A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *npj Climate and Atmospheric Science* (in press).

Allwood, J.M., M.F. Ashby, T.G. Gutowski, and E. Worrell, 2013: Material efficiency: providing material services with less material production. *Phil. Trans. R. Soc. A*, **371(1986)**, 20120496, doi:10.1098/rsta.2012.0496.

Anderson, K. and G. Peters, 2016: The trouble with negative emissions. *Science*, **354(6309)**, 182-183, doi:10.1126/science.aah4567.

Anenberg, S.C. et al., 2012: Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls. *Environmental Health Perspectives*, **120(6)**, 831-839, doi:10.1289/ehp.1104301.

Anthoff, D. and R.S.J. Tol, 2009: The impact of climate change on the balanced growth equivalent: An application of FUND. *Environmental and Resource Economics*, **43(3)**, 351-367, doi:10.1007/s10640-009-9269-5.

Armour, K.C., 2017: Energy budget constraints on climate sensitivity in light of inconstant climate feedbacks. *Nature Clim. Change*, **7(5)**, 331-335, doi:10.1038/nclimate3278.

Arneth, A. et al., 2010: Terrestrial biogeochemical feedbacks in the climate system. *Nature Geoscience*, **3(8)**, 525-532, doi:10.1038/ngeo905.

Arroyo-Currás, T. et al., 2015: Carbon leakage in a fragmented climate regime: The dynamic response of global energy markets. *Technological Forecasting & Social Change*, **90**, 192-203, doi:10.1016/j.techfore.2013.10.002.

Bachu, S., 2015: Review of CO_2 storage efficiency in deep saline aquifers. *International Journal of Greenhouse Gas Control*, **40**, 188-202, doi:10.1016/j.ijggc.2015.01.007.

Bachu, S. et al., 2007a: *Phase II Final Report from the Task Force for Review and Identification of Standards for* CO_2 *Storage Capacity Estimation*. Estimation of CO_2 Storage Capacity in Geological Media - Phase 2, 43 pp.

Bachu, S. et al., 2007b: CO_2 storage capacity estimation: Methodology and gaps. *International Journal of Greenhouse Gas Control*, **1(4)**, 430-443, doi:10.1016/S1750-5836(07)00086-2.

Bajželj, B. et al., 2014: Importance of food-demand management for climate mitigation. *Nature Climate Change*, **4(10)**, 924-929, doi:10.1038/nclimate2353.

Banerjee, R. et al., 2012: GEA Chapter 8 - Energy End Use: Industry. In: *Global Energy Assessment - Toward a Sustainable Future*. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 513-574.

Baranzini, A. et al., 2017: Carbon pricing in climate policy: seven reasons, complementary instruments, and political economy considerations. *Wiley Interdisciplinary Reviews: Climate Change*, **8(4)**, e462, doi:10.1002/wcc.462.

Bataille, C., H. Waisman, M. Colombier, L. Segafredo, and J. Williams, 2016a: The Deep Decarbonization Pathways Project (DDPP): insights and emerging issues. *Climate Policy*, **16(sup1)**, S1-S6, doi:10.1080/14693062.2016.1179620.

Bataille, C. et al., 2016b: The need for national deep decarbonization pathways for effective climate policy. *Climate Policy*, **16(sup1)**, S7-S26, doi:10.1080/14693062.2016.1173005.

Bauer, N. et al., 2017: Shared Socio-Economic Pathways of the Energy Sector - Quantifying the Narratives. *Global Environmental Change*, **42**, 316-330, doi:10.1016/j.gloenvcha.2016.07.006.

Bauer, N. et al., 2018: Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF 33 model comparison. *Climatic Change* (in press), doi:10.1007/s10584-018-2226-y.

Beck, S. and M. Mahony, 2017: The IPCC and the politics of anticipation. *Nature Climate Change*, **7(5)**, 311-313,

doi:10.1038/nclimate3264.
Bentham, M., T. Mallows, J. Lowndes, and A. Green, 2014: CO_2 STORage evaluation database (CO_2 Stored). The UK's online storage atlas. *Energy Procedia*, **63**, 5103-5113, doi:10.1016/j.egypro.2014.11.540.
Benveniste, H. et al., 2018: Impacts of nationally determined contributions on 2030 global greenhouse gas emissions: Uncertainty analysis and distribution of emissions. *Environmental Research Letters*, **13(1)**, 014022, doi:10.1088/1748-9326/aaa0b9.
Berger, A. et al., 2017a: Nuclear energy and bio energy carbon capture and storage, keys for obtaining 1.5°C mean surface temperature limit. *International Journal of Global Energy Issues*, **40(3/4)**, 240, doi:10.1504/IJGEI.2017.086622.
Berger, A. et al., 2017b: How much can nuclear energy do about global warming? *International Journal of Global Energy Issues*, **40(1/2)**, 43, doi:10.1504/IJGEI.2017.080766.
Bertram, C., G. Luderer, A. Popp, J.C. Minx, and W. Lamb, 2018: Targeted policies can compensate most of the increased sustainability risks in 1.5°C mitigation scenarios. *Environ. Res. Lett* (in press), doi: 10.1088/1748-9326/aac3ec.
Bertram, C. et al., 2015a: Carbon lock-in through capital stock inertia associated with weak near-term climate policies. *Technological Forecasting and Social Change*, **90(PA)**, 62-72, doi:10.1016/j.techfore.2013.10.001.
Bertram, C. et al., 2015b: Complementing carbon prices with technology policies to keep climate targets within reach. *Nature Climate Change*, **5(3)**, 235-239, doi:10.1038/nclimate2514.
Bindoff, N. et al., 2013: Detection and Attribution of Climate Change: from Global to Regional. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 867-952.
Blanco, G. et al., 2014: Drivers, Trends and Mitigation. 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, United Kingdom and New York, NY, USA, pp. 351-412.
Boardman, A.E., 2006: *Cost-Benefit Analysis: Concepts and Practice*. Pearson/Prentice Hall, 560 pp.
Bodirsky, B.L. et al., 2012: N2O emissions from the global agricultural nitrogen cycle-current state and future scenarios. *Biogeosciences*, **9(10)**, 4169-4197, doi:10.5194/bg-9-4169-2012.
Bodirsky, B.L. et al., 2014: Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. *Nature Communications*, **5**, doi:10.1038/ncomms4858.
Bond, T.C. et al., 2013: Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres*, **118(11)**, 5380-5552, doi:10.1002/jgrd.50171.
Bonsch, M. et al., 2014: Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy*, **8(1)**, 11-24, doi:10.1111/gcbb.12226.
Bosetti, V. and D.G. Victor, 2011: Politics and Economics of Second-Best Regulation of Greenhouse Gases: The Importance of Regulatory Credibility. *The Energy Journal*, **32(1)**, 1-24.
Bosetti, V., C. Carraro, E. Massetti, and M. Tavoni, 2008: International energy R&D spillovers and the economics of greenhouse gas atmospheric stabilization. *Energy Economics*, **30(6)**, 2912-2929, doi:10.1016/j.eneco.2008.04.008.
Bosetti, V., C. Carraro, A. Sgobbi, and M. Tavoni, 2009: Delayed action and uncertain stabilisation targets. How much will the delay cost? *Climatic Change*, **96(3)**, 299-312, doi:10.1007/s10584-009-9630-2.
Bosetti, V., C. Carraro, M. Galeotti, E. Massetti, and M. Tavoni, 2006: WITCH - A world induced technical change hybrid model. *The Energy Journal, Special Issue. Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down*, 13-38.
Bosetti, V. et al., 2015: Sensitivity to energy technology costs: A multi-model comparison analysis. *Energy Policy*, **80**, 244-263, doi:10.1016/j.enpol.2014.12.012.
Boucher, O. and G.A. Folberth, 2010: New Directions: Atmospheric methane removal as a way to mitigate climate change? *Atmospheric Environment*, **44(27)**, 3343-3345, doi:10.1016/J.ATMOSENV.2010.04.032.
Bowen, A., E. Campiglio, and M. Tavoni, 2014: A macroeconomic perspective on climate change mitigation: Meeting the financing challenge. *Climate Change Economics*, **05(01)**, 1440005, doi:10.1142/S2010007814400053.
Bowerman, N.H.A., D.J. Frame, C. Huntingford, J.A. Lowe, and M.R. Allen, 2011: Cumulative carbon emissions, emissions floors and short-term rates of warming: implications for policy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **369(1934)**, 45-66, doi:10.1098/rsta.2010.0288.
Bowerman, N.H.A. et al., 2013: The role of short-lived climate pollutants in meeting temperature goals. *Nature Climate Change*, **3(12)**, 1021-1024, doi:10.1038/nclimate2034.
Boysen, L.R., W. Lucht, and D. Gerten, 2017a: Trade-offs for food production, nature conservation and climate limit the terrestrial carbon dioxide removal potential. *Global Change Biology*, **23(10)**, 4303-4317, doi:doi:10.1111/gcb.13745.

Boysen, L.R., W. Lucht, D. Gerten, and V. Heck, 2016: Impacts devalue the potential of large-scale terrestrial CO_2 removal through biomass plantations. *Environmental Research Letters*, **11(9)**, 1-10, doi:10.1088/1748-9326/11/9/095010.
Boysen, L.R. et al., 2017b: The limits to global-warming mitigation by terrestrial carbon removal. *Earth's Future*, **5(5)**, 463-474, doi:10.1002/2016EF000469.
Breyer, C. et al., 2017: On the role of solar photovoltaics in global energy transition scenarios. *Progress in Photovoltaics: Research and Applications*, **25(8)**, 727-745, doi:10.1002/pip.2885.
Brown, M.A. and Y. Li, 2018: Carbon Pricing and Energy Efficiency: Pathways to Deep Decarbonization of the U.S. Electric Sector. *Energy Efficiency* (in press), doi:10.1007/s12053-018-9686-9.
Brown, P.T. and K. Caldeira, 2017: Greater future global warming inferred from Earth's recent energy budget. *Nature*, **552(7683)**, 45-50, doi:10.1038/nature24672.
Bruckner, T., I.A. Bashmakov, and Y. Mulugetta, 2014: Energy Systems. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 511-598.
Brunner, S. and K. Enting, 2014: Climate finance: A transaction cost perspective on the structure of state-to-state transfers. *Global Environmental Change*, **27**, 138-143.
Brynolf, S., M. Taljegard, M. Grahn, and J. Hansson, 2018: Electrofuels for the transport sector: A review of production costs. *Renewable and Sustainable Energy Reviews*, **81**, 1887-1905, doi:https://doi.org/10.1016/j.rser.2017.05.288.
Buck, H.J., 2016: Rapid scale-up of negative emissions technologies: social barriers and social implications. *Climatic Change*, 1-13, doi:10.1007/s10584-016-1770-6.
Burke, E.J., I.P. Hartley, and C.D. Jones, 2012: Uncertainties in the global temperature change caused by carbon release from permafrost thawing. *Cryosphere*, **6(5)**, 1063-1076, doi:10.5194/tc-6-1063-2012.
Burke, E.J. et al., 2017: Quantifying uncertainties of permafrost carbon-climate feedbacks. *Biogeosciences*, **14(12)**, 3051-3066, doi:10.5194/bg-14-3051-2017.
Burns, W. and S. Nicholson, 2017: Bioenergy and carbon capture with storage (BECCS): the prospects and challenges of an emerging climate policy response. *Journal of Environmental Studies and Sciences*, **7(4)**, 527-534, doi:10.1007/s13412-017-0445-6.
Cadule, P., L. Bopp, and P. Friedlingstein, 2009: A revised estimate of the processes contributing to global warming due to climate-carbon feedback. *Geophysical Research Letters*, **36(14)**, doi:10.1029/2009GL038681.
Cai, Y., K.L. Judd, T.M. Lenton, T.S. Lontzek, and D. Narita, 2015: Environmental tipping points significantly affect the cost-benefit assessment of climate policies. *Proceedings of the National Academy of Sciences*, **112(15)**, 4606-4611, doi:10.1073/pnas.1503890112.
Calvin, K. et al., 2014: Trade-offs of different land and bioenergy policies on the path to achieving climate targets. *Climatic Change*, **123(3-4)**, 691-704, doi:10.1007/s10584-013-0897-y.
Calvin, K. et al., 2017: The SSP4: A world of deepening inequality. *Global Environmental Change*, **42**, 284-296, doi:10.1016/j.gloenvcha.2016.06.010.
Canadell, J.G. and M.R. Raupach, 2008: Managing Forests for Climate Change Mitigation. *Science*, **320(5882)**, 1456-1457, doi:10.1126/SCIENCE.1155458.
Carslaw, K.S. et al., 2013: Large contribution of natural aerosols to uncertainty in indirect forcing. *Nature*, **503(7474)**, doi:10.1038/nature12674.
Ceppi, P. and J.M. Gregory, 2017: Relationship of tropospheric stability to climate sensitivity and Earth's observed radiation budget. *Proceedings of the National Academy of Sciences of the United States of America*, 201714308, doi:10.1073/pnas.1714308114.
Chan, S., P. Ellinger, and O. Widerberg, 2018: Exploring national and regional orchestration of non-state action for a < 1.5 °C world. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 135-152, doi:10.1007/s10784-018-9384-2.
Chen, C. and M. Tavoni, 2013: Direct air capture of CO_2 and climate stabilization: A model based assessment. *Climatic Change*, **118(1)**, 59-72, doi:10.1007/s10584-013-0714-7.
Choi, Y.S., D. Young, S. Nešić, and L.G.S. Gray, 2013: Wellbore integrity and corrosion of carbon steel in CO_2 geologic storage environments: A literature review. *International Journal of Greenhouse Gas Control*, **16**, S70 - S77, doi:https://doi.org/10.1016/j.ijggc.2012.12.028.
Clack, C.T.M. et al., 2017: Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar.. *Proceedings of the National Academy of Sciences of the United States of America*, **114(26)**, 6722-6727, doi:10.1073/pnas.1610381114.
Clarke, L. et al., 2014: Assessing transformation pathways. 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, United Kingdom and New York, NY, USA, pp. 413-510.
Collins, M. et al., 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the*

Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1029-1136.
Collins, W.J. et al., 2018: Increased importance of methane reduction for a 1.5 degree target. *Environmental Research Letters*, **13(5)**, 054003, doi:10.1088/1748-9326/aab89c.
Comyn-Platt, E. et al., 2018: Natural CH4 release and permafrost thaw lower CO_2 emissions to achieve 1.5 and 2°C targets. *Nat. Geosci.* (in press).
Cox, P.M., C. Huntingford, and M.S. Williamson, 2018: Emergent constraint on equilibrium climate sensitivity from global temperature variability. *Nature*, **553(7688)**, 319-322, doi:10.1038/nature25450.
Crespo Cuaresma, J., 2017: Income projections for climate change research: A framework based on human capital dynamics. *Global Environmental Change*, **42**, 226-236, doi:10.1016/j.gloenvcha.2015.02.012.
Creutzig, F., 2016: Evolving Narratives of Low-Carbon Futures in Transportation. *Transport Reviews*, **36(3)**, 341-360, doi:10.1080/01441647.2015.1079277.
Creutzig, F. et al., 2012: Reconciling top-down and bottom-up modelling on future bioenergy deployment. *Nature Climate Change*, **2(5)**, 320-327, doi:10.1038/nclimate1416.
Creutzig, F. et al., 2015: Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy*, **7(5)**, 916-944, doi:10.1111/gcbb.12205.
Creutzig, F. et al., 2017: The underestimated potential of solar energy to mitigate climate change. *Nature Energy*, **2(9)**, 17140, doi:10.1038/nenergy.2017.140.
Davis, S.C. et al., 2013: Management swing potential for bioenergy crops. *GCB Bioenergy*, **5(6)**, 623-638, doi:10.1111/gcbb.12042.
Davis, S.J. and K. Caldeira, 2010: Consumption-based accounting of CO_2 emissions. *Proceedings of the National Academy of Sciences of the United States of America*, **107(12)**, 5687-92, doi:10.1073/pnas.0906974107.
de Richter, R., T. Ming, P. Davies, W. Liu, and S. Caillol, 2017: Removal of non-CO_2 greenhouse gases by large-scale atmospheric solar photocatalysis. *Progress in Energy and Combustion Science*, **60**, 68-96, doi:10.1016/j.pecs.2017.01.001.
de Vries, W., M. Posch, D. Simpson, and G.J. Reinds, 2017: Modelling long-term impacts of changes in climate, nitrogen deposition and ozone exposure on carbon sequestration of European forest ecosystems. *Science of the Total Environment*, **605-606**, 1097-1116, doi:10.1016/j.scitotenv.2017.06.132.
Dell, M., B.F. Jones, and B.A. Olken, 2014: What Do We Learn from the Weather ? The New Climate-Economy Literature. *Journal of Economic Literature*, **52(3)**, 740-798.
Dellink, R., J. Chateau, E. Lanzi, and B. Magné, 2017: Long-term economic growth projections in the Shared Socioeconomic Pathways. *Global Environmental Change*, **42**, 1-15, doi:10.1016/j.gloenvcha.2015.06.004.
Delponte, I., I. Pittaluga, and C. Schenone, 2017: Monitoring and evaluation of Sustainable Energy Action Plan: Practice and perspective. *Energy Policy*, **100**, 9-17, doi:10.1016/j.enpol.2016.10.003.
den Elzen, M.G.J., D.P. van Vuuren, and J. van Vliet, 2010: Postponing emission reductions from 2020 to 2030 increases climate risks and long-term costs. *Climatic Change*, **99(1)**, 313-320, doi:10.1007/s10584-010-9798-5.
den Elzen, M.G.J. et al., 2016: Contribution of the G20 economies to the global impact of the Paris agreement climate proposals. *Climatic Change*, **137(3-4)**, 655-665, doi:10.1007/s10584-016-1700-7.
Dennig, F., M.B. Budolfson, M. Fleurbaey, A. Siebert, and R.H. Socolow, 2015: Inequality, climate impacts on the future poor, and carbon prices. *Proceedings of the National Academy of Sciences*, **112(52)**, 15827-15832, doi:10.1073/pnas.1513967112.
DOE/NETL, 2013: *Cost and performance of PC and IGCC plants for a range of carbon dioxide capture: revision 1*. DOE/NETL-2011/1498, National Energy Technology Laboratory (NETL), 518 pp.
Doelman, J.C. et al., 2018: Exploring SSP land-use dynamics using the IMAGE model: Regional and gridded scenarios of land-use change and land-based climate change mitigation. *Global Environmental Change*, **48**, 119-135, doi:https://doi.org/10.1016/j.gloenvcha.2017.11.014.
Dooley, J.J., 2013: Estimating the supply and demand for deep geologic CO_2 storage capacity over the course of the 21st century: A meta-analysis of the literature. *Energy Procedia*, **37**, 5141-5150, doi:10.1016/j.egypro.2013.06.429.
Dooley, K. and S. Kartha, 2018: Land-based negative emissions: risks for climate mitigation and impacts on sustainable development. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 79-98, doi:10.1007/s10784-017-9382-9.
Duce, R.A. et al., 2008: Impacts of Atmospheric Anthropogenic Nitrogen on the Open Ocean. *Science*, **320(5878)**, 893-897.
EC, 2017: *High-Level Expert Group on Sustainable Finance interim report - Financing a sustainable European economy*. European Commission, Brussels, Belgium, 72 pp.
Edenhofer, O., J.C. Steckel, M. Jakob, and C. Bertram, 2018: Reports of coal's terminal decline may be exaggerated. *Environ. Res. Lett*, **13**, 024019.
Erb, K.H., H. Haberl, and C. Plutzar, 2012: Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability. *Energy Policy*, **47**, 260-269, doi:10.1016/j.enpol.2012.04.066.

Erb, K.H. et al., 2016a: Biomass turnover time in terrestrial ecosystems halved by land use. *Nature Geoscience*, **9(9)**, 674-678, doi:10.1038/ngeo2782.
Erb, K.H. et al., 2016b: Exploring the biophysical option space for feeding the world without deforestation. *Nature Communications*, **7**, 11382, doi:10.1038/ncomms11382.
Erb, K.H. et al., 2018: Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature*, **553**, 73-76.
Erickson, P., S. Kartha, M. Lazarus, and K. Tempest, 2015: Assessing carbon lock-in. *Environmental Research Letters*, **10(8)**, 84023.
Etminan, M., G. Myhre, E.J. Highwood, and K.P. Shine, 2016: Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters*, **43(24)**, 12,614-12,623, doi:10.1002/2016GL071930.
Faehn, T. and E. Isaksen, 2016: Diffusion of Climate Technologies in the Presence of Commitment Problems. *The Energy Journal*, **37(2)**, 155-180, doi:10.5547/01956574.37.2.tfae.
Fankhauser, S., A. Sahni, A. Savvas, and J. Ward, 2016: Where are the gaps in climate finance? *Climate and Development*, **8(3)**, 203-206, doi:10.1080/17565529.2015.1064811.
FAOSTAT, 2017: Database Collection of the Food and Agriculture Organization of the United Nations. http://www.fao.org/faostat
Fawcett, A.A. et al., 2015: Can Paris pledges avert severe climate change? *Science*, **350(6265)**, 1168-1169, doi:10.1126/science.aad5761.
Forster, P.M., 2016: Inference of Climate Sensitivity from Analysis of Earth's Energy Budget. *Annual Review of Earth and Planetary Sciences*, **44(1)**, 85-106, doi:10.1146/annurev-earth-060614-105156.
Frank, S. et al., 2017: Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters*, **12(10)**, 105004, doi:10.1088/1748-9326/aa8c83.
Frank, S. et al., 2018: Structural change as a key component for agricultural non-CO_2 mitigation efforts. *Nature Communications*, **9(1)**, 1060, doi:10.1038/s41467-018-03489-1.
Frankfurt School-UNEP Centre/BNEF, 2017: Global Trends in Renewable Energy Investment 2017. , 90.
Fricko, O. et al., 2016: Energy sector water use implications of a 2 °C climate policy. *Environmental Research Letters*, **11(3)**, 034011, doi:10.1088/1748-9326/11/3/034011.
Fricko, O. et al., 2017: The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change*, **42**, 251-267, doi:10.1016/j.gloenvcha.2016.06.004.
Friedlingstein, P. et al., 2014a: Persistent growth of CO_2 emissions and implications for reaching climate targets. *Nature Geoscience*, **7(10)**, 709-715, doi:10.1038/ngeo2248.
Friedlingstein, P. et al., 2014b: Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks. *Journal of Climate*, **27(2)**, 511-526, doi:10.1175/JCLI-D-12-00579.1.
Frölicher, T.L. and F. Joos, 2010: Reversible and irreversible impacts of greenhouse gas emissions in multi-century projections with the NCAR global coupled carbon cycle-climate model. *Climate Dynamics*, **35(7)**, 1439-1459, doi:10.1007/s00382-009-0727-0.
Fuglestvedt, J.S. et al., 2010: Transport impacts on atmosphere and climate: Metrics. *Atmospheric Environment*, **44(37)**, 4648-4677, doi:10.1016/j.atmosenv.2009.04.044.
Fujimori, S., 2017: SSP3: AIM Implementation of Shared Socioeconomic Pathways. *Global Environmental Change*, **42**, 268-283, doi:10.1016/j.gloenvcha.2016.06.009.
Fujimori, S. et al., 2016: Implication of Paris Agreement in the context of long-term climate mitigation goals. *SpringerPlus*, **5(1)**, 1620, doi:10.1186/s40064-016-3235-9.
Fuss, S. et al., 2014: Betting on negative emissions. *Nature Climate Change*, **4(10)**, 850-853, doi:10.1038/nclimate2392.
Fuss, S. et al., 2016: Research priorities for negative emissions. *Environmental Research Letters*, **11(11)**, doi:10.1088/1748-9326/11/11/115007.
Fuss, S. et al., 2018: Negative emissions - Part 2: Costs, potentials and side effects. *Environmental Research Reviews* (in press), doi:10.1088/1748-9326/aabf9f.
Geden, O., 2015: Policy: Climate advisers must maintain integrity. *Nature*, **521(7550)**, 27-28, doi:10.1038/521027a.
Geels, F.W., B.K. Sovacool, T. Schwanen, and S. Sorrell, 2017: Sociotechnical transitions for deep decarbonization. *Science*, **357(6357)**.
Gerber, P.J. et al., 2013: *Tackling Climate Change through Livestock: A global assessment of emissions and mitigation opportunities*. 115 pp.
Gernaat, D.E.H.J. et al., 2015: Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. *Global Environmental Change*, **33**, 142-153, doi:10.1016/j.gloenvcha.2015.04.010.
Ghan, S.J. et al., 2013: A simple model of global aerosol indirect effects. *Journal of Geophysical Research: Atmospheres*, **118(12)**, 6688-6707, doi:10.1002/jgrd.50567.
Ghota, S., C. Huizenga, K. Peet, N. Medimorec, and S. Bakker, 2018: Decarbonising Transport to Achieve Paris Agreement Targets. *Energy Efficiency* (in press).
Giannakidis, G., K. Karlsson, M. Labriet, and B. Ó Gallachóir (eds.), 2018: *Limiting Global Warming to Well Below 2 °C: Energy System Modelling and Policy Development*. Springer International Publishing, 423 pp.

Gillett, N.P., V.K. Arora, D. Matthews, and M.R. Allen, 2013: Constraining the Ratio of Global Warming to Cumulative CO_2 Emissions Using CMIP5 Simulations. *Journal of Climate*, **26(18)**, 6844-6858, doi:10.1175/JCLI-D-12-00476.1.

Gillett, N.P., V.K. Arora, K. Zickfeld, S.J. Marshall, and W.J. Merryfield, 2011: Ongoing climate change following a complete cessation of carbon dioxide emissions. *Nature Geoscience*, **4(2)**, 83-87, doi:10.1038/ngeo1047.

Global CCS Institute, 2016: *The Global Status of CCS: 2016 Summary Report*. 28 pp.

González-Eguino, M., A. Olabe, and T. Ribera, 2017: New Coal-Fired Plants Jeopardise Paris Agreement. *Sustainability*, **9(2)**.

Goodwin, P., S. Brown, I.D. Haigh, R.J. Nicholls, and J.M. Matter, 2018a: Adjusting Mitigation Pathways to Stabilize Climate at 1.5°C and 2.0°C Rise in Global Temperatures to Year 2300. *Earth's Future*, 0-3, doi:10.1002/2017EF000732.

Goodwin, P. et al., 2018b: Pathways to 1.5 and 2 °C warming based on observational and geological constraints. *Nature Geoscience*, **11(1)**, 1-22, doi:10.1038/s41561-017-0054-8.

Gough, C. and P. Upham, 2011: Biomass energy with carbon capture and storage (BECCS or Bio-CCS). *Greenhouse Gases: Science and Technology*, **1(4)**, 324-334, doi:10.1002/ghg.34.

Goulder, L. and A. Schein, 2013: Carbon Taxes vs. Cap and Trade: A Critical Review. *Climate Change Economics*, **04(03)**, 1350010, doi:10.1142/S2010007813500103.

Grassi, G. et al., 2017: The key role of forests in meeting climate targets requires science for credible mitigation. *Nature Climate Change*, **7(3)**, 220-226, doi:10.1038/nclimate3227.

Greene, C.H. et al., 2017: Geoengineering, Marine Microalgae, and Climate Stabilization in the 21st Century. *Earth's Future*, doi:10.1002/2016EF000486.

Gregory, J.M. and T. Andrews, 2016: Variation in climate sensitivity and feedback parameters during the historical period. *Geophysical Research Letters*, **43(8)**, 3911-3920, doi:10.1002/2016GL068406.

Gren, I.M. and A.Z. Aklilu, 2016: Policy design for forest carbon sequestration: A review of the literature. *Forest Policy and Economics*, **70**, 128-136, doi:https://doi.org/10.1016/j.forpol.2016.06.008.

Griscom, B.W. et al., 2017: Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America*, **114(44)**, 11645-11650, doi:10.1073/pnas.1710465114.

Grubb, M., J.C. Hourcade, and K. Neuhoff, 2014: *Planetary economics: energy, climate change and the three domains of sustainable development*. Routledge Earthscan, Oxon, New York, 520 pp.

Grubler, A. and C. Wilson, 2014: *Energy Technology Innovation - Learning from Historical Succeses and Failures*. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 400 pp.

Grubler, A. et al., 2018: A Global Scenario of Low Energy Demand for Sustainable Development below 1.5°C without Negative Emission Technologies. *Nature Energy* (in press).

Guivarch, C. and J. Rogelj, 2017: *Carbon price variations in 2°C scenarios explored*. 15 pp.

Güneralp, B. et al., 2017: Global scenarios of urban density and its impacts on building energy use through 2050. *Proceedings of the National Academy of Sciences*, **114(34)**, 8945-8950, doi:10.1073/pnas.1606035114.

Gupta, S. and J. Harnisch, 2014: Cross-cutting Investment and Finance Issues. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Inter- governmental 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, United Kingdom and New York, NY, USA, pp. 1207-1246.

Haberl, H., 2015: Competition for land: A sociometabolic perspective. *Ecological Economics*, **119**, 424-431, doi:https://doi.org/10.1016/j.ecolecon.2014.10.002.

Haberl, H. et al., 2011: Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. *Biomass and Bioenergy*, **35(12)**, 4753-4769, doi:https://doi.org/10.1016/j.biombioe.2011.04.035.

Haberl, H. et al., 2013: Bioenergy: how much can we expect for 2050? *Environmental Research Letters*, **8(3)**, 031004, doi:10.1088/1748-9326/8/3/031004.

Harmes, A., 2011: The Limits of Carbon Disclosure: Theorizing the Business Case for Investor Environmentalism. *Global Environmental Politics*, **11(2)**, 98-119.

Hartmann, J. et al., 2013: Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Reviews of Geophysics*, **51(2)**, 113-149, doi:10.1002/rog.20004.

Hauglustaine, D.A., Y. Balkanski, and M. Schulz, 2014: A global model simulation of present and future nitrate aerosols and their direct radiative forcing of climate. *Atmos. Chem. Phys*, **14**, 11031-11063, doi:10.5194/acp-14-11031-2014.

Havlik, P. et al., 2013: Crop Productivity and the Global Livestock Sector: Implications for Land Use Change and Greenhouse Gas Emissions. *American Journal of Agricultural Economics*, **95(2)**, 442-448, doi:10.1093/ajae/aas085.

Havlík, P. et al., 2014: Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences of the United States of America*, **111(10)**, 3709-14, doi:10.1073/pnas.1308044111.

Heck, V., D. Gerten, W. Lucht, and L.R. Boysen, 2016: Is extensive terrestrial carbon dioxide removal a 'green' form of

geoengineering? A global modelling study. *Global and Planetary Change*, **137**, 123-130, doi:10.1016/j.gloplacha.2015.12.008.
Heck, V., D. Gerten, W. Lucht, and A. Popp, 2018: Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change*, **8(2)**, 151-155, doi:10.1038/s41558-017-0064-y.
Hejazi, M. et al., 2014: Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. *Technological Forecasting and Social Change*, **81**, 205-226, doi:10.1016/j.techfore.2013.05.006.
Herrero, M. et al., 2016: Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change*, **6(5)**, 452-461, doi:10.1038/nclimate2925.
Herrington, T. and K. Zickfeld, 2014: Path independence of climate and carbon cycle response over a broad range of cumulative carbon emissions. *Earth System Dynamics*, **5**, 409-422, doi:10.5194/esd-5-409-2014.
Herzog, H., K. Caldeira, and J. Reilly, 2003: An Issue of Permanence: Assessing the Effectiveness of Temporary Carbon Storage. *Climate Change*, **59**, 293-310.
Hildingsson, R. and B. Johansson, 2016: Governing low-carbon energy transitions in sustainable ways: Potential synergies and conflicts between climate and environmental policy objectives. *Energy Policy*, **88**, 245-252, doi:10.1016/J.ENPOL.2015.10.029.
Hoesly, R.M. et al., 2018: Historical (1750-2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). *Geoscientific Model Development*, **11(1)**, 369-408, doi:10.5194/gmd-11-369-2018.
Hof, A.F. et al., 2017: Global and regional abatement costs of Nationally Determined Contributions (NDCs) and of enhanced action to levels well below 2 °C and 1.5 °C. *Environmental Science & Policy*, **71**, 30-40, doi:10.1016/j.envsci.2017.02.008.
Höglund-Isaksson, L. et al., 2017: Cost estimates of the Kigali Amendment to phase-down hydrofluorocarbons. *Environmental Science & Policy*, **75**, 138-147, doi:10.1016/j.envsci.2017.05.006.
Holz, C., S. Kartha, and T. Athanasiou, 2018a: Fairly sharing 1.5: national fair shares of a 1.5C-compliant global mitigation effort. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 117-134, doi:10.1007/s10784-017-9371-z.
Holz, C., L. Siegel, E. Johnston, A.P. Jones, and J. Sterman, 2018b: Ratcheting ambition to limit warming to 1.5°C - trade-offs between emission reductions and carbon dioxide removal. *Environmental Research Letters* (in press), doi:10.1088/1748-9326/aac0c1.
Honegger, M. and D. Reiner, 2018: The political economy of negative emissions technologies: consequences for international policy design. *Climate Policy*, **18(3)**, 306-321, doi:10.1080/14693062.2017.1413322.
Hong, S., C.J.A. Bradshaw, and B.W. Brook, 2015: Global zero-carbon energy pathways using viable mixes of nuclear and renewables. *Applied Energy*, **143**, 451-459, doi:10.1016/J.APENERGY.2015.01.006.
Hope, C., 2006: The Marginal Impact of CO_2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern. *The Integrated Assessment Journal*, **6(1)**, 16-56.
Hristov, A.N. et al., 2015: An inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production.. *Proceedings of the National Academy of Sciences of the United States of America*, **112(34)**, 10663-8, doi:10.1073/pnas.1504124112.
Hsiang, S. et al., 2017: Estimating economic damage from climate change in the United States. *Science*, **356(6345)**, 1362 LP - 1369.
Humpenöder, F. et al., 2014: Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environmental Research Letters*, **9(6)**, 64029, doi:10.1088/1748-9326/9/6/064029.
Humpenöder, F. et al., 2017: Large-scale bioenergy production: How to resolve sustainability trade-offs? *Environmental Research Letters*, doi:10.1088/1748-9326/aa9e3b.
Huntingford, C. and J. Lowe, 2007: "Overshoot" Scenarios and Climate Change. *Science*, **316(5826)**, 829, doi:10.1126/science.316.5826.829b.
IEA, 2014: *Energy Technology Perspectives 2014*. International Energy Agency (IEA), Paris, France, 382 pp.
IEA, 2015a: *Energy and Climate Change. World Energy Outlook Special Report*. International Energy Agency (IEA), 200 pp.
IEA, 2015b: *Energy Technology Perspectives 2015*. International Energy Agency (IEA), Paris, France, 418 pp.
IEA, 2016a: *Energy Technology Perspectives 2016*. International Energy Agency (IEA), Paris, France, 418 pp.
IEA, 2016b: *World Energy Investment 2016*. IEA/OECD, Paris, 177 pp.
IEA, 2017a: *Energy Technology Perspectives 2017: Catalyzing Energy Technology Transformations*. International Energy Agency (IEA), Paris, France, France, 443 pp.
IEA, 2017b: *Renewables Information - Overview (2017 edition)*. International Energy Agency (IEA), Paris, 11 pp.
IEA, 2017c: *World Energy Investment 2017*. International Energy Agency (IEA), Paris, France, 191 pp.
IEA, 2017d: World Energy Outlook 2017. , 782.
IEA, 2017e: *World Energy Statistics 2017*. International Energy Agency (IEA).
IEAGHG, 2006: *Near zero emission technology for* CO_2 *capture from power plant*. IEA Greenhouse Gas R&D Programme, Cheltenham, UK, 114 pp.
Ilyina, T., D. Wolf-Gladrow, G. Munhoven, and C. Heinze, 2013: Assessing the potential of calcium-based artificial ocean alkalinization to mitigate rising atmospheric CO_2 and ocean acidification. *Geophysical Research Letters*,

40(22), 5909-5914, doi:10.1002/2013GL057981.
Interagency Working Group on Social Cost of Greenhouse Gases, 2016: *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*. 35 pp.
IPCC, 2005: IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. [Metz, B., O. Davidson, H.C. de Coninck, M. Loos, and L.A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.
IPCC, 2013a: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambirdge University Press, Cambride, United Kingdom and New York, USA, 1535 pp.
IPCC, 2013b: Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.
IPCC, 2014a: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Core Writing Team, R.K. Pachauri, and L.A. Meyer (eds.)]. 151 pp.
IPCC, 2014b: Summary for Policymakers. 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. Kadne, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-30.
IPCC/TEAP, 2005: Special Report on Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons. Cambridge University Press, Cambridge, UK and New York, NY, USA, 485 pp.
Irlam, L., 2017: *Global Costs of Carbon Capture and Storage*. Global CCS Institute, 14 pp.
Iyer, G.C. et al., 2015: Improved representation of investment decisions in assessments of CO_2 mitigation. *Nature Climate Change*, **5(5)**, 436-440, doi:10.1038/nclimate2553.
Jackson, R.B. et al., 2017: Warning signs for stabilizing global CO 2 emissions. *Environmental Research Letters*, **12(11)**, 110202, doi:10.1088/1748-9326/aa9662.
Jacobson, M.Z., 2002: Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming. *Journal of Geophysical Research*, **107(D19)**, 4410, doi:10.1029/2001JD001376.
Jacobson, M.Z., 2010: Short-term effects of controlling fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health. *Journal of Geophysical Research*, **115(D14)**, D14209, doi:10.1029/2009JD013795.
Jacobson, M.Z., 2017: Roadmaps to Transition Countries to 100% Clean, Renewable Energy for All Purposes to Curtail Global Warming, Air Pollution, and Energy Risk. *Earth's Future*, **5(10)**, 948-952, doi:10.1002/2017EF000672.
Jacobson, M.Z. et al., 2017: 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. *Joule*, **1(1)**, 108-121, doi:10.1016/j.joule.2017.07.005.
Jakob, M. and J.C. Steckel, 2016: Implications of climate change mitigation for sustainable development. *Environmental Research Letters*, **11(10)**, 104010, doi:10.1088/1748-9326/11/10/104010.
Jakob, M. et al., 2014: Feasible mitigation actions in developing countries. *Nature Climate Change*, **4(11)**, 961-968, doi:10.1038/nclimate2370.
Jie Di, H. and K. Cameron, 2016: Inhibition of nitrification to mitigate nitrate leaching and nitrous oxide emissions in grazed grassland: A review. *Journal of Soils and Sediments*, **16**, 1401-1420, doi:10.1007/s11368-016-1403-8.
Johnson, N. et al., 2015: Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. *Technological Forecasting and Social Change*, **90**, 89-102, doi:10.1016/j.techfore.2014.02.028.
Jones, A., J.M. Haywood, and C.D. Jones, 2018: Can reducing black carbon and methane below RCP2.6 levels keep global warming below 1.5 °C? *Atmospheric Science Letters*, doi:10.1002/asl.821.
Jones, C.D. et al., 2016: Simulating the Earth system response to negative emissions. *Environmental Research Letters*, **11(9)**, 95012, doi:10.1088/1748-9326/11/9/095012.
Jones, D.G. et al., 2015: Developments since 2005 in understanding potential environmental impacts of CO_2 leakage from geological storage. *International Journal of Greenhouse Gas Control*, **40**, 350-377, doi:10.1016/J.IJGGC.2015.05.032.
Joshi, V. and S. Kumar, 2015: Meat Analogues: Plant based alternatives to meat products- A review. *International journal of food fermentation and technology*, **5(2)**, 107-119.
Kandlikar, M., 1995: The relative role of trace gas emissions in greenhouse abatement policies. *Energy Policy*, **23(10)**, 879-883, doi:10.1016/0301-4215(95)00108-U.
KC, S. and W. Lutz, 2017: The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change*, **42**, 181-192, doi:10.1016/j.gloenvcha.2014.06.004.
Kearns, J. et al., 2017: Developing a consistent database for regional geologic CO_2 storage capacity worldwide. *Energy*

Procedia, **114**, 4697-4709, doi:10.1016/j.egypro.2017.03.1603.
Keith, D.W. and J.S. Rhodes, 2002: Bury, Burn or Both: A Two-for-One Deal on Biomass Carbon and Energy. *Climatic Change*, **54(3)**, 375-377, doi:10.1023/A:1016187420442.
Keith, D.W., M. Ha-Duong, and J.K. Stolaroff, 2006: Climate Strategy with CO_2 Capture from the Air. *Climatic Change*, **74(1-3)**, 17-45, doi:10.1007/s10584-005-9026-x.
Kheshgi, H.S., 1995: Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. *Energy*, **20(9)**, 915-922, doi:10.1016/0360-5442(95)00035-F.
Kim, S.H., K. Wada, A. Kurosawa, and M. Roberts, 2014: Nuclear energy response in the EMF27 study. *Climatic Change*, **123(3-4)**, 443-460, doi:10.1007/s10584-014-1098-z.
Klein, D. et al., 2014: The value of bioenergy in low stabilization scenarios: An assessment using REMIND-MAgPIE. *Climatic Change*, **123(3-4)**, 705-718, doi:10.1007/s10584-013-0940-z.
Klimont, Z. et al., 2017: Global anthropogenic emissions of particulate matter including black carbon. *Atmospheric Chemistry and Physics*, **17(14)**, 8681-8723, doi:10.5194/acp-17-8681-2017.
Klinsky, S. and H. Winkler, 2018: Building equity in: strategies for integrating equity into modelling for a 1.5°C world, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, doi:10.1098/rsta.2016.0461.
Knutti, R. and J. Rogelj, 2015: The legacy of our CO_2 emissions: a clash of scientific facts, politics and ethics. *Climatic Change*, **133(3)**, 361-373, doi:10.1007/s10584-015-1340-3.
Knutti, R., M.A.A. Rugenstein, and G.C. Hegerl, 2017: Beyond equilibrium climate sensitivity. *Nature Geoscience*, **10(10)**, 727-736, doi:10.1038/ngeo3017.
Kolstad, C. et al., 2014: Social, Economic and Ethical Concepts and Methods. 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. Kadne, 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 Univeristy Press, Cambridge, United Kingdom and New York, NY, USA, pp. 207-282.
Krasting, J.P., J.P. Dunne, E. Shevliakova, and R.J. Stouffer, 2014: Trajectory sensitivity of the transient climate response to cumulative carbon emissions. *Geophysical Research Letters*, **41(7)**, 2520-2527, doi:10.1002/(ISSN)1944-8007.
Krause, A. et al., 2017: Global consequences of afforestation and bioenergy cultivation on ecosystem service indicators. *Biogeosciences*, **14(21)**, 4829-4850, doi:10.5194/bg-14-4829-2017.
Kraxner, F. et al., 2013: Global bioenergy scenarios - Future forest development, land-use implications, and trade-offs. *Biomass and Bioenergy*, **57**, 86-96, doi:10.1016/j.biombioe.2013.02.003.
Kreidenweis, U. et al., 2016: Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects. *Environmental Research Letters*, **11(8)**, 85001, doi:10.1088/1748-9326/11/8/085001.
Kretzschmar, J. et al., 2017: Comment on "Rethinking the Lower Bound on Aerosol Radiative Forcing". *Journal of Climate*, **30(16)**, 6579-6584, doi:10.1175/JCLI-D-16-0668.1.
Krey, V., G. Luderer, L. Clarke, and E. Kriegler, 2014a: Getting from here to there - energy technology transformation pathways in the EMF27 scenarios. *Climatic Change*, **123**, 369-382, doi:10.1007/s10584-013-0947-5.
Krey, V. et al., 2014b: Annex II: Metrics & Methodology. 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, United Kingdom and New York, NY, USA, pp. 1281-1328.
Kriegler, E., O. Edenhofer, L. Reuster, G. Luderer, and D. Klein, 2013a: Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Climatic Change*, **118(1)**, doi:10.1007/s10584-012-0681-4.
Kriegler, E. et al., 2012: The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. *Global Environmental Change*, **22(4)**, 807-822, doi:10.1016/j.gloenvcha.2012.05.005.
Kriegler, E. et al., 2013b: What Does the 2°C Target Imply for a Global Climate Agreement in 2020? The Limits Study on Durban Platform Scenarios. *Climate Change Economics*, **04(04)**, 1340008, doi:10.1142/S2010007813400083.
Kriegler, E. et al., 2014a: A new scenario framework for climate change research: the concept of shared climate policy assumptions. *Climatic Change*, **122(3)**, 401-414, doi:10.1007/s10584-013-0971-5.
Kriegler, E. et al., 2014b: The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change*, **123(3-4)**, 353-367, doi:10.1007/s10584-013-0953-7.
Kriegler, E. et al., 2015a: Diagnostic indicators for integrated assessment models of climate policy. *Technological Forecasting and Social Change*, **90(PA)**, 45-61, doi:10.1016/j.techfore.2013.09.020.
Kriegler, E. et al., 2015b: Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technological Forecasting and Social Change*, **90(PA)**, 24-44, doi:10.1016/j.techfore.2013.09.021.

Kriegler, E. et al., 2016: Will economic growth and fossil fuel scarcity help or hinder climate stabilization?: Overview of the RoSE multi-model study. *Climatic Change*, **136(1)**, 7-22, doi:10.1007/s10584-016-1668-3.
Kriegler, E. et al., 2017: Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Global Environmental Change*, **42**, 297-315, doi:10.1016/j.gloenvcha.2016.05.015.
Kriegler, E. et al., 2018a: Pathways limiting warming to 1.5°C: A tale of turning around in no time? *Philosophical Transactions of the Royal Society A - Mathematical Physical and Engineering Sciences*, **376**, 20160457.
Kriegler, E. et al., 2018b: Short term policies to keep the door open for Paris climate goals. *Environ. Res. Lett* (in press), doi:10.1088/1748-9326/aac4f1.
Kuramochi, T. et al., 2017: Ten key short-term sectoral benchmarks to limit warming to 1.5°C. *Climate Policy*, **18(3)**, 1-19, doi:10.1080/14693062.2017.1397495.
Lamarque, J.F. et al., 2011: Global and regional evolution of short-lived radiatively-active gases and aerosols in the Representative Concentration Pathways. *Climatic Change*, **109(1-2)**, 191-212, doi:10.1007/s10584-011-0155-0.
Lambin, E.F. and P. Meyfroidt, 2011: Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences of the United States of America*, **108(9)**, 3465-72, doi:10.1073/pnas.1100480108.
Le Quéré, C. et al., 2018: Global Carbon Budget 2017. *Earth System Science Data*, **10(1)**, 405-448, doi:10.5194/essd-10-405-2018.
Lehtilä, A. and T. Koljonen, 2018: Pathways to Post-fossil Economy in a Well Below 2 ℃ World. In: *Limiting Global Warming to Well Below 2 °C: Energy System Modelling and Policy Development* [Giannakidis, G., K. Karlsson, M. Labriet, and B. Gallachóir (eds.)]. Springer International Publishing, Cham, pp. 33-49.
Leimbach, M., E. Kriegler, N. Roming, and J. Schwanitz, 2017: Future growth patterns of world regions - A GDP scenario approach. *Global Environmental Change*, **42**, 215-225, doi:10.1016/j.gloenvcha.2015.02.005.
Lemoine, D. and C. Traeger, 2014: Watch Your Step: Optimal Policy in a Tipping Climate. *American Economic Journal: Economic Policy*, **6(1)**, 137-166, doi:10.1257/pol.6.1.137.
Lenton, A., R.J. Matear, D.P. Keller, V. Scott, and N.E. Vaughan, 2018: Assessing carbon dioxide removal through global and regional ocean alkalinization under high and low emission pathways. *Earth System Dynamics*, **9(2)**, 339-357, doi:10.5194/esd-9-339-2018.
Lewis, N. and J.A. Curry, 2015: The implications for climate sensitivity of AR5 forcing and heat uptake estimates. *Climate Dynamics*, **45(3-4)**, 1009-1023, doi:10.1007/s00382-014-2342-y.
Lewis, N. and J. Curry, 2018: The impact of recent forcing and ocean heat uptake data on estimates of climate sensitivity. *Journal of Climate*, JCLI-D-17-0667.1, doi:10.1175/JCLI-D-17-0667.1.
Liu, J., T.W. Hertel, F. Taheripour, T. Zhu, and C. Ringler, 2014: International trade buffers the impact of future irrigation shortfalls. *Global Environmental Change*, **29**, 22-31, doi:10.1016/J.GLOENVCHA.2014.07.010.
Liu, J.Y. et al., 2017: Socio-economic factors and future challenges of the goal of limiting the increase in global average temperature to 1.5°C. *Carbon Management* (in press).
Löffler, K. et al., 2017: Designing a Model for the Global Energy System-GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS). *Energies*, **10(10)**, 1468, doi:10.3390/en10101468.
Lontzek, T.S., Y. Cai, K.L. Judd, and T.M. Lenton, 2015: Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy. *Nature Climate Change*, **5(5)**, 441-444.
Lowe, J.A. and D. Bernie, 2018: The impact of Earth system feedbacks on carbon budgets and climate response. *Philosophical Transactions of the Royal Society A - Mathematical Physical and Engineering Sciences*, doi:10.1098/rsta.2017.0263.
Lowe, J.A. et al., 2009: How difficult is it to recover from dangerous levels of global warming? *Environmental Research Letters*, **4(1)**, 014012, doi:10.1088/1748-9326/4/1/014012.
Lucon, O. et al., 2014: Buildings. 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, United Kingdom and New York, NY, USA, pp. 671-738.
Luderer, G., C. Bertram, K. Calvin, E. De Cian, and E. Kriegler, 2016a: Implications of weak near-term climate policies on long-term mitigation pathways. *Climatic Change*, **136(1)**, 127-140, doi:10.1007/s10584-013-0899-9.
Luderer, G. et al., 2013: Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environmental Research Letters*, **8(3)**, 034033, doi:10.1088/1748-9326/8/3/034033.
Luderer, G. et al., 2014: The role of renewable energy in climate stabilization: results from the {EMF}27 scenarios. *Climatic Change*, **123(3-4)**, 427-441, doi:10.1007/s10584-013-0924-z.
Luderer, G. et al., 2016b: *Deep Decarbonization towards 1.5°C - 2°C stabilization: Policy findings from the ADVANCE project*. 42 pp.
Luderer, G. et al., 2017: Assessment of wind and solar power in global low-carbon energy scenarios: An introduction. *Energy Economics*, **64**, 542-551, doi:10.1016/J.ENECO.2017.03.027.
Luderer, G. et al., 2018: Residual fossil CO_2 emissions in 1.5-2°C pathways. *Nature Climate Change* (in press), doi:10.1038/s41558-018-0198-6.

Lutz, W. and S. KC, 2011: Global Human Capital: Integrating Education and Population. *Science*, **333(6042)**, 587-592, doi:10.1126/science.1206964.
MacDougall, A.H., K. Zickfeld, R. Knutti, and H.D. Matthews, 2015: Sensitivity of carbon budgets to permafrost carbon feedbacks and non-CO 2 forcings. *Environmental Research Letters*, **10(12)**, 125003, doi:10.1088/1748-9326/10/12/125003.
Madeira, M.S. et al., 2017: Microalgae as feed ingredients for livestock production and meat quality: A review. *Livestock Science*, **205**, 111-121, doi:10.1016/j.livsci.2017.09.020.
Mahowald, N.M. et al., 2017: Aerosol Deposition Impacts on Land and Ocean Carbon Cycles. *Current Climate Change Reports*, **3(1)**, 16-31, doi:10.1007/s40641-017-0056-z.
Malavelle, F.F. et al., 2017: Strong constraints on aerosol-cloud interactions from volcanic eruptions. *Nature*, **546(7659)**, 485-491, doi:10.1038/nature22974.
Marangoni, G. and M. Tavoni, 2014: The Clean Energy R&D Strategy for 2°C. *Climate Change Economics*, **05(01)**, 1440003, doi:10.1142/S201000781440003X.
Marangoni, G. et al., 2017: Sensitivity of projected long-term CO_2 emissions across the Shared Socioeconomic Pathways. *Nature Climate Change*, **7(January)**, 113-119, doi:10.1038/nclimate3199.
Marcucci, A., S. Kypreos, and E. Panos, 2017: The road to achieving the long-term Paris targets: Energy transition and the role of direct air capture. *Climatic Change*, **144(2)**, 181-193, doi:10.1007/s10584-017-2051-8.
Marten, A.L., E.A. Kopits, C.W. Griffiths, S.C. Newbold, and A. Wolverton, 2015: Incremental CH4 and N2O mitigation benefits consistent with the US Government's SC-CO_2 estimates. *Climate Policy*, **15(2)**, 272-298, doi:10.1080/14693062.2014.912981.
Marvel, K., G.A. Schmidt, R.L. Miller, and L.S. Nazarenko, 2016: Implications for climate sensitivity from the response to individual forcings. *Nature Clim. Change*, **6(4)**, 386-389, doi:10.1038/NCLIMATE2888.
Masui, T. et al., 2011: An emission pathway for stabilization at 6 Wm-2 radiative forcing. *Climatic Change*, **109(1)**, 59-76, doi:10.1007/s10584-011-0150-5.
Matter, J.M. et al., 2016: Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science*, **352(6291)**, 1312 LP - 1314.
Matthews, H.D. and K. Caldeira, 2008: Stabilizing climate requires near-zero emissions. *Geophysical Research Letters*, **35(4)**, 1-5, doi:10.1029/2007GL032388.
Matthews, H.D. and K. Zickfeld, 2012: Climate response to zeroed emissions of greenhouse gases and aerosols. *Nature Climate Change*, **2(5)**, 338-341, doi:10.1038/NCLIMATE1424.
Matthews, H.D., N.P. Gillett, P.A. Stott, and K. Zickfeld, 2009: The proportionality of global warming to cumulative carbon emissions. *Nature*, **459(7248)**, 829-832, doi:10.1038/nature08047.
Matthews, H.D. et al., 2017: Estimating Carbon Budgets for Ambitious Climate Targets. *Current Climate Change Reports*, **3**, 69-77, doi:10.1007/s40641-017-0055-0.
Mazzotti, M. et al., 2005: Mineral carbonation and industrial uses of carbon dioxide. In: *IPCC Special Report on Carbon dioxide Capture and Storage* [Metz, B., O. Davidson, H.C. de Coninck, M. Loos, and L.A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 319-338.
McCollum, D.L., V. Krey, and K. Riahi, 2011: An integrated approach to energy sustainability. *Nature Climate Change*, **1(9)**, 428-429, doi:10.1038/nclimate1297.
McCollum, D.L., W. Zhou, C. Bertram, H.S. de Boer, and V. Bosetti, 2018: Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy*, doi:10.1038/s41560-018-0179-z.
McCollum, D.L. et al., 2013: Energy Investments Under Climate Policy: A Comparison of Global Models. *Clim. Change Econ.*, **4(4)**, doi:10.1142/s2010007813400101.
McCollum, D.L. et al., 2017: Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. *Transportation Research Part D: Transport and Environment*, **55**, 322-342, doi:10.1016/j.trd.2016.04.003.
McFarland, J.R., A.A. Fawcett, A.C. Morris, J.M. Reilly, and P.J. Wilcoxen, 2018: Overview of the EMF 32 Study on U.S. Carbon Tax Scenarios. *Climate Change Economics*, **09(01)**, 1840002, doi:10.1142/S201000781840002X.
McLeod, E. et al., 2011: A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Frontiers in Ecology and the Environment*, **9(10)**, 552-560, doi:10.1890/110004.
Mehling, M. and E. Tvinnereim, 2018: Carbon Pricing and the 1.5°C Target: Near-Term Decarbonisation and the Importance of an Instrument Mix. *Carbon & Climate Law Review*, **12(1)**, 50-61, doi:https://doi.org/10.21552/cclr/2018/1/9.
Meinshausen, M., S.C.B. Raper, and T.M.L. Wigley, 2011a: Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 1: Model description and calibration. *Atmospheric Chemistry and Physics*, **11(4)**, 1417-1456, doi:10.5194/acp-11-1417-2011.
Meinshausen, M. et al., 2009: Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature*, **458(7242)**, 1158-1162, doi:10.1038/nature08017.
Meinshausen, M. et al., 2011b: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change*, **109(1-2)**, 213-241, doi:10.1007/s10584-011-0156-z.
Méjean, A., C. Guivarch, J. Lefèvre, and M. Hamdi-Cherif, 2018: The transition in energy demand sectors to limit

global warming to 1.5°C. *Energy Efficiency* (in press), doi: 10.1007/s12053-018-9682-0.
Mengis, N., A. Partanen, J. Jalbert, and H.D. Matthews, 2018: 1.5 °C carbon budget dependent on carbon cycle uncertainty and future non-CO_2 forcing. *Scientific Reports*, **8(1)**, 5831, doi:10.1038/s41598-018-24241-1.
Michaelowa, A., M. Allen, and F. Sha, 2018: Policy instruments for limiting global temperature rise to 1.5°C - can humanity rise to the challenge? *Climate Policy*, **18(3)**, 275-286, doi:10.1080/14693062.2018.1426977.
Millar, R.J. and P. Friedlingstein, 2018: The utility of the historical record for assessing the transient climate response to cumulative emissions. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, 20160449, doi:10.1098/rsta.2016.0449.
Millar, R.J. et al., 2017: Emission budgets and pathways consistent with limiting warming to 1.5 °C. *Nature Geoscience*, **10(10)**, 741-747, doi:10.1038/ngeo3031.
Minx, J.C., W.F. Lamb, M.W. Callaghan, L. Bornmann, and S. Fuss, 2017: Fast growing research on negative emissions. *Environmental Research Letters*, **12(3)**, 035007, doi:10.1088/1748-9326/aa5ee5.
Minx, J.C., W.F. Lamb, M.W. Callaghan, S. Fuss, and J. Hilaire, 2018: Negative emissions: Part 1 - research landscape and synthesis. *Environmental Research Reviews* (in press), doi:doi.org/10.1088/1748-9326/aabf9b.
Moore, F.C. and D.B. Diaz, 2015: Temperature impacts on economic growth warrant stringent mitigation policy. *Nature Climate Change*, **5(January)**, 127-132, doi:10.1038/nclimate2481.
Mouratiadou, I. et al., 2016: The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways. *Environmental Science and Policy*, **64**, 48-58, doi:10.1016/j.envsci.2016.06.007.
Muller, A. et al., 2017: Strategies for feeding the world more sustainably with organic agriculture. *Nature Communications*, **8(1)**, 1290, doi:10.1038/s41467-017-01410-w.
Mundaca, L. and A. Markandya, 2016: Assessing regional progress towards a Green Energy Economy. *Applied Energy*, **179**, 1372-1394, doi:10.1016/j.apenergy.2015.10.098.
Mundaca, L., M. Mansoz, L. Neij, and G. Timilsina, 2013: Transaction costs analysis of low-carbon technologies. *Climate Policy*, **13(4)**, 490-513, doi:10.1080/14693062.2013.781452.
Mundaca, L., L. Neij, A. Markandya, P. Hennicke, and J. Yan, 2016: Towards a Green Energy Economy? Assessing policy choices, strategies and transitional pathways. *Applied Energy*, **179**, 1283-1292, doi:10.1016/j.apenergy.2016.08.086.
Myhre, G. et al., 2013: Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659-740.
Myhre, G. et al., 2017: Multi-model simulations of aerosol and ozone radiative forcing due to anthropogenic emission changes during the period 1990-2015. *Atmospheric Chemistry and Physics*, **17(4)**, 2709-2720, doi:10.5194/acp-17-2709-2017.
Narayan, C., P.M. Fernandes, J. van Brusselen, and A. Schuck, 2007: Potential for CO_2 emissions mitigation in Europe through prescribed burning in the context of the Kyoto Protocol. *Forest Ecology and Management*, **251(3)**, 164-173, doi:10.1016/j.foreco.2007.06.042.
NASEM, 2016: *Assessment of Approaches to Updating the Social Cost of Carbon: Phase 1 Report on a Near-Term Update*. The National Academies Press, Washington DC, USA.
NASEM, 2017: *Valuing Climate Damages: Updating estimation of the social costs of carbon dioxide*. National Academies of Sciences, Engineering, and Medicine (NASEM), The National Academies Press, Washington DC, USA.
Naudts, K. et al., 2016: Europe's forest management did not mitigate climate warming. *Science*, **351(6273)**, 597-600, doi:10.1126/science.aad7270.
Nelson, G.C. et al., 2014: Climate change effects on agriculture: economic responses to biophysical shocks.. *Proceedings of the National Academy of Sciences of the United States of America*, **111(9)**, 3274-9, doi:10.1073/pnas.1222465110.
Nemet, G.F. et al., 2018: Negative emissions - Part 3: Innovation and upscaling. *Environmental Research Letters* (in press), 1-51, doi:10.1088/1748-9326/aabff4.
NETL, 2015: Carbon Storage Atlas - Fifth Edition (Atlas V). U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL).
Nicol, A. et al., 2013: Induced seismicity; observations, risks and mitigation measures at CO_2 storage sites. *Energy Procedia*, **37**, 4749-4756, doi:10.1016/j.egypro.2013.06.384.
Nohara, D. et al., 2015: Examination of a climate stabilization pathway via zero-emissions using Earth system models. *Environmental Research Letters*, **10(9)**, 095005, doi:10.1088/1748-9326/10/9/095005.
Nordhaus, W.D., 2005: A Review of The Stern Review on the Economics of Climate Change. *Journal of Economic Literature*, **XLV**, 686-702.
Nordhaus, W.D., 2007: To Tax or Not to Tax: Alternative Approaches to Slowing Global Warming. *Review of Environmental Economics and Policy*, **1(1)**, 26-44, doi:10.1093/reep/rem008.
Nordhaus, W.D., 2013: The Climate Casino: Risk, Uncertainty, and Economics for a Warming World. Yale University Press, 392 pp.

Nordhaus, W.D., 2014: Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches. *Journal of the Association of Environmental and Resource Economists*, **1(1-2)**, 273-312, doi:10.1086/676035.
Nordhaus, W.D., 2017: Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, **114(7)**, 1518-1523, doi:10.1073/pnas.1609244114.
Nordhaus, W.D. and J. Boyer, 2000: *Warming the World: Economic Models of Global Warming*. MIT Press, Cambridge, MA, USA and London, UK, 244 pp.
NRC, 2015: *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. The National Academies Press, Washington, DC.
Obersteiner, M. et al., 2001: Managing Climate Risk. *Science*, **294(5543)**, 786-787, doi:10.1126/science.294.5543.786b.
Obersteiner, M. et al., 2016: Assessing the land resource-food price nexus of the Sustainable Development Goals. *Science Advances*, **2(9)**, doi:10.1126/sciadv.1501499.
Obersteiner, M. et al., 2018: How to spend a dwindling greenhouse gas budget. *Nature Climate Change*, **8(1)**, 7-10, doi:10.1038/s41558-017-0045-1.
OECD, 2017: *Investing in Climate, Investing in Growth*. OECD Publishing, Paris, France, 314 pp.
OECD/IEA and IRENA, 2017: *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*. OECD/IEA and IRENA, 204 pp.
Ogawa, T., S. Nakanishi, T. Shidahara, T. Okumura, and E. Hayashi, 2011: Saline-aquifer CO_2 sequestration in Japan-methodology of storage capacity assessment. *International Journal of Greenhouse Gas Control*, **5(2)**, 318-326, doi:10.1016/j.ijggc.2010.09.009.
O'Neill, B.C. et al., 2014: A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change*, **122(3)**, 387-400, doi:10.1007/s10584-013-0905-2.
O'Neill, B.C. et al., 2017: The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, **42**, 169-180, doi:10.1016/j.gloenvcha.2015.01.004.
Painter, T.H. et al., 2013: End of the Little Ice Age in the Alps forced by industrial black carbon. *Proceedings of the National Academy of Sciences of the United States of America*, **110(38)**, 15216-21, doi:10.1073/pnas.1302570110.
Patt, A., 2017: Beyond the tragedy of the commons: Reframing effective climate change governance. *Energy Research & Social Science*, **34**, 1-3, doi:10.1016/J.ERSS.2017.05.023.
Patterson, J.J. et al., 2018: Political feasibility of 1.5°C societal transformations: the role of social justice. *Current Opinion in Environmental Sustainability*, **31**, 1-9, doi:10.1016/j.cosust.2017.11.002.
Paustian, K. et al., 2016: Climate-smart soils. *Nature*, **532**, 49, doi:10.1038/nature17174.
Pawar, R.J. et al., 2015: Recent advances in risk assessment and risk management of geologic CO_2 storage. *International Journal of Greenhouse Gas Control*, **40**, 292-311, doi:10.1016/J.IJGGC.2015.06.014.
Pehl, M. et al., 2017: Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. *Nature Energy*, **2(12)**, 939-945, doi:10.1038/s41560-017-0032-9.
Peters, G.P., 2016: The 'best available science' to inform 1.5 °C policy choices. *Nature Climate Change*, **6(7)**, 646-649, doi:10.1038/nclimate3000.
Pietzcker, R.C. et al., 2017: System integration of wind and solar power in integrated assessment models: A cross-model evaluation of new approaches. *Energy Economics*, **64**, 583-599, doi:10.1016/j.eneco.2016.11.018.
Pikaar, I. et al., 2018: Decoupling livestock from land use through industrial feed production pathways. *Environmental Science & Technology* (in press).
Pindyck, R.S., 2013: Climate Change Policy: What Do the Models Tell Us? *Journal of Economic Literature*, **51(3)**, 1-23, doi:10.1257/jel.51.3.860.
Pizer, W. et al., 2014: Using and improving the social cost of carbon. *Science*, **346(6214)**, 1189-1190, doi:10.1126/science.1259774.
Popp, A., H. Lotze-Campen, and B. Bodirsky, 2010: Food consumption, diet shifts and associated non-CO_2 greenhouse gases from agricultural production. *Global Environmental Change*, **20(3)**, 451-462, doi:10.1016/j.gloenvcha.2010.02.001.
Popp, A. et al., 2014a: Land-use protection for climate change mitigation. *Nature Climate Change*, **4(12)**, 1095-1098, doi:10.1038/nclimate2444.
Popp, A. et al., 2014b: Land-use transition for bioenergy and climate stabilization: Model comparison of drivers, impacts and interactions with other land use based mitigation options. *Climatic Change*, **123(3-4)**, 495-509, doi:10.1007/s10584-013-0926-x.
Popp, A. et al., 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, **42**, 331-345, doi:10.1016/j.gloenvcha.2016.10.002.
Post, M.J., 2012: Cultured meat from stem cells: Challenges and prospects. *Meat Science*, **92(3)**, 297-301, doi:https://doi.org/10.1016/j.meatsci.2012.04.008.
Prestele, R. et al., 2016: Hotspots of uncertainty in land-use and land-cover change projections: a global-scale model comparison. *Global Change Biology*, **22(12)**, 3967-3983, doi:10.1111/gcb.13337.
Proistosescu, C. and P.J. Huybers, 2017: Slow climate mode reconciles historical and model-based estimates of climate sensitivity. *Science Advances*, **3(7)**.

Psarras, P. et al., 2017: Slicing the pie: how big could carbon dioxide removal be? *Wiley Interdisciplinary Reviews: Energy and Environment*, **6(5)**, e253, doi:10.1002/wene.253.
Purohit, P. and L. Höglund-Isaksson, 2017: Global emissions of fluorinated greenhouse gases 2005-2050 with abatement potentials and costs. *Atmospheric Chemistry and Physics*, **17(4)**, 2795-2816, doi:10.5194/acp-17-2795-2017.
Rao, S. et al., 2016: A multi-model assessment of the co-benefits of climate mitigation for global air quality. *Environmental Research Letters*, **11(12)**, 124013, doi:10.1088/1748-9326/11/12/124013.
Rao, S. et al., 2017: Future air pollution in the Shared Socio-economic Pathways. *Global Environmental Change*, **42**, 346-358, doi:10.1016/j.gloenvcha.2016.05.012.
Rau, G.H., 2011: CO_2 Mitigation via Capture and Chemical Conversion in Seawater. *Environmental Science & Technology*, **45(3)**, 1088-1092, doi:10.1021/es102671x.
Revesz, R. et al., 2014: Global warming: Improve economic models of climate change. *Nature*, **508(7495)**, 173-175, doi:10.1038/508173a.
Riahi, K. et al., 2011: RCP 8.5 - A scenario of comparatively high greenhouse gas emissions. *Climatic Change*, **109(1)**, 33, doi:10.1007/s10584-011-0149-y.
Riahi, K. et al., 2012: Chapter 17 - Energy Pathways for Sustainable Development. In: *Global Energy Assessment - Toward a Sustainable Future*. pp. 1203-1306.
Riahi, K. et al., 2015: Locked into Copenhagen pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change*, **90(PA)**, 8-23, doi:10.1016/j.techfore.2013.09.016.
Riahi, K. et al., 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, **42**, 153-168, doi:10.1016/j.gloenvcha.2016.05.009.
Ricke, K.L., R.J. Millar, and D.G. MacMartin, 2017: Constraints on global temperature target overshoot. *Scientific Reports*, **7(1)**, 1-7, doi:10.1038/s41598-017-14503-9.
Riis, F. and E. Halland, 2014: CO_2 storage atlas of the Norwegian Continental shelf: Methods used to evaluate capacity and maturity of the CO_2 storage potential. *Energy Procedia*, **63**, 5258-5265, doi:10.1016/j.egypro.2014.11.557.
Rockström, J. et al., 2017: A roadmap for rapid decarbonization. *Science*, **355(6331)**, 1269-1271, doi:10.1126/science.aah3443.
Roelfsema, M., M. Harmsen, J.J.G. Olivier, A.F. Hof, and D.P. van Vuuren, 2018: Integrated assessment of international climate mitigation commitments outside the UNFCCC. *Global Environmental Change*, **48**, 67-75, doi:10.1016/J.GLOENVCHA.2017.11.001.
Rogelj, J., D.L. McCollum, B.C. O'Neill, and K. Riahi, 2013a: 2020 emissions levels required to limit warming to below 2 C. *Nature Climate Change*, **3(4)**, 405-412, doi:10.1038/nclimate1758.
Rogelj, J., M. Meinshausen, J. Sedláček, and R. Knutti, 2014a: Implications of potentially lower climate sensitivity on climate projections and policy. *Environmental Research Letters*, **9(3)**, 031003, doi:10.1088/1748-9326/9/3/031003.
Rogelj, J., D.L. McCollum, A. Reisinger, M. Meinshausen, and K. Riahi, 2013b: Probabilistic cost estimates for climate change mitigation. *Nature*, **493(7430)**, 79-83, doi:10.1038/nature11787.
Rogelj, J., M. Meinshausen, M. Schaeffer, R. Knutti, and K. Riahi, 2015a: Impact of short-lived non-CO_2 mitigation on carbon budgets for stabilizing global warming. *Environmental Research Letters*, **10(7)**, 075001, doi:10.1088/1748-9326/10/7/075001.
Rogelj, J. et al., 2011: Emission pathways consistent with a 2 °C global temperature limit. *Nature Climate Change*, **1(8)**, 413-418, doi:10.1038/nclimate1258.
Rogelj, J. et al., 2014b: Disentangling the effects of CO_2 and short-lived climate forcer mitigation. *Proceedings of the National Academy of Sciences*, **111(46)**, 16325-16330, doi:10.1073/pnas.1415631111.
Rogelj, J. et al., 2015b: Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nature Climate Change*, **5(6)**, 519-527, doi:10.1038/nclimate2572.
Rogelj, J. et al., 2015c: Mitigation choices impact carbon budget size compatible with low temperature goals. *Environmental Research Letters*, **10(7)**, 075003, doi:10.1088/1748-9326/10/7/075003.
Rogelj, J. et al., 2015d: Zero emission targets as long-term global goals for climate protection. *Environmental Research Letters*, **10(10)**, 105007, doi:10.1088/1748-9326/10/10/105007.
Rogelj, J. et al., 2016a: Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature*, **534(7609)**, 631-639, doi:10.1038/nature18307.
Rogelj, J. et al., 2016b: Differences between carbon budget estimates unravelled. *Nature Climate Change*, **6(3)**, 245-252, doi:10.1038/nclimate2868.
Rogelj, J. et al., 2017: Understanding the origin of Paris Agreement emission uncertainties. *Nature Communications*, **8**, 15748, doi:10.1038/ncomms15748.
Rogelj, J. et al., 2018: Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, **8(4)**, 325-332, doi:10.1038/s41558-018-0091-3.
Rose, S.K., 2012: The role of the social cost of carbon in policy. *Wiley Interdisciplinary Reviews: Climate Change*, **3(2)**, 195-212, doi:10.1002/wcc.163.
Rose, S.K., D.B. Diza, and G.J. Blanford, 2017a: Undesterstanding the Social Cost of Carbon: A Model diagnostic and Inter-comparison Study. *Climate Change Economics*, **08(02)**, 1750009, doi:10.1142/S2010007817500099.

Rose, S.K., R. Richels, G. Blanford, and T. Rutherford, 2017b: The Paris Agreement and next steps in limiting global warming. *Climatic Change*, **142(1-2)**, 1-16, doi:10.1007/s10584-017-1935-y.

Rose, S.K. et al., 2014a: Bioenergy in energy transformation and climate management. *Climatic Change*, **123(3-4)**, 477-493, doi:10.1007/s10584-013-0965-3.

Rose, S.K. et al., 2014b: Non-Kyoto radiative forcing in long-run greenhouse gas emissions and climate change scenarios. *Climatic Change*, **123(3-4)**, 511-525, doi:10.1007/s10584-013-0955-5.

Rugenstein, M.A.A. et al., 2016: Multiannual Ocean-Atmosphere Adjustments to Radiative Forcing. *Journal of Climate*, **29(15)**, 5643-5659, doi:10.1175/JCLI-D-16-0312.1.

Samset, B.H. et al., 2016: Fast and slow precipitation responses to individual climate forcers: A PDRMIP multimodel study. *Geophysical Research Letters*, **43(6)**, 2782-2791, doi:10.1002/2016GL068064.

Samset, B.H. et al., 2018: Climate Impacts From a Removal of Anthropogenic Aerosol Emissions. *Geophysical Research Letters*, **45(2)**, 1020-1029, doi:10.1002/2017GL076079.

Sand, M. et al., 2015: Response of Arctic temperature to changes in emissions of short-lived climate forcers. *Nature Climate Change*, **6(3)**, 286-289, doi:10.1038/nclimate2880.

Sanderson, B.M., B.C. O'Neill, and C. Tebaldi, 2016: What would it take to achieve the Paris temperature targets? *Geophysical Research Letters*, **43(13)**, 7133-7142, doi:10.1002/2016GL069563.

Sands, R.D., 2018: U.S. Carbon Tax Scenarios and Bioenergy. *Climate Change Economics*, **09(01)**, 1840010, doi:10.1142/S2010007818400109.

Sarofim, M.C., S.T. Waldhoff, and S.C. Anenberg, 2017: Valuing the Ozone-Related Health Benefits of Methane Emission Controls. *Environmental and Resource Economics*, **66(1)**, 45-63, doi:10.1007/s10640-015-9937-6.

Saunders, H.D., 2015: Recent Evidence for Large Rebound: Elucidating the Drivers and their Implications for Climate Change Models. *The Energy Journal*, **36(1)**, 23-48.

Schädel, C. et al., 2014: Circumpolar assessment of permafrost C quality and its vulnerability over time using long-term incubation data. *Global Change Biology*, **20(2)**, 641-652, doi:10.1111/gcb.12417.

Schädel, C. et al., 2016: Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. *Nature Climate Change*, **6(10)**, 950-953, doi:10.1038/nclimate3054.

Schleussner, C.F. et al., 2016: Science and policy characteristics of the Paris Agreement temperature goal. *Nature Climate Change*, **6**, 827-835, doi:10.1038/nclimate3096.

Schmidt, M.G.W., H. Held, E. Kriegler, and A. Lorenz, 2013: Climate Policy Under Uncertain and Heterogeneous Climate Damages. *Environmental and Resource Economics*, **54(1)**, 79-99, doi:10.1007/s10640-012-9582-2.

Schmitz, C. et al., 2012: Trading more food: Implications for land use, greenhouse gas emissions, and the food system. *Global Environmental Change*, **22(1)**, 189-209, doi:10.1016/J.GLOENVCHA.2011.09.013.

Schneider, T. et al., 2017: Climate goals and computing the future of clouds. *Nature Climate Change*, **7(1)**, 3-5, doi:10.1038/nclimate3190.

Schneider von Deimling, T. et al., 2012: Estimating the near-surface permafrost-carbon feedback on global warming. *Biogeosciences*, **9(2)**, 649-665, doi:10.5194/bg-9-649-2012.

Schneider von Deimling, T. et al., 2015: Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity. *Biogeosciences*, **12(11)**, 3469-3488, doi:10.5194/bg-12-3469-2015.

Schuiling, R.D. and P. Krijgsman, 2006: Enhanced Weathering: An Effective and Cheap Tool to Sequester CO_2. *Climatic Change*, **74(1-3)**, 349-354, doi:10.1007/s10584-005-3485-y.

Schurer, A.P. et al., 2018: Interpretations of the Paris climate target. *Nature Geoscience*, **11(4)**, 220-221, doi:10.1038/s41561-018-0086-8.

Schuur, E.A.G. et al., 2015: Climate change and the permafrost carbon feedback. *Nature*, **520(7546)**, 171-179, doi:10.1038/nature14338.

Scott, C.E. et al., 2017: Substantial large-scale feedbacks between natural aerosols and climate. *Nature Geoscience*, 1, doi:10.1038/s41561-017-0020-5.

Scott, V., R.S. Haszeldine, S.F.B. Tett, and A. Oschlies, 2015: Fossil fuels in a trillion tonne world. *Nature Climate Change*, **5(5)**, 419-423, doi:10.1038/nclimate2578.

Searle, S.Y. and C.J. Malins, 2014: Will energy crop yields meet expectations? *Biomass and Bioenergy*, **65**, 3-12, doi:10.1016/J.BIOMBIOE.2014.01.001.

Séférian, R., M. Rocher, C. Guivarch, and J. Colin, 2018: Constraints on biomass energy deployment in mitigation pathways: the case of water limitation. *Environmental Research Letters*, 1-32, doi:10.1088/1748-9326/aabcd7.

Seto, K.C. et al., 2016: Carbon lock-in: Types, causes, and policy implications. *Annual Review of Environment and Resources*, **41**, 425-452.

Shah, N., M. Wei, V. Letschert, and A. Phadke, 2015: *Benefits of Leapfrogging to Superefficiency and Low Global Warming Potential Refrigerants in Room Air Conditioning*. LBNL-1003671, 58 pp.

Shearer, C., N. Mathew-Shah, L. Myllyvirta, A. Yu, and T. Nace, 2018: *Boom and Bust 2018: Tracking the global coal plant pipeline*. Coalswarm, Sierra Club, Greenpeace, 16 pp.

Shell International B.V., 2018: *Shell Scenarios: Sky - Meeting the Goals of the Paris Agreement*. Shell International B.V. 36 pp.

Sherwood, S.C., S. Bony, and J.L. Dufresne, 2014: Spread in model climate sensitivity traced to atmospheric convective mixing. *Nature*, **505(7481)**, 37-42, doi:10.1038/nature12829.

Shindell, D.T., 2015: The social cost of atmospheric release. *Climatic Change*, **130(2)**, 313-326, doi:10.1007/s10584-015-1343-0.
Shindell, D.T. and G. Faluvegi, 2010: The net climate impact of coal-fired power plant emissions. *Atmospheric Chemistry and Physics*, **10(7)**, 3247-3260, doi:10.5194/acp-10-3247-2010.
Shindell, D.T., Y. Lee, and G. Faluvegi, 2016: Climate and health impacts of US emissions reductions consistent with 2C. *Nature Climate Change*, **6**, 503-509.
Shindell, D.T., J.S. Fuglestvedt, and W.J. Collins, 2017a: The social cost of methane: theory and applications. *Faraday Discussions*, **200**, 429-451, doi:10.1039/C7FD00009J.
Shindell, D.T., G. Faluvegi, L. Rotstayn, and G. Milly, 2015: Spatial patterns of radiative forcing and surface temperature response. *Journal of Geophysical Research: Atmospheres*, **120(11)**, 5385-5403, doi:10.1002/2014JD022752.
Shindell, D.T., G. Faluvegi, K. Seltzer, and C. Shindell, 2018: Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. *Nature Climate Change*, **8(4)**, 291-295, doi:10.1038/s41558-018-0108-y.
Shindell, D.T. et al., 2012: Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. *Science*, **335(6065)**, 183-189, doi:10.1126/science.1210026.
Shindell, D.T. et al., 2017b: A climate policy pathway for near- and long-term benefits. *Science*, **356(6337)**, 493-494, doi:10.1126/science.aak9521.
Shukla, P.R. and V. Chaturvedi, 2012: Low carbon and clean energy scenarios for India: Analysis of targets approach. *Energy Economics*, **34(Suppl.3)**, S487-S495, doi:10.1016/j.eneco.2012.05.002.
Siegmeier, J. et al., 2018: The fiscal benefits of stringent climate change mitigation: an overview. *Climate Policy*, **18(3)**, 352-367, doi:10.1080/14693062.2017.1400943.
Silva, R.A. et al., 2016: The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble. *Atmospheric Chemistry and Physics*, doi:10.5194/acp-16-9847-2016.
Sims, R. et al., 2014: Transport. 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. Kadne, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 599-670.
Smith, C.J. et al., 2018: FAIR v1.3: A simple emissions-based impulse response and carbon cycle model. *Geoscientific Model Development* (in press), doi:10.5194/gmd-2017-266.
Smith, L.J. and M.S. Torn, 2013: Ecological limits to terrestrial biological carbon dioxide removal. *Climatic Change*, **118(1)**, 89-103, doi:10.1007/s10584-012-0682-3.
Smith, P., 2016: Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*, **22(3)**, 1315-1324, doi:10.1111/gcb.13178.
Smith, P. and M. Bustamante, 2014: Agriculture, Forestry and Other Land Use (AFOLU). 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, United Kingdom and New York, NY, USA, pp. 811-922.
Smith, P. et al., 2013: How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Global Change Biology*, **19(8)**, 2285-2302, doi:10.1111/gcb.12160.
Smith, P. et al., 2015: Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change*, **6(1)**, 42-50, doi:10.1038/nclimate2870.
Snopkowski, K., M.C. Towner, M.K. Shenk, and H. Colleran, 2016: Pathways from education to fertility decline: a multi-site comparative study. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, **371(1692)**, 20150156, doi:10.1098/rstb.2015.0156.
Socolow, R. et al., 2011: *Direct Air Capture of* CO_2 *with Chemicals: A Technology Assessment for the APS Panel on Public Affairs*. American Physical Society, 100 pp.
Somanthan, E. et al., 2014: National and Sub-national Policies and Institutions. 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, United Kingdom and New York, NY, USA, pp. 1141-1206.
Sonnenschein, J., R. van Buskirk, J. Luth Richter, and C. Dalhammar, 2018: Minimum energy performance standards for the 1.5°C target: an effective complement to carbon pricing? *Energy Efficiency* (in press), doi:10.1007/s12053-018-9669-x.
Spencer, T., R. Pierfederici, H. Waisman, and M. Colombier, 2015: *Beyond the Numbers. Understanding the Transformation Induced by INDCs*. Study N°05/15, MILES Project Consortium, Paris, 80 pp.
Springmann, M., H.C.J. Godfray, M. Rayner, and P. Scarborough, 2016: Analysis and valuation of the health and climate change cobenefits of dietary change. *Proceedings of the National Academy of Sciences of the United States of America*, **113(15)**, 4146-4151, doi:10.1073/pnas.1523119113.

Steckel, J.C., O. Edenhofer, and M. Jakob, 2015: Drivers for the renaissance of coal. *Proceedings of the National Academy of Sciences*, **112(29)**, E3775--E3781, doi:10.1073/pnas.1422722112.
Stehfest, E. et al., 2009: Climate benefits of changing diet. *Climatic Change*, **95(1-2)**, 83-102, doi:10.1007/s10584-008-9534-6.
Stern, N., 2007: *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge, United Kingdom, 692 pp.
Stern, N., 2013: The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models. *Journal of Economic Literature*, **51(3)**, 838-859, doi:10.1257/jel.51.3.838.
Stern, N., 2016: Current climate models are grossly misleading. *Nature*, **530**, 407-409, doi:10.1038/530407a.
Stevanović, M. et al., 2017: Mitigation Strategies for Greenhouse Gas Emissions from Agriculture and Land-Use Change: Consequences for Food Prices. *Environmental Science & Technology*, **51(1)**, 365-374, doi:10.1021/acs.est.6b04291.
Stiglitz, J.E. et al., 2017: *Report of the High-Level Commission on Carbon Prices*. Carbon Pricing Leadership Coalition, 68 pp.
Stocker, T.F. et al., 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33-115.
Stohl, A. et al., 2015: Evaluating the climate and air quality impacts of short-lived pollutants. *Atmospheric Chemistry and Physics*, **15(18)**, 10529-10566, doi:10.5194/acp-15-10529-2015.
Strapasson, A. et al., 2017: On the global limits of bioenergy and land use for climate change mitigation. *GCB Bioenergy*, **9(12)**, 1721-1735, doi:10.1111/gcbb.12456.
Strefler, J., T. Amann, N. Bauer, E. Kriegler, and J. Hartmann, 2018a: Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters*, **13(3)**, 034010, doi:10.1088/1748-9326/aaa9c4.
Strefler, J., N. Bauer, E. Kriegler, A. Popp, and O. Giannousakis, Anastasis Edenhofer, 2018b: Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. *Environ. Res. Lett*, **13**, 044015.
Su, X. et al., 2017: Emission pathways to achieve 2.0°C and 1.5°C climate targets. *Earth's Future*, **5(6)**, 592-604, doi:10.1002/2016EF000492.
Subbarao, G. et al., 2013: Potential for biological nitrification inhibition to reduce nitrification and N2O emissions in pasture crop-livestock systems. *animal*, **7(s2)**, 322-332, doi:10.1017/S1751731113000761.
Subharat, S. et al., 2016: Vaccination of Sheep with a Methanogen Protein Provides Insight into Levels of Antibody in Saliva Needed to Target Ruminal Methanogens. *PLOS ONE*, **11(7)**, e0159861, doi:10.1371/journal.pone.0159861.
Szulczewski, M.L., C.W. MacMinn, and R. Juanes, 2014: Theoretical analysis of how pressure buildup and CO_2 migration can both constrain storage capacity in deep saline aquifers. *International Journal of Greenhouse Gas Control*, **23**, 113-118, doi:10.1016/j.ijggc.2014.02.006.
Tachiiri, K., T. Hajima, and M. Kawamiya, 2015: Increase of uncertainty in transient climate response to cumulative carbon emissions after stabilization of atmospheric CO_2 concentration. *Environmental Research Letters*, **10(12)**, 125018, doi:10.1088/1748-9326/10/12/125018.
Tan, I., T. Storelvmo, and M.D. Zelinka, 2016: Observational constraints on mixed-phase clouds imply higher climate sensitivity. *Science*, **352(6282)**, 224-227, doi:10.1126/science.aad5300.
Tavoni, M. and R.S.J. Tol, 2010: Counting only the hits? The risk of underestimating the costs of stringent climate policy. *Climatic Change*, **100(3-4)**, 769-778, doi:10.1007/s10584-010-9867-9.
The Royal Society, 2009: *Geoengineering the climate: science, governance and uncertainty*.
Thomson, A.M. et al., 2011: RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Climatic Change*, **109(1-2)**, 77-94, doi:10.1007/s10584-011-0151-4.
Tilman, D. and M. Clark, 2014: Global diets link environmental sustainability and human health. *Nature*, **515(7528)**, 518-522, doi:10.1038/nature13959.
Tokarska, K.B. and N.P. Gillett, 2018: Cumulative carbon emissions budgets consistent with 1.5 °C global warming. *Nature Climate Change*, **8(4)**, 296-299, doi:10.1038/s41558-018-0118-9.
Tokarska, K.B., N.P. Gillett, V.K. Arora, W.G. Lee, and K. Zickfeld, 2018: The influence of non-CO_2 forcings on cumulative carbon emissions budgets. *Environmental Research Letters*, **13(3)**, 034039, doi:10.1088/1748-9326/aaafdd.
Tol, R.S.J., 1999: Spatial and Temporal Efficiency in Climate Policy: Applications of FUND. *Environmental and Resource Economics*, **14(1)**, 33-49.
Tol, R.S.J., 2017: The structure of the climate debate. *Energy Policy*, **104**, 431-438, doi:10.1016/J.ENPOL.2017.01.005.
Tuomisto, H.L. and M.J. Teixeira de Mattos, 2011: Environmental Impacts of Cultured Meat Production. *Environmental Science & Technology*, **45(14)**, 6117-6123, doi:10.1021/es200130u.
UNEP, 2015: *Aligning the Financial System with Sustainable Development: Pathways to Scale*. United Nations

Environment Programme (UNEP), Geneva, 26 pp.
UNEP, 2016: *The Emissions Gap Report 2016: A UNEP Synthesis Report.* United Nations Environment Programme (UNEP), Nairobi, Kenya, 85 pp.
UNEP, 2017: *The Emissions Gap Report 2017: A UN Environment Synthesis Report*. 116 pp.
UNFCCC, 2016: *Aggregate effect of the intended nationally determined contributions: an update*. FCCC/CP/2016/2, The Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany, 75 pp.
Unruh, G.C. and J. Carrillo-Hermosilla, 2006: Globalizing carbon lock-in. *Energy Policy*, **34(10)**, 1185-1197, doi:10.1016/j.enpol.2004.10.013.
Unruh, J.D., 2011: Tree-Based Carbon Storage in Developing Countries: Neglect of the Social Sciences. *Society & Natural Resources*, **24(2)**, 185-192, doi:10.1080/08941920903410136.
US EPA, 2013: *Global Mitigation of Non-*CO_2 *Greenhouse Gases: 2010-2030. Report No. EPA-430-R-13-011*. United States Environmental Protection Agency (US EPA), Washington DC, USA, 410 pp.
Valin, H. et al., 2013: Agricultural productivity and greenhouse gas emissions: trade-offs or synergies between mitigation and food security? *Environmental Research Letters*, **8(3)**, 035019, doi:10.1088/1748-9326/8/3/035019.
van den Bergh, J.C.J.M., 2017: Rebound policy in the Paris Agreement: instrument comparison and climate-club revenue offsets. *Climate Policy*, **17(6)**, 801-813, doi:10.1080/14693062.2016.1169499.
van Sluisveld, M.A.E., S.H. Martínez, V. Daioglou, and D.P. van Vuuren, 2016: Exploring the implications of lifestyle change in 2 °C mitigation scenarios using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **102**, 309-319, doi:10.1016/J.TECHFORE.2015.08.013.
van Soest, H.L. et al., 2017: Low-emission pathways in 11 major economies: comparison of cost-optimal pathways and Paris climate proposals. *Climatic Change*, **142(3-4)**, 491-504, doi:10.1007/s10584-017-1964-6.
van Vuuren, D.P. and K. Riahi, 2011: The relationship between short-term emissions and long-term concentration targets. *Climatic Change*, **104(3)**, 793-801, doi:10.1007/s10584-010-0004-6.
van Vuuren, D.P., A.F. Hof, M.A.E. van Sluisveld, and K. Riahi, 2017a: Open discussion of negative emissions is urgently needed. *Nature Energy*, **2(12)**, 902-904, doi:10.1038/s41560-017-0055-2.
van Vuuren, D.P. et al., 2007: Stabilizing greenhouse gas concentrations at low levels: An assessment of reduction strategies and costs. *Climatic Change*, **81(2)**, 119-159, doi:10.1007/s10584-006-9172-9.
van Vuuren, D.P. et al., 2011a: The representative concentration pathways: An overview. *Climatic Change*, **109(1)**, 5-31, doi:10.1007/s10584-011-0148-z.
van Vuuren, D.P. et al., 2011b: RCP2.6: Exploring the possibility to keep global mean temperature increase below 2°C. *Climatic Change*, **109(1)**, 95-116, doi:10.1007/s10584-011-0152-3.
van Vuuren, D.P. et al., 2015: Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **98**, 303-323, doi:10.1016/J.TECHFORE.2015.03.005.
van Vuuren, D.P. et al., 2016: Carbon budgets and energy transition pathways. *Environmental Research Letters*, **11(7)**, 075002, doi:10.1088/1748-9326/11/7/075002.
van Vuuren, D.P. et al., 2017b: Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change*, **42**, 237-250, doi:10.1016/j.gloenvcha.2016.05.008.
van Vuuren, D.P. et al., 2018: Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nature Climate Change*, **8(5)**, 391-397, doi:10.1038/s41558-018-0119-8.
Vangkilde-Pedersen, T. et al., 2009: Assessing European capacity for geological storage of carbon dioxide-the EU GeoCapacity project. *Energy Procedia*, **1(1)**, 2663-2670, doi:10.1016/j.egypro.2009.02.034.
Veland, S. et al., 2018: Narrative matters for sustainability: the transformative role of storytelling in realizing 1.5°C futures. *Current Opinion in Environmental Sustainability*, **31**, 41-47, doi:10.1016/J.COSUST.2017.12.005.
Velders, G.J.M., D.W. Fahey, J.S. Daniel, S.O. Andersen, and M. McFarland, 2015: Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. *Atmospheric Environment*, **123**, 200-209, doi:10.1016/j.atmosenv.2015.10.071.
Vogt-Schilb, A. and S. Hallegatte, 2017: Climate policies and nationally determined contributions: reconciling the needed ambition with the political economy. *Wiley Interdisciplinary Reviews: Energy and Environment*, **6(6)**, 1-23, doi:10.1002/wene.256.
Voigt, C. et al., 2017a: Warming of subarctic tundra increases emissions of all three important greenhouse gases - carbon dioxide, methane, and nitrous oxide. *Global Change Biology*, **23(8)**, 3121-3138, doi:10.1111/gcb.13563.
Voigt, C. et al., 2017b: Increased nitrous oxide emissions from Arctic peatlands after permafrost thaw. *Proceedings of the National Academy of Sciences*, **114(24)**, 6238-6243, doi:10.1073/pnas.1702902114.
von Stechow, C. et al., 2015: Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. *Annual Review of Environment and Resources*, **40(1)**, 363-394, doi:10.1146/annurev-environ-021113-095626.
von Stechow, C. et al., 2016: 2 °C and SDGs: united they stand, divided they fall? *Environmental Research Letters*, **11(3)**, 034022, doi:10.1088/1748-9326/11/3/034022.
Vrontisi, Z., G. Luderer, B. Saveyn, K. Keramidas, and L.A. Reis, 2018: Enhancing global climate policy ambition

towards a 1.5°C stabilization: a short-term multi-model assessment. *Environ. Res. Lett*, **13**, 044039.
Wachsmuth, J. and V. Duscha, 2018: Achievability of the Paris targets in the EU-the role of demand-side-driven mitigation in different types of scenarios. *Energy Efficiency*, 1-19, doi:10.1007/s12053-018-9670-4.
Walsh, M.J. et al., 2016: Algal food and fuel coproduction can mitigate greenhouse gas emissions while improving land and water-use efficiency. *Environmental Research Letters*, **11(11)**, 114006.
Wang, X. et al., 2016: Taking account of governance: Implications for land-use dynamics, food prices, and trade patterns. *Ecological Economics*, **122**, 12-24, doi:10.1016/J.ECOLECON.2015.11.018.
Warwick, P.D., M.K. Verma, P.A. Freeman, M.D. Corum, and S.H. Hickman, 2014: U.S. geological survey carbon sequestration - geologic research and assessments. *Energy Procedia*, **63**, 5305-5309, doi:10.1016/j.egypro.2014.11.561.
Wedlock, D.N., P.H. Janssen, S.C. Leahy, D. Shu, and B.M. Buddle, 2013: Progress in the development of vaccines against rumen methanogens. *animal*, **7(s2)**, 244-252, doi:10.1017/S1751731113000682.
Wei, N. et al., 2013: A preliminary sub-basin scale evaluation framework of site suitability for onshore aquifer-based CO_2 storage in China. *International Journal of Greenhouse Gas Control*, **12**, 231-246, doi:10.1016/j.ijggc.2012.10.012.
Weindl, I. et al., 2015: Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. *Environmental Research Letters*, **10(9)**, 094021, doi:10.1088/1748-9326/10/9/094021.
Weindl, I. et al., 2017: Livestock and human use of land: Productivity trends and dietary choices as drivers of future land and carbon dynamics. *Global and Planetary Change*, **159**, 1-10, doi:10.1016/j.gloplacha.2017.10.002.
Weitzman, M.L., 2014: Can Negotiating a Uniform Carbon Price Help to Internalize the Global Warming Externality? *Journal of the Association of Environmental and Resource Economists*, **1(1/2)**, 29-49, doi:10.1086/676039.
Werner, C., H.P. Schmidt, D. Gerten, W. Lucht, and C. Kammann, 2018: Biogeochemical potential of biomass pyrolysis systems for limiting global warming to 1.5 °C. *Environmental Research Letters*, **13(4)**, 044036, doi:10.1088/1748-9326/aabb0e.
West, J.J. et al., 2013: Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nature Climate Change*, **3(10)**, 885-889, doi:10.1038/nclimate2009.
Weyant, J., 2017: Some Contributions of Integrated Assessment Models of Global Climate Change. *Review of Environmental Economics and Policy*, **11(1)**, 115-137, doi:10.1093/reep/rew018.
Weyant, J.P., F.C. Chesnaye, and G.J. Blanford, 2006: Overview of EMF-21: Multigas Mitigation and Climate Policy. *The Energy Journal*, **27**, 1-32, doi:10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI3-1.
Wiebe, K. et al., 2015: Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. *Environmental Research Letters*, **10(8)**, 085010, doi:10.1088/1748-9326/10/8/085010.
Wigley, T.M.L., R. Richels, and J. Edmonds, 2007: Overshoot Pathways to CO_2 stabilization in a multi-gas context. In: *Human Induced Climate Change: An Interdisciplinary Perspective* [Schlesinger, M.E., H.S. Kheshgi, J. Smith, F.C. de la Chesnaye, J.M. Reilly, T. Wilson, and C. Kolstad (eds.)]. Cambridge University Press, Cambridge, pp. 84-92.
Williams, P.J.L.B. and L.M.L. Laurens, 2010: Microalgae as biodiesel & biomass feedstocks: Review & analysis of the biochemistry, energetics & economics. *Energy & Environmental Science*, **3(5)**, 554, doi:10.1039/b924978h.
Williamson, P., 2016: Emissions reduction: Scrutinize CO_2 removal methods. *Nature*, **530(153)**, 153-155, doi:10.1038/530153a.
Williamson, P. and R. Bodle, 2016: *Update on Climate Geoengineering in Relation to the Convention on Biological Diversity: Potential Impacts and Regulatory Framework*. CBD Technical Series No. 84, Secretariat of the Convention on Biological Diversity, Montreal, QC, Canada, 158 pp.
Wise, M., K. Calvin, P. Kyle, P. Luckow, and J. Edmonds, 2014: Economic and physical modeling of land use in GCAM 3.0 and an application to agricultural productivity, land, and terrestrial carbon. *Climate Change Economics*, **05(02)**, 1450003, doi:10.1142/S2010007814500031.
Woolf, D., J.E. Amonette, F.A. Street-Perrott, J. Lehmann, and S. Joseph, 2010: Sustainable biochar to mitigate global climate change. *Nature Communications*, **1(5)**, 1-9, doi:10.1038/ncomms1053.
Xiao, X. and K. Jiang, 2017: Prospect of and preliminary feasibility study on China's nuclear power under the Global 1.5°C Target. *Advances in Climate Change Research* (in press), doi:10.1016/j.accre.2018.05.002.
Xu, Y. and V. Ramanathan, 2017: Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes. *Proceedings of the National Academy of Sciences of the United States of America*, **114(39)**, 10315-10323, doi:10.1073/pnas.1618481114.
Yeh, S. et al., 2016: Detailed assessment of global transport-energy models' structures and projections. *Transportation Research Part D: Transport and Environment*, **55**, 294-309, doi:10.1016/j.trd.2016.11.001.
Zeman, F.S. and K. Lackner, 2004: Capturing carbon dioxide directly from the atmosphere. *World Resource Review*, **16(2)**, 157-172.
Zeman, F.S. and D.W. Keith, 2008: Carbon Neutral Hydrocarbons. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, **366(1882)**, 3901-3918, doi:10.1098/rsta.2008.0143.
Zhai, C., J.H. Jiang, and H. Su, 2015: Long-term cloud change imprinted in seasonal cloud variation: More evidence of high climate sensitivity. *Geophysical Research Letters*, **42(20)**, 8729-8737, doi:10.1002/2015GL065911.
Zhang, R., S. Fujimori, and T. Hanaoka, 2018: The contribution of transport policies to the mitigation potential and cost of 2°C and 1.5°C goals. *Environmental Research Letters*, **13(5)**, 054008.

Zickfeld, K. and T. Herrington, 2015: The time lag between a carbon dioxide emission and maximum warming increases with the size of the emission. *Environmental Research Letters*, **10(3)**, 031001, doi:10.1088/1748-9326/10/3/031001.

Zickfeld, K., A.H. MacDougall, and H.D. Matthews, 2016: On the proportionality between global temperature change and cumulative CO_2 emissions during periods of net negative CO_2 emissions. *Environmental Research Letters*, **11(5)**, 055006, doi:10.1088/1748-9326/11/5/055006.

Zickfeld, K., M. Eby, H.D. Matthews, and A.J. Weaver, 2009: Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **106(38)**, 16129-16134, doi:10.1073/pnas.0805800106.

Zomer, R.J., D.A. Bossio, R. Sommer, and L.V. Verchot, 2017: Global Sequestration Potential of Increased Organic Carbon in Cropland Soils. *Scientific Reports*, **7(1)**, 15554.

Zomer, R.J. et al., 2016: Global Tree Cover and Biomass Carbon on Agricultural Land: The contribution of agroforestry to global and national carbon budgets. *Scientific Reports*, **6**, 29987.

Table of Content

Chapter 2 – Technical Annex - Part 1 - Mitigation pathways compatible with 1.5°C in the context of sustainable development 3

2.A.1 Geophysical relationships and constraints 3

2.A.1.1 Reduced complexity climate models 3

2.A.1.2 Methods for assessing remaining carbon budgets 6

2.A.1.2.1 Median remaining carbon budget basis 6

2.A.1.2.2 Checks on approach 9

2.A.1.2.3 Uncertainties 9

2.A.2 Integrated Assessment Models 11

2.A.2.1 Short introduction to the scope, use and limitations of integrated assessment modelling 11

2.A.2.2. Economics and Policy Assumptions in IAMs 12

2.A.2.3. Technology assumptions and transformation modelling 13

2.A.2.4. Land use and bioenergy modelling in IAMs 14

2.A.2.5. Contributing modelling framework reference cards 15

2.A.2.6 Overview mitigation measures in contributed IAM scenarios 16

2.A.3 Overview of SR1.5 scenario database collected for the assessment in the Chapter 20

2.A.3.1 Configuration of SR1.5 scenario database 20

2.A.3.1.1 Criteria for submission to the scenario database 20

2.A.3.1.2 Historical consistency analysis of submitted scenarios 21

2.A.3.1.3 Verification of completeness and harmonization for climate impact assessment 21

2.A.3.1.4 Validity assessment of historical emissions for aggregate Kyoto greenhouse gases 21

2.A.3.1.5 Plausibility assessment of near-term development 22

2.A.3.1.6 Missing carbon price information 22

2.A.3.2. Contributions to the SR1.5 database by modelling framework 22

2.A.3.3. Overview and scope of studies available in SR1.5 database 24

2.A.3.4. Data collected 25

2.A.4 Scenario classification 26

2.A.5 Mitigation and SDG pathway synthesis 28

References 31

Chapter 2 - Technical Annex – Part II - Mitigation pathways compatible with 1.5°C in the context of sustainable development 37

Reference card – AIM-CGE 37

Reference card – BET 40

Reference card – C-ROADS 43

Reference card – DNE21 45

Reference card – FARM 3.2 49

Reference card – GCAM 4.2 52

Reference card – GEM-E3 .... **56**
Reference card – GENeSYS-MOD 1.0 .... **60**
Reference card – GRAPE-15 1.0 .... **63**
Reference card – ETP Model **67**
Reference card – IEA World Energy Model **70**
Reference card – IMACLIM **73**
Reference card – IMAGE **76**
Reference card – MERGE-ETL 6.0 .... **80**
Reference card – MESSAGE(ix)-GLOBIOM **83**
Reference card – POLES **87**
Reference card – REMIND - MAgPIE **90**
Reference card – Shell - World Energy Model **94**
Reference card – WITCH **97**

Chapter 2 – Technical Annex - Part 1 - Mitigation pathways compatible with 1.5°C in the context of sustainable development

Authors: Piers Forster (UK), Daniel Huppmann (Austria), Elmar Kriegler (Germany), Luis Mundaca (Chile/Sweden), Chris Smith (UK), Joeri Rogelj (Belgium/Austria), Roland Séférian (France),)

2.A.1 Geophysical relationships and constraints

2.A.1.1 Reduced complexity climate models

The 'Model for the Assessment of Greenhouse Gas Induced Climate Change' (MAGICC6, Meinshausen et al., 2011a), is a reduced complexity carbon-cycle, atmospheric composition and climate model that has been widely used in prior IPCC Assessments and policy literature. This model is used with its parameter set as identical to that employed in AR5 for backwards compatibility. This model has been shown to match temperature trends very well compared to CMIP5 models (Collins et al., 2013; Clarke et al., 2014).

The 'Finite Amplitude Impulse Response' (FAIRv1.3, Smith et al., 2018) model is similar to MAGICC but has even simpler representations of the carbon cycle and some atmospheric chemistry. Its parameter sets are based on AR5 physics with updated methane radiative forcing (Etminan et al., 2016). The FAIR model is a reasonable fit to CMIP5 model for lower emission pathways but underestimates the temperature response compared to CMIP5 models for RCP8.5 (Smith et al., 2018). It has been argued that its near-term temperature trends are more realistic than MAGICC (Leach et al., 2018).

The MAGICC model is used in this report to classify the different pathways in terms of temperature thresholds and its results are averaged with the FAIR model to support the evaluation of the non-CO_2 forcing contribution to the remaining carbon budget. The FAIR model is less established in the literature but can be seen as being more up to date in regards to its radiative forcing treatment. It is used in this report to help assess the uncertainty in the pathway classification approach and also used to support the carbon budget evaluation (Section 2.2 and 2.A.1.2).

The section analyses geophysical differences between FAIR and MAGICC to help provide confidence in the assessed climate response findings of the main report (Sections 2.2 and 2.3).

There are structural choices in how the models relate emissions to concentrations and effective radiative forcing. There are also differences in their ranges of climate sensitivity, their choice of carbon-cycle parameters, and how they are constrained, even though both models are consistent with AR5 ranges. Overall their temperature trends are similar for the range of emission trajectories (Figure 2.1 of the main report). However, differences exist in their near-term trends, with MAGICC exhibiting stronger warming trends than FAIR (see Figure 2.A.1). Leach et al. (2018) also note that that MAGICC warms more strongly than current warming rates. By adjusting FAIR parameters to match those in MAGICC, more than half the difference in mean near-term warming trends can be traced to parameter choices. The remaining differences are due to choices regarding model structure (Figure 2.A.1).

A structural difference exists in the way the models transfer from the historical period to the future. The setup of MAGICC used for AR5 uses a parametrisation that is constrained by observations of hemispheric temperatures and ocean heat uptake, as well as assessed ranges of radiative forcing consistent with AR4 (Meinshausen et al., 2009). From 1765 to 2005 the setup used for AR5 bases forcing on observed concentrations and uses emissions from 2006. It also ramps down the magnitude of volcanic forcing from 1995 to 2000 to give zero forcing in future scenarios, and solar forcing is fixed at 2009 values in the future. In contrast, FAIR produces a constrained set of parameters from emissions runs over the historic period (1765-2017) using both natural and anthropogenic forcings, and then uses this set to run the emissions model with only anthropogenic emissions for the full period of analysis (1765-2110). Structural choices in how aerosol, CH_4 and N_2O are implemented in the model are apparent (see Figure 2.A.2). As well as a weaker CH_4 radiative forcing, MAGICC also has a stronger total aerosol effective radiative forcing that is close to the AR4 best estimate of -1.2 Wm^{-2} for the total aerosol radiative forcing (Forster et al., 2007). As a result its forcing is larger than either FAIR or the AR5 best estimate (Figure 2.A.2), although its median aerosol forcing is well within the IPCC range (Myhre et al., 2013). The difference in N_2O forcings between the models result both from a slightly downwards-revised radiative forcing estimate for N_2O in (Etminan et al., 2016) and the treatment of how the models account for natural emissions and atmospheric lifetime of N_2O. The stronger aerosol forcing and its stronger recovery in MAGICC has the largest effect on near-term trends, with CH_4 and N_2O also contributing to stronger warming trends in the MAGICC model.

TCRE differences between the models are an informative illustration of their parametric differences. (Figure 2.A.3). In their setups used in this report, FAIR has a TCRE median of 0.38°C (5–95% range of 0.25 to 0.57°C) per 1000 GtO_2 and MAGICC a TCRE median of 0.47°C (5–95% range of 0.13 to 1.02°C) per 1000 $GtCO_2$. When directly used for the estimation of carbon budgets, this would make the remaining carbon budgets considerably larger in FAIR compared to MAGICC. As a result, rather than to use their budgets directly, this report bases its budget estimate on the AR5 TCRE *likely* (greater than 16–84%) range of 0.2 to 0.7°C per 1000 $GtCO_2$ (Collins et al., 2013) (see Section 2.A.1.2).

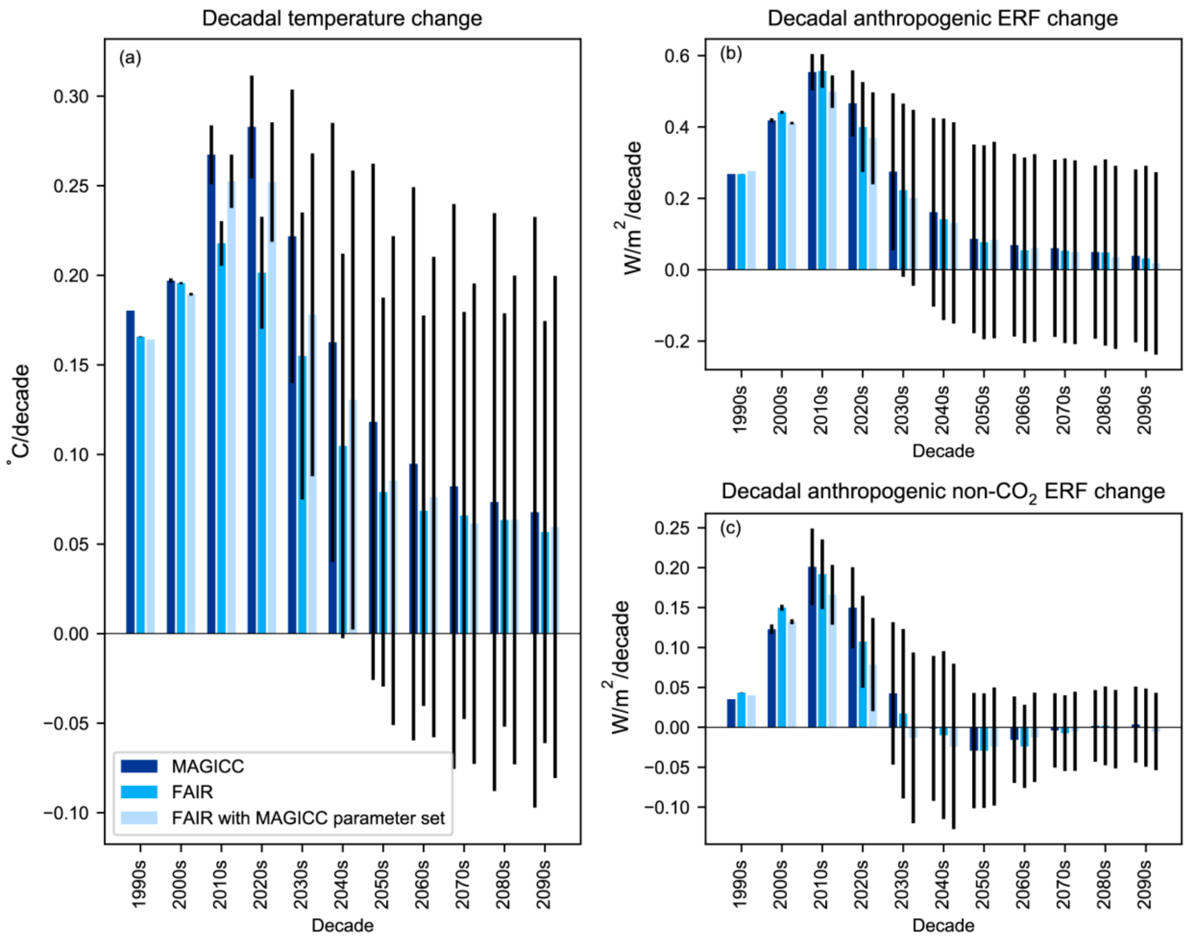


Figure 2.A.1: Warming rates per decade for MAGICC (dark blue), FAIR (sky blue) and FAIR matching the MAGICC parameter set (light blue) for the scenario dataset used in this report. Bars represent the mean of regression slopes taken over each decade (years 0 to 9) for scenario median temperature changes, over all scenarios. The black bars show the standard deviation over the set of scenarios.

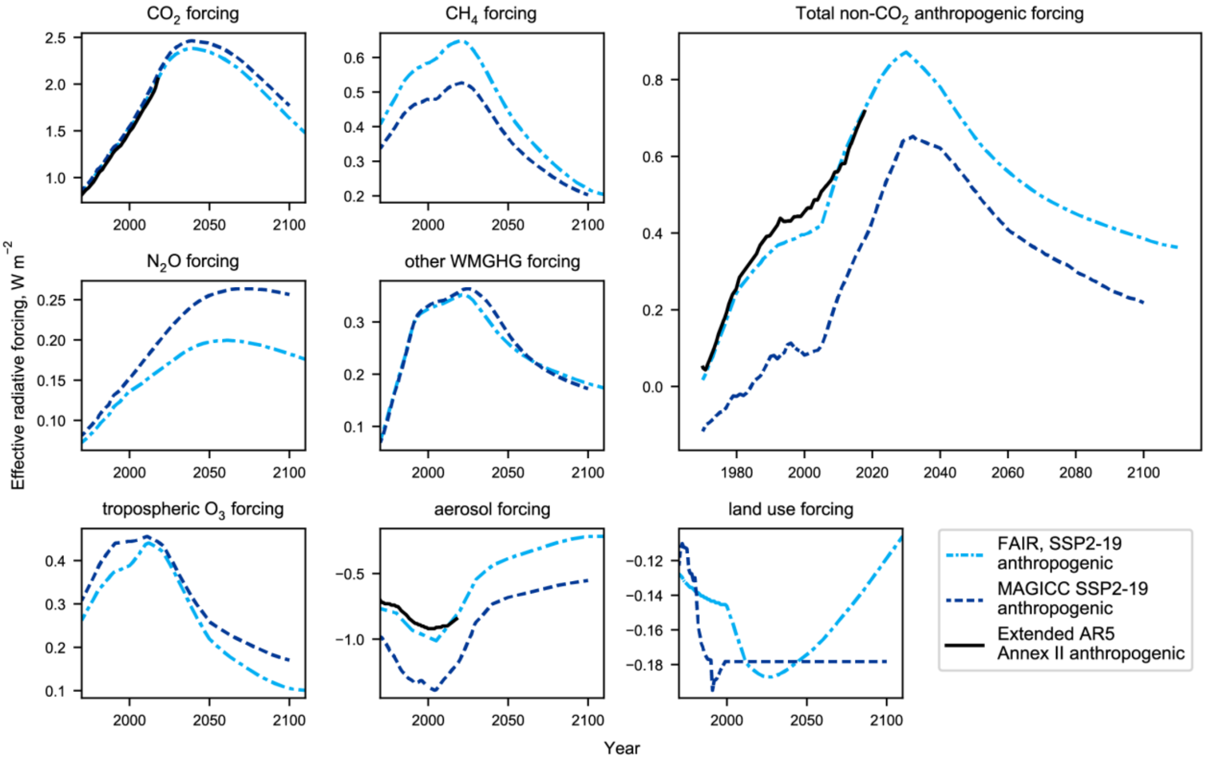


Figure 2.A.2: Time series of MAGICC (dark blue dashed) and FAIR (sky blue dash-dotted) effective radiative forcing for an example emission scenario for the main forcing agents where the models exhibit differences. AR5 data is from Myhre et al. (2013), extended from 2011 until the end of 2017 with greenhouse gas data from NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/), updated radiative forcing approximations for greenhouse gases (Etminan et al., 2016) and extended aerosol forcing following (Myhre et al., 2017).

The summary assessment is that both models exhibit plausible temperature responses to emissions. It is too premature to say that either model may be biased. As MAGICC is more established in the literature than FAIR and has been tested against CMIP5 models, the classification of scenarios used in this report is based on MAGICC temperature projections. There is *medium confidence* in this classification and the likelihoods used at the boundaries could prove to underestimate the probability of staying below given temperatures thresholds if near-term temperatures in the applied setup of MAGICC turn out to be warming too strongly. However, neither model accounts for possible permafrost melting in their setup used for this report (although MAGICC does have a setting that would allow them to be included (Schneider von Deimling et al., 2012, 2015)), so biases in MAGICC could cancel in terms of their effect on long-term temperature targets. The veracity of these reduced complexity climate models is a substantial knowledge gap in the overall assessment of pathways and their temperature thresholds.

The differences between FAIR and MAGICC have a substantial effect on their remaining carbon budgets (see Figure 2.A.3), and the strong near-term warming in the specific MAGICC setup applied here (Leach et al., 2018) may bias its results to smaller remaining budgets (green line on Figure 2.A.3). Likewise, the relatively small TCRE in FAIR (compared to AR5) might bias its results to higher remaining budgets (orange line on Figure 2.A.3). Rather than using the entire model response, only the contribution of non-CO_2 warming from each model is used, using the method discussed next.

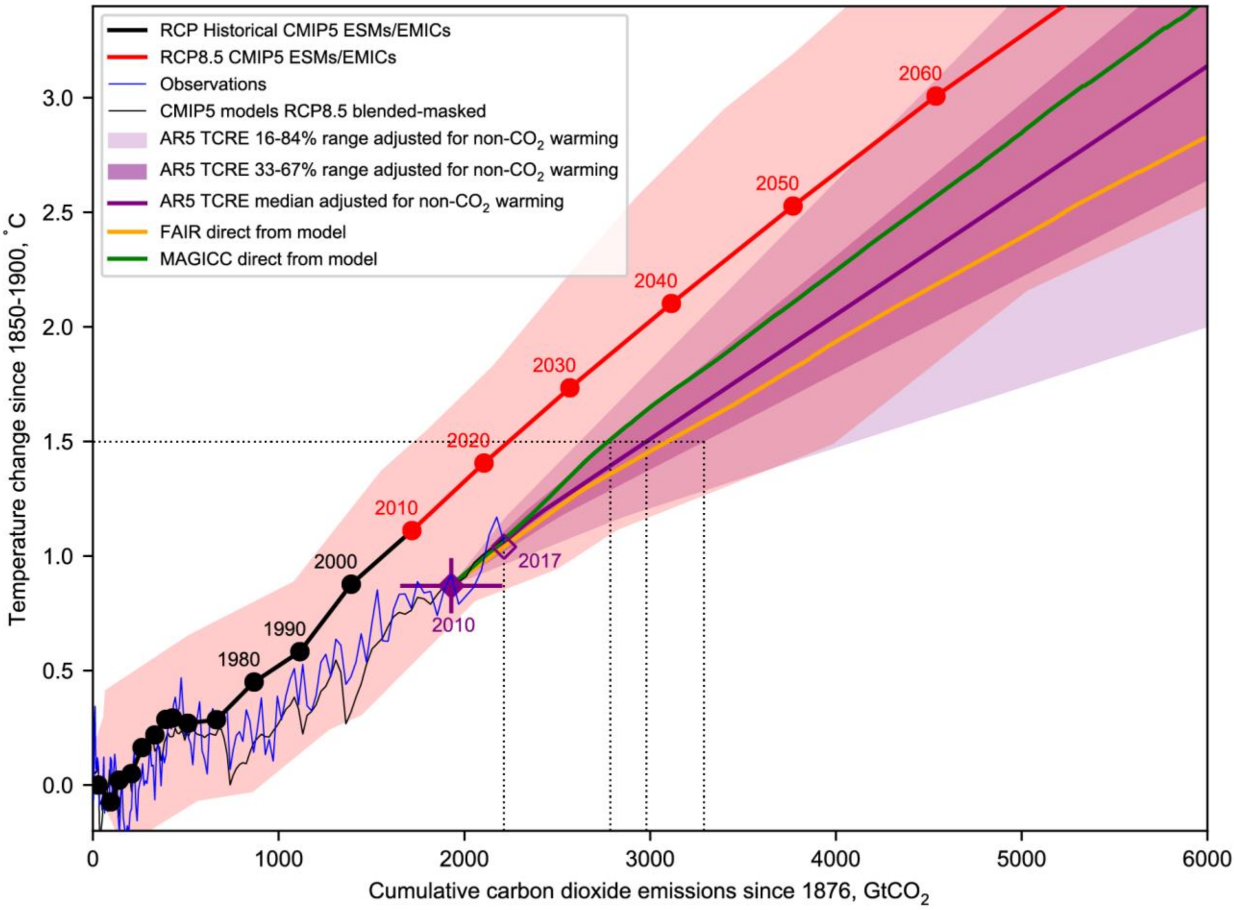


Figure 2.A.3: This figure follows Figure 2.3 of the main report with two extra lines on each showing FAIR (orange) and MAGICC (green) results separately. These additional lines show the full model response averaged across all scenarios and geophysical parameters.

2.A.1.2 Methods for assessing remaining carbon budgets

First, the basis for the median remaining carbon budget estimate is described based on MAGICC and FAIR non-CO_2 warming contributions. This is then compared to a simple analysis approach. Lastly, the uncertainty analysis is detailed.

2.A.1.2.1 Median remaining carbon budget basis

This assessment employs historical net cumulative CO_2 emissions reported by the Global Carbon Project (Le Quéré et al., 2018). They report 2170±240 $GtCO_2$ emitted between 1 January 1876 and 31 December 2016. Annual CO_2 emissions for 2017 are estimated at about 41±4 $GtCO_2$/yr (Le Quéré et al., 2018) (Version 1.3 accessed 22 May 2018). From 1 Jan 2011 until 31 December 2017, an additional 290 $GtCO_2$ (270-310 $GtCO_2$, 1σ range) has been emitted (Le Quéré et al., 2018).

In WG1 AR5, TCRE was assessed to have a likely range of 0.22°C to 0.68°C per 1000 $GtCO_2$. The middle of this range (0.45°C per 1000 $GtCO_2$) is taken to be the best estimate, although no best estimate was explicitly defined (Collins et al., 2013; Stocker et al., 2013).

TCRE is diagnosed from integrations of climate models forced with CO_2 emissions only. However, also the influence of other climate forcers on global temperatures should also be taken into account (see Figure 3 in Knutti and Rogelj (2015).

The Reference Non-CO_2 Temperature Contribution (RNCTC) is defined as the median future warming due to non-CO_2 radiative forcing until the time of net-zero CO_2 emissions. The RNCTC is then removed from pre-defined levels of future peak warming (ΔT_{peak}) between 0.3 to 1.2 °C. The CO_2-only carbon budget is subsequently computed for this revised set of warming levels ($\Delta T_{\mathrm{peak}} - RNCTC$).

In FAIR, the RNCTC is defined as the difference in temperature between two experiments, one where all anthropogenic emissions are included and one where only CO_2 emissions are included, using the constrained parameter set. Parallel integrations with matching physical parameters are performed for the suite of 205 scenarios in which CO_2 emissions become net zero during the 21st century. The non-CO_2 warming from a 2006-2015 average baseline is evaluated at the time in which CO_2 emissions become net zero. A linear regression between peak temperature relative to 2006-2015 and non-CO_2 warming relative to 2006-2015 at the time of net zero emissions is performed over the set of 205 scenarios (Figure 2.A.4). The RNCTC acts to reduce the ΔT_{peak} by an amount of warming caused by non-CO_2 agents, which also takes into account warming effects of non-CO_2 forcing on the carbon-cycle response . In the MAGICC model the non-CO_2 temperature contribution is computed from the non-CO_2 effective radiative forcing time series for the same 205 scenarios, using the AR5 impulse response function (Myhre et al., 2013). As in FAIR, the RNCTC is then calculated from a linear regression of non-CO_2 temperature change against peak temperature.

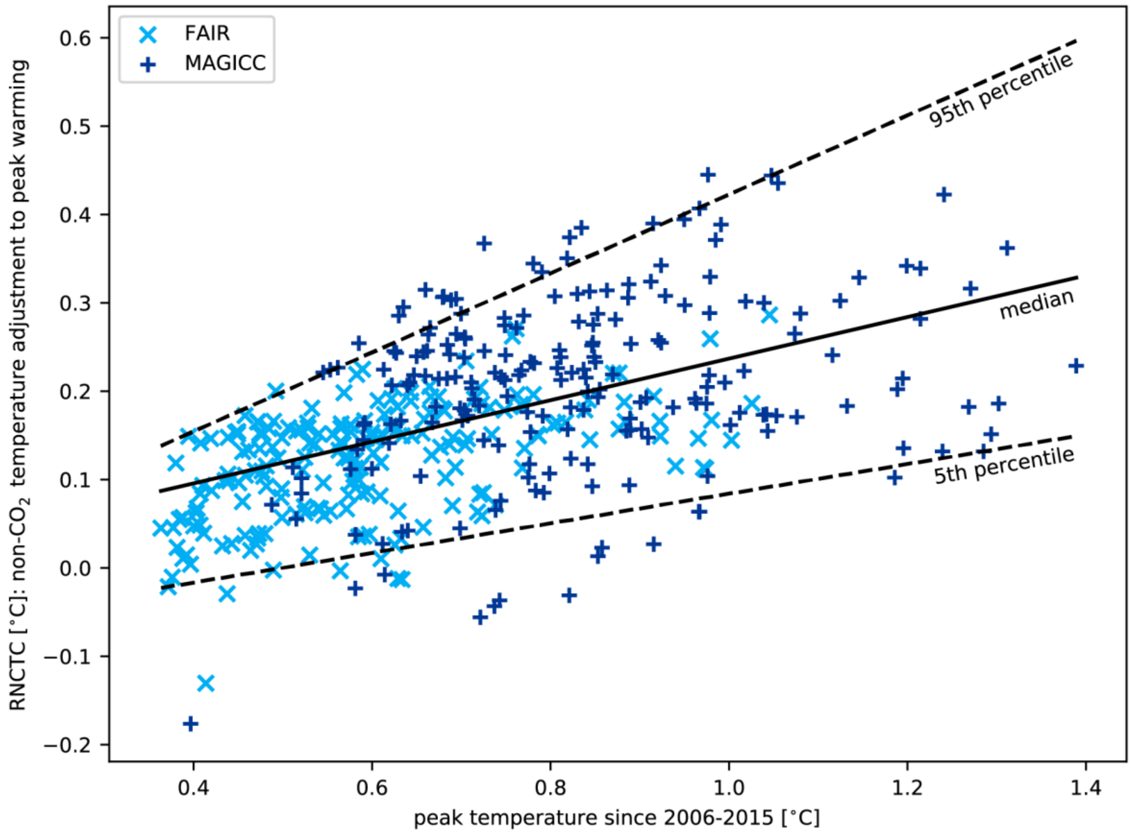


Figure 2.A.4: Relationship of RNCTC with peak temperature in the FAIR and MAGICC models. The black line is the linear regression relationship between peak temperature and RNCTC. The dashed lines show the quantile regressions at the 5th and 95th percentile.

Table 2.A.1 presents the CO_2 only budgets for different levels of future warming assuming both a normal and a log-normal TCRE distribution, where the overall distribution matches the AR5 *likely* TCRE range of 0.2° to 0.7°C per 1000 $GtCO_2$. Table 2.A.2 presents the RNCTC values for different levels of future warming and how they affect the remaining carbon budget for the individual models assuming the normal distribution of TCRE. These are then averaged and rounded to give the numbers presented in the main chapter (Table 2.2). The budgets are taken with respect to the 2006–2015 baseline for temperature and 1 January 2018 for cumulative emissions. In the main report (Section 2.2), as well as in Table 2.A.1, the estimates account for cumulative CO_2 emissions between the start of 2011 and the end of 2017 of about 290 $GtCO_2$.

Table 2.A.1: Remaining carbon dioxide only budget in $GtCO_2$ from 1.1.2018 for different levels of warming from 2006–2015 for normal and log-normal distributions of TCRE based on the AR5 likely range. 290 $GtCO_2$ has been removed to account for emissions between the start of 2011 and the end of 2017. The assessed warming from 1850–1900 to 2006–2015 is about 0.87°C with 1-σ uncertainty range of ±0.12°C.

CO_2 only Remaining budgets ($GtCO_2$)	**Normal distribution**			**Log-normal distribution**		
	TCRE 0.35 °C per 1000$GtCO_2$	TCRE 0.45 °C per 1000$GtCO_2$	TCRE 0.55 °C per 1000$GtCO_2$	TCRE 0.30 °C per 1000$GtCO_2$	TCRE 0.38 °C per 1000$GtCO_2$	TCRE 0.50 °C per 1000$GtCO_2$
Additional warming from 2005-2015 °C	TCRE 33%	TCRE 50%	TCRE 67%	TCRE 33%	TCRE 50%	TCRE 67%
0.3	571	376	253	709	487	315
0.4	859	598	434	1042	746	517
0.5	1146	820	615	1374	1005	718
0.6	1433	1042	796	1707	1265	920
0.63	1519	1109	851	1807	1342	980
0.7	1720	1264	977	2040	1524	1122
0.8	2007	1486	1158	2373	1783	1323
0.9	2294	1709	1339	2706	2042	1525
1	2581	1931	1520	3039	2301	1726
1.1	2868	2153	1701	3372	2560	1928
1.13	2955	2219	1756	3472	2638	1989
1.2	3156	2375	1882	3705	2819	2130

Table 2.A.2: Remaining carbon dioxide budget from 1.1.2018 reduced by the effect of non-CO_2 forcers. Budgets are for different levels of warming from 2006–2015 for a normal distribution of TCRE based on the AR5 *likely* range of 0.2°C to 0.7°C per 1000 $GtCO_2$. 290 $GtCO_2$ has been removed to account for emissions between the start of 2011 and the end of 2017. This method employed the RNCTC estimates of non-CO_2 temperature change until the time of net zero CO_2 emissions.

Remaining carbon budgets ($GtCO_2$) Additional warming from 2006-2015 °C	**MAGICC RNCTC °C**	**MAGICC** TCRE 33%	TCRE 50%	TCRE 67%	**FAIR RNCTC °C**	**FAIR** TCRE 33%	TCRE 50%	TCRE 67%
0.3	0.14	184	77	9	0.06	402	245	146
0.4	0.15	434	270	166	0.08	629	421	289
0.5	0.16	681	461	322	0.10	856	596	433
0.6	0.18	930	654	480	0.12	1083	772	576
0.63	0.18	1005	712	527	0.13	1152	825	619
0.7	0.19	1177	845	635	0.14	1312	949	720
0.8	0.20	1427	1038	793	0.16	1539	1125	863
0.9	0.22	1674	1229	948	0.18	1766	1300	1006
1	0.23	1924	1422	1106	0.20	1993	1476	1149
1.1	0.24	2171	1613	1262	0.22	2223	1653	1294
1.13	0.25	2246	1671	1309	0.23	2291	1707	1338
1.2	0.26	2421	1806	1419	0.25	2449	1829	1437

2.A.1.2.2 Checks on approach

A simple approach to infer the carbon budget contribution from non-CO_2 forcers has been proposed based on global warming potential and is found to hold for a wide range of mitigation scenarios (Allen et al., 2018). This is based on an empirical relationship between peak temperature, TCRE, cumulative CO_2 emissions (G_{CO2}), non-CO_2 forcing ($\Delta F_{\text{non-CO2}}$) and the Absolute Global Warming Potential of CO_2 ($\text{AGWP}_H(\text{CO}_2)$) over time horizon H, taken to be 100 years:

$$\Delta T_{\text{peak}} \approx \text{TCRE} \times \left(G_{\text{CO2}} + \Delta F_{\text{non-CO2}} \times (H/\text{AGWP}_H(\text{CO}_2))\right) \quad (1)$$

This method reduces the budget by an amount proportional to the change in non-CO_2 forcing. To determine this non-CO_2 forcing contribution, a Reference Non-CO_2 Forcing Contribution (RNCFC) is estimated from the MAGICC and FAIR runs. The RNCFC is defined as $\Delta F_{\text{non-CO2}}$ in eq. (1) which is a watts-per-metre-squared difference in the non-CO_2 effective radiative forcing between the 20 years before peak temperature is reached and 1996–2015. This provides an estimate of the non-CO_2 forcing contribution to the change in carbon budget. A similar calculation was performed for aerosol forcing in isolation (ΔF_{aer}) to show that the weakening aerosol forcing is the largest contributor to the smaller carbon budget, compared to the CO_2 only budget. AGWP_{100} values are taken from AR5 (Myhre et al., 2013) and the resultant remaining carbon budgets given in Table 2.A.3. This method reduces the remaining carbon budget by 1091 $GtCO_2$ per Wm^{-2} of non-CO_2 effective radiative forcing (with a 5% to 95% range of 886 to 1474 $GtCO_2$). These results show good agreement to those computed with the RNCTC method from Table 2.A.2, adding confidence to both methods. The RNCFC method is approximate and the choice of periods to use for averaging forcing is somewhat subjective, so the RNCTC is preferred over the RNCFC for this assessment.

Table 2.A.3: Remaining carbon dioxide budgets from 1.1.2018 reduced by the effect of non-CO_2 forcers calculated by using a simple empirical approach based on non-CO_2 forcing (RNCFC) computed by the FAIR model. Budgets are for different levels of warming from 2006–2015 and for a normal distribution of TCRE based on the AR5 likely range of 0.2°C to 0.7°C per 1000 $GtCO_2$. 290 $GtCO_2$ has been removed to account for emissions between the start of 2011 and the end of 2017.

Remaining budgets ($GtCO_2$) Additional warming from 2006-2015 °C	**FAIR RNCFC** (Wm^{-2})	**FAIR** TCRE 33%	TCRE 50%	TCRE 67%
0.3	0.191	363	168	45
0.4	0.211	629	368	204
0.5	0.232	893	568	362
0.6	0.253	1157	767	521
0.63	0.259	1237	827	568
0.7	0.273	1423	967	680
0.8	0.294	1687	1166	838
0.9	0.314	1952	1366	997
1	0.335	2216	1566	1155
1.1	0.356	2481	1765	1314
1.13	0.362	2560	1825	1361
1.2	0.376	2746	1965	1473

2.A.1.2.3 Uncertainties

Uncertainties are explored across several lines of evidence and summarised in Table 2.2 of the main report. Expert judgement is both used to estimate an overall uncertainty estimate and the estimate to remove 100 $GtCO_2$ to account for possible missing permafrost and wetlands feedbacks (see Section 2.2). The uncertainty in the warming to the base period (1850–1900 to 2006–2015) estimated in Chapter 1 is 0.87°C with a ±0.12 °C *likely* (1-σ) range affects how close warming since preindustrial levels is to the 1.5°C and

2°C limits, so the remaining budgets for a range of future warming thresholds between 0.3 and 1.2 °C above present-day are analysed. The uncertainty in 2006–2015 warming compared to 1850–1900 relates to a ±250 $GtCO_2$ uncertainty in carbon budgets for a best estimate TCRE.

A measure of the uncertainty due to variations in the consistent level of non-CO_2 mitigation at the time net-zero CO_2 emissions are reached in pathways is analysed by a quantile regression of each pathway's median peak temperature against its corresponding median RNCTC (evaluated with the FAIR model), for the 5th, median and 95th percentiles of scenarios. A variation of approximately ±0.1°C around the median RNCTC is observed for median peak temperatures between 0.3 and 1.2°C above the 2006-2015 mean. This variation is equated to a ±250 $GtCO_2$ uncertainty in carbon budgets for a median TCRE estimate of about 0.45°C per 1000 $GtCO_2$. An uncertainty of -400 to +200 $GtCO_2$ is associated with the non-CO_2 forcing and response. This is analysed from a regression of 5th and 95th percentile RNCTC against 5th and 95th percentile peak temperature calculated with FAIR, compared to the median RNCTC response. These uncertainty contributions are shown in Table 2.2 in the main chapter

The effects of uncertainty in the TCRE distribution was gauged by repeating the remaining budget estimate for a log-normal distribution of the AR5 *likely* range. This reduces the median TCRE from 0.45 °C per 1000 $GtCO_2$ to 0.38°C per 1000 $GtCO_2$ (see Table 2A.1). Table 2.A.4 presents these remaining budgets and shows that around 200 $GtCO_2$ would be added to the budget by assuming a log-normal *likely* range. The assessment and evidence supporting either distribution is discussed in the main chapter.

Table 2.A.4: Remaining carbon dioxide budget from 1.1.2018 reduced by the effect of non-CO_2 forcers. Numbers are differences between estimates of the remaining budget made with the log-normal distribution compared to that estimated with a normal distribution of TCRE based on the AR5 *likely* range (see Table 2.A.1). 290 $GtCO_2$ has been removed to account for emissions between the start of 2011 and the end of 2017. This method employed the FAIR model RNCTC estimates of non-CO_2 temperature response.

Remaining budgets ($GtCO_2$)	**Log-normal minus normal TCRE distribution**		
Additional warming from 2006-2015 °C	TCRE 33%	TCRE 50%	TCRE 67%
0.3	110	89	50
0.4	146	118	66
0.5	183	148	82
0.6	219	177	99
0.63	230	186	103
0.7	255	207	115
0.8	291	236	131
0.9	328	265	148
1	364	294	164
1.1	400	324	180
1.13	411	333	185
1.2	436	353	197

Uncertainties in past CO_2 emissions ultimately impact estimates of the remaining carbon budgets for 1.5°C or 2°C. Uncertainty in CO_2 emissions induced by past land-use and land-cover changes contributes most, representing about 240 $GtCO_2$ from 1870 to 2017. Yet, this uncertainty is substantially reduced when deriving cumulative CO_2 emissions from a recent period. The cumulative emissions from the 2006–2015 reference period to 2017 used employed in this report are approximately 290 $GtCO_2$ with an uncertainty of about 20 $GtCO_2$.

2.A.2 Integrated Assessment Models

The set of process-based integrated assessment models (IAMs) that provided input to this assessment is not fundamentally different from those underlying the IPCC AR5 assessment of transformation pathways (Clarke et al., 2014) and an overview of these integrated modelling tools can be found there. However, there have been a number of model developments since AR5, in particular improving the sectorial detail of IAMs (Edelenbosch et al., 2017b), the representation of solar and wind energy (Creutzig et al., 2017; Johnson et al., 2017; Luderer et al., 2017; Pietzcker et al., 2017), the description of bioenergy and food production and associated sustainability trade-offs (Havlík et al., 2014; Weindl et al., 2017; Bauer et al., 2018; Frank et al., 2018), the representation of a larger portfolio of carbon dioxide removal (CDR) technologies (Chen and Tavoni, 2013; Marcucci et al., 2017; Strefler et al., 2018b), the accounting of behavioural change (McCollum et al., 2016; van Sluisveld et al., 2016; van Vuuren et al., 2018) and energy demand developments (Edelenbosch et al., 2017a, c; Grubler et al., 2018), and the modelling of sustainable development implications (van Vuuren et al., 2015; Bertram et al., 2018), for example, relating to water use (Bonsch et al., 2014; Hejazi et al., 2014; Fricko et al., 2016; Mouratiadou et al., 2016, 2018), access to clean water and sanitation (Parkinson et al., 2017), materials use (Pauliuk et al., 2017), energy access (Cameron et al., 2016), air quality (Rao et al., 2017), and bioenergy use and food security (Frank et al., 2017; Humpenöder et al., 2018). Furthermore, since AR5, a harmonised model documentation of IAMs and underlying assumptions has been established within the framework of the EU ADVANCE project, and made available at http://www.fp7-advance.eu/content/model-documentation.

2.A.2.1 Short introduction to the scope, use and limitations of integrated assessment modelling

IAMs are characterised by a dynamic representation of coupled systems, including energy, land, agricultural, economic and climate systems (Weyant, 2017). They are global in scope, and typically cover sufficient sectors and sources of greenhouse gas emissions to project anthropogenic emissions and climate change and identify consistency of different pathways with long-term goals of limiting warming to specific levels (Clarke et al., 2014). IAMs can be applied in a forward-looking manner to explore internally consistent socio-economic-climate futures, often extrapolating current trends under a range of assumptions or using counterfactual "no policy" assumptions to generate baselines for subsequent climate policy analysis. They can also be used in a back-casting mode to explore the implications of climate policy goals and climate targets for systems transitions and near-to-medium term action. In most IAM-based studies, both applications of IAMs are used concurrently (Clarke et al., 2009; Edenhofer et al., 2010; Luderer et al., 2012; Kriegler et al., 2014, 2015b, 2016; Riahi et al., 2015; Tavoni et al., 2015). Sometimes the class of IAMs is defined more narrowly as the subset of integrated pathway models with an economic core and equilibrium assumptions on supply and demand, although non-equilibrium approaches to integrated assessment modelling exist (Guivarch et al., 2011; Mercure et al., 2018). IAMs with an economic core describe consistent price-quantity relationships, where the "shadow price" of a commodity generally reflects its scarcity in the given setting. To this end, the price of greenhouse gas emissions emerging in IAMs reflects the restriction of future emissions imposed by a warming limit (Cross-chapter Box 5 in Chapter 2, Section 2.A.2.2). Such price needs to be distinguished from suggested levels of emissions pricing in multi-dimensional policy contexts that are adapted to existing market environments and often include a portfolio of policy instruments (Section 2.5.2) (Stiglitz et al., 2017).

Detailed-process IAMs that describe energy-land transitions on a process level are critically different from stylized cost-benefit IAMs that aggregate such processes into stylized abatement cost and climate damage relationships to identify cost-optimal responses to climate change (Weyant, 2017). A key component of cost-benefit IAMs is the representation of climate damages which has been debated in the recent literature (Revesz et al., 2014; Cai et al., 2015; Lontzek et al., 2015; Burke et al., 2016; Stern, 2016). In the meantime, new approaches and estimates for improving the representation of climate damages are emerging (Dell et al., 2014; Burke et al., 2015, 2018; Hsiang et al., 2017) (Chapter 3 Box 3.6). A detailed discussion of the strengths and weaknesses of cost-benefit IAMs is provided in AR5 (Clarke et al., 2014; Kolstad et al., 2014; Kunreuther et al., 2014) (see also Cross-Chapter Box 5 in Chapter 2). The assessment of 1.5°C-consistent pathways in Chapter 2 relies entirely on detailed-process IAMs. These IAMs have so far rarely attempted a full representation of climate damages on socio-economic systems for mainly three reasons: a focus on the implications of mitigation goals for transition pathways (Clarke et al., 2014), the computational challenge to represent, estimate and integrate the complete range of climate impacts on a process level (Warszawski et al., 2014), and ongoing fundamental research on measuring the breadth and depth of how bio-physical climate impacts can affect societal welfare (Dennig et al., 2015; Adler et al., 2017; Hallegatte and Rozenberg, 2017). While some detailed-process IAMs account for climate impacts in selected sectors, e.g. agriculture (Stevanović et al., 2016), these IAMs do not take into account climate impacts as a whole in their pathway modelling. 1.5°C and 2°C-consistent pathways available to this report hence do not reflect climate impacts and adaptation challenges below 1.5°C and 2°C, respectively. Pathway modelling to date is also not able to identify socio-economic benefits of avoided climate damages between 1.5°C-consistent pathways and pathways leading to higher warming levels. These limitations are important knowledge gaps (Section 2.6) and subject of active research. Due to these limitations, the use of the integrated pathway literature in this report is concentrated on the assessment of mitigation action to limit warming to 1.5°C, while the assessment of impacts and adaptation challenges in 1.5°C warmer worlds relies on a different body of literature (see Chapters 3 to 5).

The use of IAMs for climate policy assessments has been framed in the context of solution-oriented assessments (Edenhofer and Kowarsch, 2015; Beck and Mahony, 2017). This approach emphasizes the exploratory nature of integrated assessment modelling to produce scenarios of internally consistent, goal-oriented futures. They describe a range of pathways that achieve long-term policy goals, and at the same time highlight trade-offs and opportunities associated with different courses of action. This literature has noted, however, that such exploratory knowledge generation about future pathways cannot be completely isolated from societal discourse, value formation and decision making and therefore needs to be reflective of its performative character (Edenhofer and Kowarsch, 2015; Beck and Mahony, 2017). This suggests an interactive approach which engages societal values and user perspectives in the pathway production process. It also requires transparent documentation of IAM frameworks and applications to enable users to contextualize pathway results in the assessment process. Integrated assessment modelling results assessed in AR5 were documented in Annex II of AR5 (Krey et al., 2014b), and this Annex aims to document the IAM frameworks that fed into the assessment of 1.5°C-consistent pathways in Chapter 2 of this report. It draws upon increased efforts to extend and harmonize IAM documentations[1] (Section 2.A.2.5). Another important aspect for the use of IAMs in solution-oriented assessments is trust building in their applicability and validity. The literature has discussed approaches to IAM evaluation (Schwanitz, 2013; Wilson et al., 2017), including model diagnostics (Kriegler et al., 2015a; Wilkerson et al., 2015; Craxton et al., 2017) and comparison with historical developments (Wilson et al., 2013; van Sluisveld et al., 2015).

2.A.2.2. Economics and Policy Assumptions in IAMs

Experiments with IAMs most often create scenarios under idealised policy conditions which assume that climate change mitigation measures are undertaken where and when they are the most effective (Clarke et al., 2014). Such 'idealised implementation' scenarios assume that a global price on GHG emissions is implemented across all countries, all economic sectors, and rises over time through 2100 in a way that will minimise discounted economic costs. The emissions price reflects marginal abatement costs and is often used as a proxy of climate policy costs (see Section 2.5.2). Scenarios developed under these assumptions are often referred to as 'least-cost' or 'cost-effective' scenarios because they result in the lowest aggregate global mitigation costs when assuming that global markets and economies operate in a frictionless, idealised way (Clarke et al., 2014; Krey et al., 2014b). However, in practice, the feasibility (see Cross-Chapter Box 3 in Chapter 1) of a global carbon pricing mechanism deserves careful consideration (see Chapter 4.4). Scenarios from idealised conditions provide benchmarks for policy makers, since deviations from the idealized approaches capture important challenges for socio-technical and economic systems and resulting climate outcomes.

Model experiments diverging from idealised policy assumptions aim to explore the influence of policy barriers to implementation of globally cost-effective climate change mitigation, particularly in the near term. Such scenarios are often referred to as 'second-best' scenarios. They include, for instance, (i) fragmented

[1] FOOTNOTE: http://www.fp7-advance.eu/content/model-documentation

policy regimes in which some regions champion immediate climate mitigation action (e.g. 2020) while other regions join this effort with a delay of one or more decades (Clarke et al., 2009; Blanford et al., 2014; Kriegler et al., 2015b), (ii) prescribed near-term mitigation efforts (until 2020 or 2030) after which a global climate target is adopted (Luderer et al., 2013, 2016; Rogelj et al., 2013b; Riahi et al., 2015), or (iii) variations in technology preferences in mitigation portfolios (Edenhofer et al., 2010; Luderer et al., 2012; Tavoni et al., 2012; Krey et al., 2014a; Kriegler et al., 2014; Riahi et al., 2015; Bauer et al., 2017, 2018). Energy transition governance adds a further layer of potential deviations from cost-effective mitigation pathways and has been shown to lead to potentially different mitigation outcomes (Trutnevyte et al., 2015; Chilvers et al., 2017; Li and Strachan, 2017). Governance factors are usually not explicitly accounted for in IAMs.

Pricing mechanisms in IAMs are often augmented by assumptions about regulatory and behavioural climate policies in the near- to mid-term (Bertram et al., 2015; van Sluisveld et al., 2016; Kriegler et al., 2018). The choice of GHG price trajectory to achieve a pre-defined climate goal varies across IAMs and can affect the shape of mitigation pathways. For example, assuming exponentially increasing CO_2 pricing to stay within a limited CO_2 emissions budget is consistent with efficiency considerations in an idealized economic setting, but can lead to temporary overshoot of the carbon budget if carbon dioxide removal (CDR technologies) are available. The pricing of non-CO_2 greenhouse gases is often pegged to CO_2 pricing using their global warming potentials (mostly GWP_{100}) as exchange rates (see Cross-Chapter Box 2 in Chapter 1). This leads to stringent abatement of non-CO_2 gases in the medium- to long-term, but also incentivizes continued compensation of these gases by CDR even after their full abatement potential is exploited, thus contributing to the pattern of peaking and declining temperatures in many mitigation pathways.

The choice of economic discount rate is usually reflected in the increase of GHG pricing over time and thus also affects the timing of emissions reductions. For example, the deployment of capital-intensive abatement options like renewable energy can be pushed back by higher discount rates. IAMs make different assumptions about the discount rate, with many of them assuming a social discount rate of ca. 5% per year (Clarke et al., 2014). In a survey of modelling teams contributing scenarios to the database for this assessment, discount rate assumptions varied between 2%/year and 8%/year depending on whether social welfare considerations or the representation of market actor behaviour is given larger weight. Some IAMs assume fixed charge rates that can vary by sector taking into account that private actors require shorter time horizons to amortize their investment. The impact of the choice of discount rate on mitigation pathways is underexplored in the literature. In general, the choice of discount rate is expected to have smaller influence on low-carbon technology deployment schedules for tighter climate targets as they leave less flexibility in the timing of emissions reductions. However, the introduction of large-scale CDR options might increase sensitivity again. It was shown, for example, that if a long-term CDR option like direct air capture with CCS (DACCS) is introduced in the mitigation portfolio, lower discount rates lead to more early abatement and less CDR deployment (Chen and Tavoni, 2013). If discount rates vary across regions, with higher costs of capital in developing countries, industrialized countries mitigate more and developing countries less at higher overall mitigation costs compared to a case with globally uniform discounting (Iyer et al., 2015). More work is needed to study the sensitivity of the deployment schedule of low-carbon technologies to the choice of the discount rate. However, as overall emissions reductions need to remain consistent with the choice of climate goal, mitigation pathways from detailed process-based IAMs are still less sensitive to the choice of discount rate than cost-optimal pathways from cost-benefit IAMs (see Box 6.1 in Clarke et al., 2014) which have to balance near-term mitigation with long-term climate damages across time (Nordhaus, 2005; Dietz and Stern, 2008; Kolstad et al., 2014; Pizer et al., 2014) (see Cross-Chapter Box 5 in Chapter 2).

2.A.2.3. Technology assumptions and transformation modelling

Although model-based assessments project drastic near, medium and long-term transformations in 1.5°C scenarios, projections also often struggle to capture a number of hallmarks of transformative change, including disruption, innovation, and nonlinear change in human behaviour (Rockström et al., 2017). Regular revisions and adjustments are standard for expert and model projections, for example, to account for new information such as the adoption of the Paris Agreement. Costs and deployment of mitigation technologies will differ in reality from the values assumed in the full-century trajectories of the model results. CCS and nuclear provide examples of where real-world costs have been higher than anticipated (Grubler, 2010; Rubin et al., 2015) while solar PV is an example where real-world costs have been lower (Creutzig et al., 2017; Figueres et al., 2017; Haegel et al., 2017). Such developments will affect the low-carbon transition for achieving stringent mitigation targets. This shows the difficulty of adequately estimating social and technological transitions and illustrates the challenges of producing scenarios consistent with a quickly evolving market (Sussams and Leaton, 2017).

Behavioural and institutional frameworks affect the market uptake of mitigation technologies and socio-technical transitions (see Chapter 4.4). These aspects co-evolve with technology change and determine, among others, the adoption and use of low-carbon technologies (Clarke et al., 2014), which in turn can affect both the design and performance of policies (Kolstad et al., 2014; Wong-Parodi et al., 2016). Pre-determining technological change in models can preclude the examination of policies that aim to promote disruptive technologies (Stanton et al., 2009). In addition, knowledge creation, networks, business strategies, transaction costs, microeconomic decision-making processes and institutional capacities influence (no-regret) actions, policy portfolios and innovation processes (and vice versa) (Mundaca et al., 2013; Lucon et al., 2014; Patt, 2015; Wong-Parodi et al., 2016; Geels et al., 2017); however, they are difficult to capture in equilibrium or cost-minimisation model-based frameworks (Laitner et al., 2000; Wilson and Dowlatabadi, 2007; Ackerman et al., 2009; Ürge-Vorsatz et al., 2009; Mundaca et al., 2010; Patt et al., 2010; Brunner and Enting, 2014; Grubb et al., 2014; Patt, 2015; Turnheim et al., 2015; Geels et al., 2017; Rockström et al., 2017). It is argued that assessments that consider greater end-user heterogeneity, realistic market behaviour, and end-use technology details can address a more realistic and varied mix of policy instruments, innovation processes and transitional pathways (Ürge-Vorsatz et al., 2009; Mundaca et al., 2010; Wilson et al., 2012; Lucon et al., 2014; Li et al., 2015; Trutnevyte et al., 2015; McCollum et al., 2016; Geels et al., 2017). So-called ‘rebound’ effects in which behavioural changes partially offset policies, such as consumers putting less effort into demand reduction when efficiency is improved, are captured to a varying and in many cases only limited degree in IAMs.

There are also substantial variation in mitigation options represented in IAMs (see Section 2.A.2.6) which depend, on the one hand, on the constraints of individual modelling frameworks and on the other hand on model development decisions influenced by modellers’ beliefs and preferences (Section 2.3.1.2). Further limitations can arise on the system level. For example, trade-offs between material use for energy versus other uses are not fully captured in many IAMs (e.g. petroleum for plastics, biomass for material substitution). An important consideration for the analysis of mitigation potential is the choice of baseline. For example, IAMs often assume, in line with historical experience, that economic growth leads to a reduction in local air pollution as populations become richer (i.e. an environmental Kuznets curve) (Rao et al., 2017). In such cases, the mitigation potential is small because reference emissions that take into account this economic development effect are already low in scenarios that see continued economic development over their modelling time horizon. Assumptions about reference emissions are important because high reference emissions lead to high perceived mitigation potentials and potential overestimates of the actual benefit, while low reference emissions lead to low perceived benefits of mitigation measures and thus less incentive to address these important climate and air pollutants (Gschrey et al., 2011; Shindell et al., 2012; Amann et al., 2013; Rogelj et al., 2014; Shah et al., 2015; Velders et al., 2015).

2.A.2.4. Land use and bioenergy modelling in IAMs

The IAMs used in the land use assessment in this chapter and that are based on the SSPs (Popp et al., 2017; Riahi et al., 2017) all include an explicit land model.[2] These land models calculate the supply of food, feed, fiber, forestry, and bioenergy products (see also Chapter 2 Box 2.1). The supply depends on the amount of land allocated to the particular good, as well as the yield for the good. Different IAMs have different means of calculating land allocation and different assumptions about yield, which is typically assumed to increase

[2] FOOTNOTE: There are other IAMs that do not include an explicit land use representation. These models use supply curves to represent bioenergy; that is, they have an exogenously specified relationship between the quantity of bioenergy supplied and the price of bioenergy. These models include land use change emissions in a similar manner, with the amount of emissions depending on the amount of bioenergy supplied. For some of these models, LUC emissions are assumed to be zero, regardless of the amount of bioenergy.

over time reflecting technological progress in the agricultural sector (see (Popp et al., 2014) for examples). In these models, the supply of bioenergy (including BECCS) depends on the price and yield of bioenergy, the policy environment (e.g., any taxes or subsidizes affecting bioenergy profits), as well the demand for land for other purposes. Dominant bioenergy feedstocks assumed in IAMs are woody and grassy energy crops (2^{nd} generation biomass) in addition to residues. Some models implement a “food first” approach, where food demands are met before any land is allocated to bioenergy. Other models use an economic land allocation approach, where bioenergy competes with other land uses depending on profitability. Competition between land uses depend strongly on socio-economic drivers such as population growth and food demand, and are typically varied across scenarios. When comparing global bioenergy yields from IAMs with the bottom-up literature, care must be taken that assumptions are comparable. An in-depth assessment of the land-use components of IAMs is outside the scope of this Special Report.

In all IAMs that include a land model, the land-use change emissions associated with these changes in land allocation are explicitly calculated. Most IAMs use an accounting approach to calculating land use change emissions, similar to Houghton (Houghton et al., 2012). These models calculate the difference in carbon content of land due to the conversion from one type to another, and then allocate that difference across time in some manner. For example, increases in forest cover will increase terrestrial carbon stock, but that increase may take decades to accumulate. If forestland is converted to bioenergy, however, those emissions will enter the atmosphere more quickly.

IAMs often account for carbon flows and trade flows related to bioenergy separately. That is, IAMs may treat bioenergy as “carbon neutral” in the energy system, in that the carbon price does not affect the cost of bioenergy. However, these models will account for any land-use change emissions associated with the land conversions needed to produce bioenergy. Additionally, some models will separately track the carbon uptake from growing bioenergy and the emissions from combusting bioenergy (assuming it is not combined with CCS).

Table 2.A.5: Land-use types descriptions as reported in pathways (adapted from the SSP database: https://tntcat.iiasa.ac.at/SspDb/)

Land use type	**Description/examples**
Energy crops	Land dedicated to second generation energy crops. (e.g., switchgrass, miscanthus, fast-growing wood species)
Other crops	Food and feed/fodder crops
Pasture	Pasture land. All categories of pasture land - not only high quality rangeland. Based on FAO definition of "permanent meadows and pastures"
Managed forest	Managed forests producing commercial wood supply for timber or energy but also afforestation (note: woody energy crops are reported under "energy crops")
Natural forest	Undisturbed natural forests, modified natural forests and regrown secondary forests
Other natural land	Unmanaged land (e.g., grassland, savannah, shrubland, rock ice, desert), excluding forests

2.A.2.5. Contributing modelling framework reference cards

For each of the contributing modelling frameworks a reference card has been created highlighting the key features of the model. These reference cards are either based on information received from contributing modelling teams upon submission of scenarios to the SR1.5 database, or alternatively drawn from the ADVANCE IAM wiki documentation, available at http://www.fp7-advance.eu/content/model-documentation, and updated. These reference cards are provided in part II of this annex.

2.A.2.6 Overview mitigation measures in contributed IAM scenarios

Table 2.A.6: Overview of representation of mitigation measures in the integrated pathway literature, as submitted to the database supporting this report. Levels of inclusion have been elicited directly from contributing modelling teams by means of a questionnaire. The table shows the reported data. Dimensions of inclusion are explicit versus implicit, and endogenous or exogenous. An implicit level of inclusion is assigned when a mitigation measure is represented by a proxy like a marginal abatement cost curve in the AFOLU sector without modelling individual technologies or activities. An exogenous level of inclusion is assigned when a mitigation measure is not part of the dynamics of the modelling framework but can be explored through alternative scenarios.

Levels of inclusion

	Explicit	Implicit
Endogenous	A	C
Exogenous	B	D

E: Not represented by model

Mitigation measure	AIM	BET	COPPE-COFFEE	C-ROADS	DNE21+	GCAM 4.2	GEM-E3 3.0	GENESYSmod 1.0	GRAPE 1.0	IEA ETP	IEA WEM	IMACLIM 1.1	IMACLIM NL	IMAGE 3.0	MERGE-ETL 6.0	MESSAGE-GLOBIOM	MESSAGEix-GLOBIOM	POLES	REMIND-MAgPIE	Shell WEM v1	WITCH
Demand side measures																					
Energy efficiency improvements in energy end uses (e.g., appliances in buildings, engines in transport, industrial processes)	A	A	C	D	A	D	B	D	B	A	A	A	A	A	C	C	B	C	C	B	C
Electrification of transport demand (e.g., electric vehicles, electric rail)	A	A	A	D	A	A	B	A	A	A	A	A	A	A	C	A	A	A	A	B	A
Electrification of energy demand for buildings (e.g., heat pumps, electric/induction stoves)	A	A	A	D	A	A	B	A	D	A	A	C	C	A	C	A	A	A	C	B	C
Electrification of industrial energy demand (e.g., electric arc furnace, heat pumps, electric boilers, conveyor belts, extensive use of motor control, induction heating, industrial use of microwave heating)	A	A	C	D	A	C	D	A	D	A	A	C	C	A	C	A	A	C	C	B	E
CCS in industrial process applications (cement, pulp and paper, iron steel, oil and gas refining, chemicals)	A	E	A	D	D	A	E	E	C	A	A	E	E	A	E	A	A	E	A	B	C
Higher share of useful energy in final energy (e.g., insulation of buildings, lighter weight vehicles, combined heat and power generation, district heating, …)	C	E	C	D	A	C	D	D	C	B	B	D	D	A	C	A	A	A	C	D	E
Reduced energy and service demand in **industry** (e.g., process innovations, better control)	C	C	C	D	C	C	C	D	D	B	B	C	C	B	C	C	B	B	C	C	D
Reduced energy and service demand in **buildings** (e.g., via behavioural change, reduced material and floor space demand, infrastructure and buildings configuration)	C	C	C	D	C	C	C	D	D	C	C	D	D	C	C	C	B	B	C	C	E
Reduced energy and service demand in **transport** (e.g., via behavioural change, new mobility business models, modal shift in individual transportation, eco-driving, car/bike-sharing schemes)	C	C	C	D	C	A	B	D	B	B	C	C	C	C	C	C	B	B	C	C	E
Reduced energy and service demand in **international transport** (international shipping and aviation)	A	E	A	D	D	A	C	E	B	B	B	C	C	C	C	B	B	A	D	C	E
Reduced material demand via higher resource efficiency, structural change, behavioural change and material substitution (e.g., steel and cement substitution, use of locally available building materials)	A	E	E	D	D	D	C	E	D	B	B	E	E	B	E	D	B	E	C	C	E
Urban form (incl. integrated on-site energy, influence of avoided transport and building energy demand)	E	E	E	D	D	E	E	D	E	B	E	D	D	E	E	E	B	E	E	C	E

Levels of inclusion	AIM	BET	COPPE-COFFEE	C-ROADS	DNE21+	GCAM 4.2	GEM-E3 3.0	GENESYSmod 1.0	GRAPE 1.0	IEA ETP	IEA WEM	IMACLIM 1.1	IMACLIM NL	IMAGE 3.0	MERGE-ETL 6.0	MESSAGE-GLOBIOM	MESSAGEix-GLOBIOM	POLES	REMIND-MAgPIE	Shell WEM v1	WITCH
Switch from traditional biomass and solid fuel use in the residential sector to modern fuels, or enhanced combustion practices, avoiding wood fuel	D	A	A	D	D	B	E	A	A	A	A	E	E	A	E	A	A	B	D	C	A
Dietary changes, reducing meat consumption	A	E	E	D	D	A	E	E	B	E	E	E	E	B	E	B	B	B	B	E	E
Substitution of livestock-based products with plant-based products (cultured meat, algae-based fodder)	C	E	E	D	E	E	E	E	E	E		E	E	B	E	E	E	E	E	E	E
Food processing (e.g., use of renewable energies, efficiency improvements, storage or conservation)	C	E	E	D	E	E	E	E	E	C	C	E	E	E	E	B	B	E	D	E	E
Reduction of food waste (incl. reuse of food processing refuse for fodder)	B	E	E	D	E	D	E	E	E	E	E	E	E	B	E	B	B	E	B	E	E
Supply side measures																					
Decarbonisation of electricity:																					
Solar PV	A	A	A	D	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Solar CSP	E	E	A	D	E	A	E	A	E	A	A	A	A	A	A	A	A	A	A	A	A
Wind (on-shore and off-shore)	A	A	A	D	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Hydropower	A	A	A	D	A	A	B	A	A	A	A	A	A	B	A	A	A	A	A	A	A
Bio-electricity, including biomass co-firing	A	A	A	D	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Nuclear energy	A	A	A	D	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Advanced, small modular nuclear reactor designs (SMR)	E	E	A	D	E	A	E	E	E	C	C	E	E	E	A	E	E	E	E	C	E
Fuel cells (hydrogen)	E	E	A	D	A	A	E	A	A	A	A	E	E	A	A	A	A	A	A	A	A
CCS at coal and gas-fired power plants	A	A	A	D	A	A	B	E	A	A	A	A	A	A	A	A	E	A	A	B	A
Ocean energy (incl. tidal and current energy)	E	E	E	D	E	E	D	A	E	A	A	E	E	E	E	E	E	A	E	A	E
High-temperature geothermal heat	A	B	A	D	A	A	D	E	A	A	A	E	E	B	E	A	A	A	E	C	E
Decarbonisation of non-electric fuels:																					
Hydrogen from biomass or electrolysis	E	A	A	D	A	A	E	A	A	A	C	E	E	A	A	A	A	A	A	A	E
1st generation biofuels	A	E	A	D	A	A	B	E	A	A	A	C	A	A	A	B	B	A	B	A	A
2nd generation biofuels (grassy or woody biomass to liquids)	A	A	A	D	A	A	D	A	A	A	A	E	A	A	A	A	A	A	A	A	A
Algae biofuels	E	E	A	D	E	E	E	C	E	E	C	E	E	E	E	E	E	E	E	A	E
Power-to-gas, methanisation, synthetic fuels	E	C	A	D	A	E	E	A	E	E	B	E	E	E	A	A	A	E	E	E	E
Solar and geothermal heating	E	E	A	D	E	E	B	A	E	A	A	E	E	E	E	A	A	A	A	A	E

Legend:

	Explicit	Implicit
Endogenous	A	C
Exogenous	B	D

E: Not represented by model

Levels of inclusion

	Explicit	Implicit
Endogenous	**A**	C
Exogenous	B	D

E – Not represented by model

Levels of inclusion / Model names	AIM	BET	COPPE-COFFEE	C-ROADS	DNE21+	GCAM 4.2	GEM-E3 3.0	GENESYSmod 1.0	GRAPE 1.0	IEA ETP	IEA WEM	IMACLIM 1.1	IMACLIM NL	IMAGE 3.0	MERGE-ETL 6.0	MESSAGE-GLOBIOM	MESSAGEix-GLOBIOM	POLES	REMIND-MAgPIE	Shell WEM v1	WITCH
Nuclear process heat	E	E	E	D	E	E	E	E	E	**A**	**A**	E	E	E	E	**A**	**A**	E	E	C	E
Other processes:																					
Fuel switching and replacing fossil fuels by electricity in end-use sectors (partially a demand-side measure)	**A**	**A**	C	D	**A**	**A**	B	**A**	**A**	**A**	**A**	C	C	**A**	C	**A**	**A**	**A**	**A**	**A**	B
Substitution of halocarbons for refrigerants and insulation	C	E	E	D	E	C	C	E	E	E	E	E	E	**A**	E	**A**	**A**	**A**	D	E	C
Reduced gas flaring and leakage in extractive industries	C	E	**A**	D	D	C	C	E	E	E	**A**	E	E	C	E	B	B	**A**	C	D	D
Electrical transmission efficiency improvements, including smartgrids	B	E	C	D	**A**	E	E	E	E	B	B	E	E	B	C	E	E	E	E	B	E
Grid integration of intermittent renewables	E	E	C	D	**A**	C	E	C	D	**A**	**A**	E	E	C	C	C	C	**A**	**A**	D	C
Electricity storage	E	E	**A**	D	**A**	C	E	**A**	E	**A**	C	E	E	C	C	**A**	**A**	**A**	**A**	E	C
AFOLU measures																					
Reduced deforestation, forest protection, avoided forest conversion	**A**	E	**A**	D	B	**A**	E	E	B	D	D	E	E	B	E	**A**	**A**	B	B	D	C
Forest management	C	E	E	D	E	C	E	E	C	D	D	E	E	B	E	**A**	**A**	B	E	D	C
Reduced land degradation, and forest restoration	C	E	D	D	E	E	E	E	C	D	D	E	E	B	E	E	E	B	C	D	E
Agroforestry and silviculture	E	E	D	D	E	E	E	E	E	D	D	E	E	E	E	E	E	E	E	E	E
Urban and peri-urban agriculture and forestry	E	E	E	D	E	E	E	E	E	D	D	E	E	E	E	E	E	E	E	E	E
Fire management and (ecological) pest control	C	E	D	D	E	C	E	E	E	D	D	E	E	E	E	E	E	E	E	E	E
Changing agricultural practices enhancing soil carbon	C	E	E	D	E	E	E	E	E	D	D	E	E	E	E	E	E	B	E	D	E
Conservation agriculture	E	E	E	D	E	E	E	E	E	D	D	E	E	E	E	**A**	**A**	E	E	E	C
Increasing agricultural productivity	**A**	E	**A**	D	**A**	B	E	E	B	D	D	E	**A**	B	E	**A**	**A**	E	**A**	D	C
Methane reductions in rice paddies	C	E	C	D	C	C	C	E	C	D	D	E	C	C	E	**A**	**A**	B	C	D	C
Nitrogen pollution reductions, e.g., by fertilizer reduction, increasing nitrogen fertilizer efficiency, sustainable fertilizers	C	E	C	D	C	C	C	E	E	D	D	E	**A**	C	E	**A**	**A**	B	C	D	C
Livestock and grazing management, for example, methane and ammonia reductions in ruminants through feeding management or feed additives, or manure management for local biogas production to replace traditional biomass use	C	E	C	D	C	C	C	E	C	D	D	E	**A**	C	E	**A**	**A**	B	C	D	C
Manure management	C	E	C	D	C	C	C	E	C	D	D	E	C	C	E	**A**	**A**	E	C	E	C
Influence on land albedo of land use change	E	E	E	D	E	E	E	E	E	D	D	E	E	E	E	E	E	E	D	D	E
Carbon dioxide (greenhouse gas) removal																					

Levels of inclusion

	Explicit	Implicit
Endogenous	A	C
Exogenous	B	D

E	Not represented by model

Levels of inclusion	AIM	BET	COPPE-COFFEE	C-ROADS	DNE21+	GCAM 4.2	GEM-E3 3.0	GENESYSmod 1.0	GRAPE 1.0	IEA ETP	IEA WEM	IMACLIM 1.1	IMACLIM NL	IMAGE 3.0	MERGE-ETL 6.0	MESSAGE-GLOBIOM	MESSAGEix-GLOBIOM	POLES	REMIND-MAgPIE	Shell WEM v1	WITCH
Biomass use for energy production with carbon capture and sequestration (BECCS) (through combustion, gasification, or fermentation)	A	A	A	D	A	A	E	E	A	A	A	A	A	A	A	A	E	A	A	B	A
Direct air capture and sequestration (DACS) of CO_2 using chemical solvents and solid absorbents, with subsequent storage	E	E	E	D	E	E	E	E	E	E	E	E	E	E	A	E	E	E	A	E	E
Mineralization of atmospheric CO_2 through enhanced weathering of rocks	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Afforestation / Reforestation	A	E	A	C	A	A	E	E	A	E	E	E	E	B	E	A	A	B	A	D	A
Restoration of wetlands (e.g., coastal and peat-land restoration, blue carbon)	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Biochar	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Soil carbon enhancement, enhancing carbon sequestration in biota and soils, e.g. with plants with high carbon sequestration potential (also AFOLU measure)	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	A	A	B	C	E	E
Carbon Capture and Usage – CCU; bioplastics (bio-based materials replacing fossil fuel uses as feedstock in the production of chemicals and polymers), carbon fibre	E	E	E	D	E	C	E	E	E	A	B	E	E	A	E	E	E	E	E	A	E
Material substitution of fossil CO_2 with bio-CO_2 in industrial application (e.g. the beverage industry)	E	E	E	D	E	C	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Ocean iron fertilization	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Ocean alkalinisation	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Removing CH_4, N_2O and halocarbons via photocatalysis from the atmosphere	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E

2.A.3 Overview of SR1.5 scenario database collected for the assessment in the Chapter

The scenario ensemble collected in the context of this report represents an ensemble of opportunity based on available published studies. The submitted scenarios cover a wide range of scenario types and thus allow exploration of a wide range of questions. For this to be possible, however, critical scenario selection based on scenario assumptions and setup is required. For example, as part of the SSP framework, a structured exploration of 1.5°C pathways was carried out under different future socioeconomic developments (Rogelj et al., 2018). This allows to determine the fraction of successful (feasible) scenarios per SSPs (Table 2.A.7), an assessment which cannot be carried out with a more arbitrary ensemble of opportunity.

Table 2.A.7: Summary of models (with scenarios in the database) attempting to create scenarios with an end-of-century forcing of 1.9W m^{-2}, consistent with limiting warming to below 1.5°C in 2100, and related SPAs. Notes: 1= successful scenario consistent with modelling protocol; 0= unsuccessful scenario; x= not modelled; 0*= not attempted because scenarios for a 2.6 W m^{-2} target were already found to be unachievable in an earlier study. SSP3-SPA3for a more stringent 1.9 W m^{-2} radiative forcing target has thus not been attempted anew by many modelling teams. Marker implementations for all forcing targets within each SSP are indicated in blue. Source: (Rogelj et al., 2018).

Model	Methodology	Reported scenario				
		SSP1-SPA1	SSP2-SPA2	SSP3-SPA3	SSP4-SPA4	SSP5-SPA5
AIM	General Equilibrium (GE)	1	1	0*	0	0
GCAM4	Partial Equilibrium (PE)	1	1	X	0	1
IMAGE	Hybrid (system dynamic models and GE for agriculture)	1	1	0*	X	X
MESSAGE-GLOBIOM	Hybrid (systems engineering PE model)	1	1	0*	X	X
REMIND-MAgPIE	General Equilibrium (GE)	1	1	X	X	1
WITCH-GLOBIOM	General Equilibrium (GE)	1	1	0	1	0

2.A.3.1 Configuration of SR1.5 scenario database

The Integrated Assessment Modelling Consortium (IAMC), as part of its ongoing cooperation with Working Group III of the IPCC, issued a call for submissions of scenarios of 1.5°C global warming and related scenarios to facilitate the assessment of mitigation pathways in this special report. This database is hosted by the International Institute for Applied Systems Analysis (IIASA) at http://data.ene.iiasa.ac.at/sr1p5/. Upon approval of this report, the database of scenarios underlying this assessment will also be published. Computer scripts and tools used to conduct the analysis and generate figures are also available for download from that website.

2.A.3.1.1 Criteria for submission to the scenario database

Scenarios submitted to the database were required to either aim at limiting warming to 1.5°C or 2°C in the long term, or to provide context for such scenarios, for example, corresponding NDC and baseline scenarios without climate policy. Model results should constitute an emissions trajectory over time with underlying socio-economic development until at least the year 2050 generated by a formal model such as a dynamic systems, energy-economy, partial or general equilibrium or integrated assessment model.

The end of the 21st century is referred to as "long term" in the context of this scenario compilation. For models with time horizons shorter than 2100, authors and/or submitting modelling teams were asked to explain how they evaluated their scenario as being consistent with 1.5°C in the long term. Ultimately, scenarios that only covered part of the 21st century could only to a very limited degree be integrated in the assessment, as the longer-term perspective was lacking. Submissions of emissions scenarios for individual regions and specific sectors were possible, but no such scenarios were received.

Each scenario submission required a supporting publication in a peer-reviewed journal that was accepted until 15 May 2018. Alternatively, the scenario must have been published by the same date in a report that has been determined by IPCC to be eligible grey literature (see Table 2.A.9). As part of the submission process, the authors of the underlying modelling team agreed to the publication of their model results in this scenario database.

2.A.3.1.2 Historical consistency analysis of submitted scenarios

Submissions to the scenario database were compared to the following data sources for historical periods to identify reporting issues.

Historical emissions database (CEDS)
Historical emissions imported from the *Community Emissions Data System (CEDS) for Historical Emissions* (http://www.globalchange.umd.edu/ceds/) have been used as a reference and for use in figures (van Marle et al., 2017; Hoesly et al., 2018). Historical N_2O emissions, which are not included in the CEDS database, are compared against the RCP database (http://tntcat.iiasa.ac.at/RcpDb/).

Historical IEA World Energy Balances and Statistics
Aggregated historical time series of the energy system from the IEA World Energy Balances and Statistics (revision 2017) were used as a reference for validation of submitted scenarios and for use in figures.

2.A.3.1.3 Verification of completeness and harmonization for climate impact assessment

Categorizing scenarios according to their long-term warming impact requires reported emissions time series until the end of the century of the following species: CO_2 from energy and industrial processes, methane, nitrous oxide and sulphur. The long-term climate impact could not be assessed for scenarios not reporting these species, and these scenarios were hence not included in any subsequent analysis.

For the diagnostic assessment of the climate impact of each submitted scenario, reported emissions were harmonized to historical values (base year 2010) as provided in the RCP database by applying an additive offset, which linearly decreased until 2050. For non-CO_2 emissions where this method resulted in negative values, a multiplicative offset was used instead. Emissions other than the required species that were not reported explicitly in the submitted scenario were filled from RCP2.6 (Meinshausen et al., 2011b; van Vuuren et al., 2011) to provide complete emissions profiles to MAGICC and FAIR (see section 2.A.1).

The harmonization and completion of non-reported emissions was only applied to the diagnostic assessment as input for the climate impact using MAGICC and FAIR. All figures and analysis used in the chapter analysis are based on emissions as reported by the modelling teams, except for column "cumulative CO_2 emissions, harmonized" in Table 2.A.12.

2.A.3.1.4 Validity assessment of historical emissions for aggregate Kyoto greenhouse gases

The AR5 WGIII report assessed Kyoto greenhouse gases (GHG) in 2010 to fall in the range of 44.5-53.5 $GtCO_2e$/yr using the GWP_{100}-metric from the IPCC Second Assessment Report. As part of the diagnostics, the Kyoto GHG aggregation was recomputed using GWP_{100} according to SAR, AR4 and AR5 for all scenarios that provided sufficient level of detail for their emissions. A total of 33 scenarios from three modelling frameworks showed recomputed Kyoto GHG outside the year-2010 range assessed by the AR5 WGIII report. These scenarios were excluded from all analysis of near-term emissions evolutions, in particular in Figures 2.6, 2.7 and 2.8, and Table 2.4.

2.A.3.1.5 Plausibility assessment of near-term development

Submitted scenarios were assessed for the plausibility of their near-term development across a number of dimensions. One issue identified were drastic reductions of CO_2 emissions from the land-use sector already in 2020. Given recent trends, this was considered implausible and all scenarios from the ADVANCE and EMF33 studies reporting negative CO_2 emissions from the land-use sector in 2020 were excluded from the analysis throughout this chapter.

2.A.3.1.6 Missing carbon price information

Out of the 132 scenarios limiting global warming to 2°C throughout the century (see Table 2.A.8), a total of twelve scenarios submitted by three modelling teams reported carbon prices of 0 or missing values in at least one year. These scenarios were excluded from the analysis.in Section 2.5 and Figure 2.26 in the chapter.

2.A.3.2. Contributions to the SR1.5 database by modelling framework

In total, 19 modelling frameworks submitted 529 individual scenarios based manuscripts that were published or accepted for publication by 15 May 2018 (Table 2.A.8).

Table 2.A.8: Overview of submitted scenarios by modelling framework, including the categorization according to the climate impact (cf. Section 2.A.4) and outcomes of validity and near-term plausibility assessment of pathways (cf. Section 2.A.3.1).

	Below-1.5°C	**1.5°C return with low OS**	**1.5°C return with high OS**	**Lower 2°C**	**Higher 2°C**	**Above 2°C**	**Scenarios assessed**	**Not full century**	**Missing emissions species for assessment**	**Negative CO^2 emissions (AFOLU) in 2020**	**Scenarios submitted**
AIM		6	1	24	10	49	**90**				**90**
BET									16		**16**
C-ROADS	2	1	2			1	**6**				**6**
DNE21+									21		**21**
FARM									13		**13**
GCAM		1	2	1	3	16	**23**			24	**47**
GEM-E3								4			**4**
GENeSYS-MOD								1			**1**
GRAPE									18		**18**
IEA ETP								1			**1**
IEA World Energy Model					1		**1**				**1**
IMACLIM								7	12		**19**
IMAGE		7	4	6	9	35	**61**				**61**
MERGE		1			1	1	**3**				**3**
MESSAGE		6	6	11	13	22	**58**				**58**
POLES	4	7	5	9	3	9	**37**				**37**
REMIND	2	11	17	16	16	31	**93**				**93**
Shell World Energy Model								1			**1**
WITCH	1	4		7	2	25	**39**				**39**
Total	**9**	**44**	**37**	**74**	**58**	**189**	**411**	**14**	**80**	**24**	**529**

2.A.3.3. Overview and scope of studies available in SR1.5 database

Table 2.A.9: Recent studies included in the scenario database that this chapter draws upon and their key foci indicating which questions can be explored by the scenarios of each study. The difference between "Scenarios submitted" and "Scenarios assessed" is due to criteria described in Section 2.A.3.1. The numbers between brackets indicate the modelling frameworks assessed.

Study/model name	Key focus	Reference papers	Modelling frameworks	Scenarios submitted	Scenarios assessed
Multi-model studies					
SSPx-1.9	Development of new community scenarios based on the full SSP framework limiting end-of-century radiative forcing to 1.9 W $m^{-2.}$	Riahi et al. (2017) Rogelj et al. (2018)	6	126	126
ADVANCE	Aggregate effect of the INDCs, comparison to optimal 2°C/1.5°C scenarios ratcheting up after 2020. Decarbonisation bottlenecks and the effects of following the INDCs until 2030 as opposed to ratcheting up to optimal ambition levels after 2020 in terms of additional emissions locked in. Constraint of 400 $GtCO_2$ emissions from energy and industry over 2011-2100.	Vrontisi et al. (2018) Luderer et al. (2018)	9 (6)	74	55
CD-LINKS	Exploring interactions between climate and sustainable development policies with the aim to identify robust integral policy packages to achieve all objectives. Evaluating implications of short-term policies on the mid-century transition in 1.5°C pathways linking the national to the global scale. Constraint of 400 $GtCO_2$ emissions over 2011-2100.	McCollum et al. (2018)	8 (6)	36	36
EMF-33	Study of the bioenergy contribution in deep mitigation scenarios. Constraint of 400 $GtCO_2$ emissions from energy and industry over 2011-2100.	Bauer et al. (2018)	11 (5)	183	86
Single-model studies					
IMAGE 1.5	Understanding the dependency of 1.5°C pathways on negative emissions.	van Vuuren et al. (2018)		8	8
IIASA LED (MESSAGEix)	A global scenario of Low Energy Demand (LED) for Sustainable Development below 1.5°C without Negative Emission Technologies.	Grubler et al. (2018)		1	1
GENeSYS-MOD	Application of the Open-Source Energy Modelling System to the question of 1.5°C and 2°C pathways.	Löffler et al. (2017)		1	0
IEA WEO	World Energy Outlook.	OECD/IEA and IRENA (2017)		1	1
OECD/IEA ETP	Energy Technology Perspectives.	IEA (2017)		1	0
PIK CEMICS (REMIND)	Study of CDR requirements and portfolios in 1.5°C pathways.	Strefler et al. (2018a)		7	7
PIK PEP (REMIND-MAgPIE)	Exploring short-term policies as entry points to global 1.5°C pathways.	Kriegler et al. (2018)		13	13
PIK SD (REMIND-MAgPIE)	Targeted policies to compensate risk to sustainable development in 1.5°C scenarios.	Bertram et al. (2018)		12	12
AIM SFCM	Socio-economic factors and future challenges of the goal of limiting the increase in global average temperature to 1.5°C.	Liu et al. (2017)		33	33
C-Roads	Interactions between emissions reductions and carbon dioxide removal.	Holz et al. (2018)		6	6
PIK EMC		Luderer et al. (2013)		8	8
MESSAGE GEA		Rogelj et al. (2013a, 2013b, 2015)		10	10
AIM TERL	The contribution of transport policies to the mitigation potential and cost of 2 °C and 1.5 °C goals	Zhang et al. (2018)		6	6
MERGE-ETL	The role of Direct Air Capture and Storage (DACS) in 1.5°C pathways.	Marcucci et al. (2017)		3	3
Shell SKY	A technically possible, but challenging pathway for society to achieve the goals of the Paris Agreement.	Shell International B.V. (2018)		1	0

2.A.3.4. Data collected

A reporting template was developed to facilitate the collection of standardized scenario results. The template was structured in nine categories, and each category was divided into four priority levels: "Mandatory", "High priority (Tier 1)", "Medium priority (Tier 2)", and "Other". In addition, one category was included to collect input assumptions on capital costs to facilitate the comparison across engineering-based models. An overview and definitions of all variables will be made available as part of the database publication.

Table 2.A.10: Number of variables (time series of scenario results) per category and priority level.

Category	Description	Mandatory (Tier 0)	High priority (Tier 1)	Medium priority (Tier 2)	Other	Total
Energy	Configuration of the energy system (for the full conversion chain of energy supply from primary energy extraction, electricity capacity, to final energy use)	19	91	83	0	193
Investment	Energy system investment expenditure	0	4	22	17	43
Emissions	Emissions by species and source	4	19	55	25	103
CCS	Carbon capture and sequestration	3	10	11	8	32
Climate	Radiative forcing and warming	0	11	2	8	21
Economy	GDP, prices, policy costs	2	15	25	7	49
SDG	Indicators on sustainable development goals achievement	1	9	11	1	22
Land	Agricultural production & demand	0	14	10	5	29
Water	Water consumption & withdrawal	0	0	16	1	17
Capital costs	Major electricity generation and other energy conversion technologies	0	0	0	31	31
Total		**29**	**173**	**235**	**103**	**540**

2.A.4 Scenario classification

A total of 529 scenarios were submitted to the scenario database. Of these, 14 scenarios did not report results until the end of the century and an additional 80 scenarios did not report the required emissions species. During the validation and diagnostics, 24 scenarios were excluded because of negative CO_2 emissions from the land-use sector by 2020 (see Section 2.A.3). Therefore, the analysis in this report is based on 411 scenarios, of which 90 scenarios are consistent with 1.5°C at the end of the century and 132 remain below 2°C throughout the century (not including the 90 scenarios that are deemed consistent with 1.5°C). Table 2.A.11 provides an overview of the number of scenarios per class. Table 2.A.12 provides an overview of geophysical characteristics per class.

Table 2.A.11: Overview of pathway class specifications

Pathway group	**Class name**	**Short name combined classes**	**MAGICC exceedance probability filter**	**Number of scenarios**
1.5°C	Below 1.5°C	-	**P(1.5°C) ≤ 0.34**	**0**
	Below 1.5°C	Below-1.5°C	**0.34 < P(1.5°C) ≤ 0.5**	**9**
	1.5°C Return with low OS	1.5°C-low-OS	**0.5 < P(1.5°C) ≤ 0.67** AND **P(1.5°C in 2100) ≤ 0.5**	**34**
			0.5 < P(1.5°C) ≤ 0.67 AND **0.34 < P(1.5°C in 2100) ≤ 0.5**	**10**
	1.5°C Return with high OS	1.5°C-high-OS	**0.67 < P(1.5°C)** AND **P(1.5°C in 2100) ≤ 0.34**	**19**
			0.67 < P(1.5°C) AND **0.34 < P(1.5°C in 2100) ≤ 0.5**	**18**
2°C	Lower 2°C	Lower-2°C	**P(2°C) ≤ 0.34** (excluding above)	**74**
	Higher 2°C	Higher-2°C	**0.34 < P(2°C) ≤ 0.5** (excluding above)	**58**
	Above 2°C	-	**0.5 < P(2°C)**	**189**

As noted in the chapter text, scenario classification was based on probabilistic temperature outcomes assessed using the AR5 assessment of composition, forcing and climate response. These were represented within the MAGICC model (Meinshausen et al., 2009, 2011a) which was used in the same setup as AR5 WGIII analyses. As discussed in Section 2.2, updates in geophysical understanding would alter such results were they incorporated within MAGICC, though central outcomes would remain well within the probability distribution of the setup used here (see Section 2.A.1).

Table 2.A.12: Geophysical characteristics of mitigation pathways derived at median peak temperature and at the end of the century (2100). Geophysical characteristics of overshoot for mitigation pathways exceeding 1.5°C is given in the last two columns. Overshoot severity is the sum of degree warming years exceeding 1.5°C over the 21[st] century. NA indicates that no mitigation pathways exhibits the given geophysical characteristics. Radiative forcing metrics are: total anthropogenic radiative forcing (RFall), CO_2 radiative forcing ($RFCO_2$), and non-CO_2 radiative forcing ($RFnonCO_2$). Cumulative CO2 emissions until peak warming or 2100 are given for submitted (Subm.) and harmonized (Harm.) IAM outputs and are rounded at the nearest 10 $GtCO_2$.

			Geophysical characteristics at peak warming											Geophysical characteristics in 2100									Geophysical characteristics of the temperature overshoot				
category	# scenario with climate assessment	peak|median warming	peak|year	peak|CO_2 [ppm]	peak|RF all [Wm2]	peak|RF CO_2 [Wm2]	peak|RF non CO_2 [Wm2]	netzero CO_2 |year	cumulative CO_2 emissions (2016 to peak, as submitted)	cumulative CO_2 emissions (2016 to peak, harmonized)	peak|Prob Exceed 1.5°C [%]	peak|Prob Exceed 2.0°C [%	peak|Prob Exceed 2.5°C [%	2100| CO_2 [ppm]	2100|RF all [Wm2]	2100|RF CO_2 [Wm2]	2100|RF non CO_2 [Wm2]	cumulative CO_2 emissions (2016-2100), as submitted	cumulative CO_2 emissions (2016-2100), harmonized	2100|Prob Exceed 1.5°C [%	2100|Prob Exceed 2.0°C [%	2100|Prob Exceed 2.5°C [%	Overshoot|Duration [years]|2.0°C	Overshoot|Exceedance year|1.5°C	Overshoot|Exceedance year|2.0°C	Overshoot|Severity [temperature-years]|1.5°C	Overshoot|Duration [years]|1.5°C
Below-1.5°C	5	1.5 (1.4, 1.5)	2041 (2040, 2048)	423 (419, 430)	2.9 (2.7, 2.9)	2.3 (2.2, 2.3)	0.6 (0.4, 0.7)	2044 (2037, 2054)	480 (470, 590)	470 (450, 600)	45 (39, 49)	5 (4, 7)	1 (1, 1)	376 (367, 386)	1.8 (1.8, 2.1)	1.6 (1.5, 1.8)	0.3 (0.2, 0.4)	180 (10, 270)	150 (5, 260)	16 (12, 24)	3 (2, 6)	1 (0, 1)	NaN	NaN	NaN	NaN	NaN
1.5°C-low-OS	37	1.6 (1.5, 1.6)	2048 (2039, 2062)	431 (424, 443)	3.0 (2.8, 3.2)	2.4 (2.3, 2.5)	0.6 (0.3, 0.8)	2050 (2038, 2082)	620 (530, 870)	630 (520, 880)	60 (51, 67)	10 (7, 14)	1 (1, 2)	380 (357, 418)	2.1 (1.8, 2.5)	1.7 (1.4, 2.2)	0.3 (0.1, 0.8)	250 (-120, 780)	260 (-130, 790)	28 (17, 45)	7 (4, 12)	1 (1, 3)	NaN	2035 (2031, 2049)	NaN	1 (0, 3)	27 (14, 54)
1.5°C-high-OS	38	1.7 (1.6, 1.9)	2051 (2043, 2058)	448 (433, 465)	3.2 (3.0, 3.5)	2.6 (2.4, 2.8)	0.6 (0.4, 0.8)	2052 (2044, 2066)	860 (610, 1050)	860 (620, 1070)	75 (67, 89)	18 (11, 34)	3 (1, 8)	385 (354, 419)	2.2 (1.8, 2.6)	1.8 (1.3, 2.2)	0.4 (0.2, 0.7)	330 (-100, 790)	340 (-90, 820)	34 (20, 50)	8 (4, 14)	2 (1, 4)	NaN	2033 (2030, 2035)	NaN	6 (2, 14)	52 (31, 68)
Lower-2°C	70	1.7 (1.5, 1.8)	2063 (2047, 2100)	453 (418, 475)	3.1 (2.7, 3.5)	2.6 (2.2, 2.9)	0.5 (0.2, 0.9)	2074 (2050, inf)	1000 (540, 1400)	990 (550, 1430)	78 (56, 86)	26 (12, 34)	7 (2, 10)	429 (379, 467)	2.8 (2.4, 3.2)	2.3 (1.7, 2.7)	0.4 (0.2, 0.9)	880 (180, 1400)	880 (190, 1420)	65 (51, 80)	20 (13, 34)	7 (3, 11)	NaN	2033 (2030, 2043)	NaN	NaN	NaN
Higher-2°C	59	1.9 (1.8, 2.0)	2075 (2051, 2100)	473 (444, 490)	3.4 (3.1, 3.6)	2.8 (2.5, 3.1)	0.5 (0.4, 1.0)	2082 (2051, inf)	1320 (880, 1690)	1340 (890, 1660)	87 (78, 93)	40 (31, 50)	13 (7, 19)	452 (401, 490)	3.1 (2.6, 3.5)	2.6 (1.0, 3.0)	0.5 (0.3, 1.0)	1270 (510, 1690)	1270 (520, 1660)	83 (59, 89)	38 (17, 50)	13 (6, 19)	NaN	2033 (2030, 2039)	NaN	NaN	NaN
Above-2°C	183	3.1 (2.0, 5.4)	2100 (2067, 2100)	651 (472, 1106)	5.4 (3.4, 9.0)	4.6 (2.8, 7.4)	0.8 (0.4, 1.9)	inf (2067, inf)	3510 (1360, 8010)	3520 (1380, 8010)	100 (89, 100)	96 (50, 100)	83 (17, 100)	651 (438, 1106)	5.4 (2.9, 9.0)	4.6 (2.4, 7.4)	0.8 (0.4, 1.9)	3510 (1090, 8010)	3520 (1090, 8010)	100 (76, 100)	96 (34, 100)	83 (12, 100)	35 (17, 39) [3]	2032 (2029, 2037)	2051 (2042, 2100)	NaN	NaN

2.A.5 Mitigation and SDG pathway synthesis

The Chapter 2 synthesis assessment (see Figure 2.28) of interactions between 1.5°C mitigation pathways and sustainable development or Sustainable Development Goals (SDGs) is based on the assessment of interactions of mitigation measures and SDGs carried out by Chapter 5 (Section 5.4). To derive a synthesis assessment of the interactions between 1.5°C mitigation pathways and SDGs, a set of clear and transparent steps are followed, as described below.

- Table 5.1 is at the basis of all interactions considered between mitigation measures and SDGs.
- A condensed set of mitigation measures, selecting and combining mitigation measures from Table 5.1, is defined (see Table 2.A.13).
- If a measure in the condensed Chapter 2 set is a combination of multiple mitigation measures from Table 5.1, the main interaction (synergies, synergy or trade-off, trade-off) is based on all interactions with 3* and 4* confidence in Table 5.1. If no 3* or 4* interactions are available, lower confidence interactions are considered if available.
- The resulting interaction is defined by the interaction of the majority of cells.
- If one cell shows a diverging interaction and this interaction has 3* or more confidence level, a "synergy or trade-off" interaction is considered.
- If all interactions for a given mitigation measure and SDG combination are the same, the resulting interaction is represented with a bold symbol.
- If all 3* and 4* interactions are of the same nature, but a lower confidence interaction is opposite, the interaction is represented with a regular symbol.
- Confidence is defined by the rounded average of all available confidence levels of the predominant direction (rounded down; 4* confidence in Table 5.1 is also reported as 3* in the Chapter 2 synthesis)
- If a measure in Table 5.1 is assessed to result in either a neutral effect or a synergy or trade-off, the synergy or trade-off is reported in the Chapter 2 synthesis, but the confidence level is reduced by one notch.

To derive relative synergy-risk profiles for the four scenario archetypes used in Chapter 2 (S1, S2, S5, LED, see Sections 2.1 and 2.3), the relative deployment of the selected mitigation measures is used. For each mitigation measure, a proxy indicator is used (see Table 2.A.14). The proxy indicator values are displayed on a relative scale from zero to one where the value of the lowest pathway is set to the origin and the values of the other pathways scaled so that the maximum is one. The pathways with proxy indicators values that are neither 0 nor 1, receive a 0.5 weighting. These 0, 0.5, or 1 values are used to determine the relative achievement of specific synergies or trade-offs per SDG in each scenario, by summation of each respective interaction type (synergy, trade-off, or synergy or trade-off) over all proxy indicators. Ultimately these sums are synthesized in one interaction based on the majority of sub-interactions (synergy, trade-off, or synergy or trade-off). In cases where both synergies and trade-offs are identified, the 'synergy or trade-off' interaction is attributed.

Table 2.A.13: Mapping of mitigation measures assessed in Table 5.1 of Chapter 5 to the condensed set of mitigation measured used for the mitigation-SDG synthesis of Chapter 2.

Table 5.1 MITIGATION MEASURES SET			Chapter 2 CONDENSED SET
Demand	Industry	Accelerating energy efficiency improvement	DEMAND: Accelerating energy efficiency improvements in end use sectors
		Low-carbon fuel switch	DEMAND: Fuel switch and access to modern low-carbon energy
		Decarbonisation/CCS/CCU	Not included
	Buildings	Behavioural response	DEMAND: Behavioural response reducing Building and Transport demand
		Accelerating energy efficiency improvement	DEMAND: Accelerating energy efficiency improvements in end use sectors
		Improved access & fuel switch to modern low-carbon energy	DEMAND: Fuel switch and access to modern low-carbon energy
	Transport	Behavioural response	DEMAND: Behavioural response reducing Building and Transport demand
		Accelerating energy efficiency improvement	DEMAND: Accelerating energy efficiency improvements in end use sectors
		Improved access & fuel switch to modern low-carbon energy	DEMAND: Fuel switch and access to modern low-carbon energy
Supply	Replacing coal	Non-biomass renewables: solar, wind, hydro	SUPPLY: Non-biomass renewables: solar, wind, hydro
		Increased use of biomass	SUPPLY: Increased use of biomass
		Nuclear/Advanced Nuclear	SUPPLY: Nuclear/Advanced Nuclear
		CCS: Bio energy	SUPPLY: Bioenergy with carbon capture and storage (BECCS)
	Advanced coal	CCS: Fossil	SUPPLY: Fossil fuels with carbon capture and storage (fossil-CCS)
Land & Ocean	Agriculture & Livestock	Behavioural response: Sustainable healthy diets and reduced food waste	DEMAND: Behavioural response: Sustainable healthy diets and reduced food waste
		Land based greenhouse gas reduction and soil carbon sequestration	LAND: Land based greenhouse gas reduction and soil carbon sequestration
		Greenhouse gas reduction from improved livestock production and manure management systems	LAND: Greenhouse gas reduction from improved livestock production and manure management systems
	Forest	Reduced deforestation, REDD+	LAND: Reduced deforestation, REDD+, Afforestation and reforestation
		Afforestation and reforestation	LAND: Reduced deforestation, REDD+, Afforestation and reforestation
		Behavioural response (responsible sourcing)	Not included
	Oceans	Ocean iron fertilization	Not included
		Blue carbon	Not included
		Enhanced Weathering	Not included

Table 2.A.14: Mitigation measure and proxy indicators reflecting relative deployment of given measure across pathway archetypes. Values of Indicators 2, 3, and 4 are inverse related with the deployment of the respective measures.

Mitigation measure		**Pathway proxy**	
Group	*description*	*number*	*description*
Demand	Accelerating energy efficiency improvements in end use sectors	1	Compound annual growth rate of primary energy (PE) to final energy (FE) conversion from 2020 to 2050
	Behavioural response reducing Building and Transport demand	2	% change in FE between 2010 and 2050
	Fuel switch and access to modern low-carbon energy	3	Year-2050 carbon intensity of FE
	Behavioural response: Sustainable healthy diets and reduced food waste	4	Year-2050 share of non-livestock in food energy supply
Supply	Non-biomass renewables: solar, wind, hydro	5	Year-2050 PE from non-biomass renewables
	Increased use of biomass	6	Year-2050 PE from biomass
	Nuclear/Advanced Nuclear	7	ear-2050 PE from nuclear
	Bioenergy with carbon capture and storage (BECCS)	8	Year-2050 BECCS deployment in $GtCO_2$
	Fossil fuels with carbon capture and storage (fossil-CCS)	9	Year-2050 Fossil-CCS deployment in $GtCO_2$
Land	Land based greenhouse gas reduction and soil carbon sequestration	10	Cumulative AFOLU CO_2 emissions over the 2020-2100 period
	Greenhouse gas reduction from improved livestock production and manure management systems	11	CH_4 and N_2O AFOLU emissions per unit of total food energy supply
	Reduced deforestation, REDD+, Afforestation and reforestation	12	Change in global forest area between 2020 and 2050

References

Ackerman, F., S.J. DeCanio, R.B. Howarth, and K. Sheeran, 2009: Limitations of integrated assessment models of climate change. *Climatic Change*, **95(3-4)**, 297-315, doi:10.1007/s10584-009-9570-x.

Adler, M.D. et al., 2017: Priority for the worse-off and the social cost of carbon. *Nature Clim. Change*, **7(6)**, 443-449, doi:10.1038/nclimate3298.

Allen, M.R. et al., 2018: Quantifying the impact of climate change agreements covering cumulative and short-lived climate pollutants. *Nature* (in press).

Amann, M., Z. Klimont, and F. Wagner, 2013: Regional and Global Emissions of Air Pollutants: Recent Trends and Future Scenarios. *Annual Review of Environment and Resources*, **38(1)**, 31-55, doi:10.1146/annurev-environ-052912-173303.

Bauer, N. et al., 2017: Shared Socio-Economic Pathways of the Energy Sector - Quantifying the Narratives. *Global Environmental Change*, **42**, 316-330, doi:10.1016/j.gloenvcha.2016.07.006.

Bauer, N. et al., 2018: Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF 33 model comparison. *Climatic Change* (in press), doi:10.1007/s10584-018-2226-y.

Beck, S. and M. Mahony, 2017: The IPCC and the politics of anticipation. *Nature Climate Change*, **7(5)**, 311-313, doi:10.1038/nclimate3264.

Bertram, C., G. Luderer, A. Popp, J.C. Minx, and W. Lamb, 2018: Targeted policies can compensate most of the increased sustainability risks in 1.5°C mitigation scenarios. *Environ. Res. Lett* (in press).

Bertram, C. et al., 2015: Complementing carbon prices with technology policies to keep climate targets within reach. *Nature Climate Change*, **5(3)**, 235-239, doi:10.1038/nclimate2514.

Blanford, G.J., E. Kriegler, and M. Tavoni, 2014: Harmonization vs. fragmentation: Overview of climate policy scenarios in EMF27. *Climatic Change*, **123(3-4)**, 383-396, doi:10.1007/s10584-013-0951-9.

Bonsch, M. et al., 2014: Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy*, **8(1)**, 11-24, doi:10.1111/gcbb.12226.

Brunner, S. and K. Enting, 2014: Climate finance: A transaction cost perspective on the structure of state-to-state transfers. *Global Environmental Change*, **27**, 138-143.

Burke, M., S.M. Hsiang, and E. Miguel, 2015: Global non-linear effect of temperature on economic production. *Nature*, **527**, 235-239, doi:10.1038/nature15725.

Burke, M., W.M. Davis, and N.S. Diffenbaugh, 2018: Large potential reduction in economic damages under UN mitigation targets. *Nature*, **557(7706)**, 549-553, doi:10.1038/s41586-018-0071-9.

Burke, M. et al., 2016: Opportunities for advances in climate change economics. *Science*, **352(6283)**, 292-293, doi:10.1126/science.aad9634.

Cai, Y., K.L. Judd, T.M. Lenton, T.S. Lontzek, and D. Narita, 2015: Environmental tipping points significantly affect the cost-benefit assessment of climate policies. *Proceedings of the National Academy of Sciences*, **112(15)**, 4606-4611, doi:10.1073/pnas.1503890112.

Cameron, C. et al., 2016: Policy trade-offs between climate mitigation and clean cook-stove access in South Asia. *Nature Energy*, **1(1)**, 15010, doi:10.1038/nenergy.2015.10.

Chen, C. and M. Tavoni, 2013: Direct air capture of CO2 and climate stabilization: A model based assessment. *Climatic Change*, **118(1)**, 59-72, doi:10.1007/s10584-013-0714-7.

Chilvers, J. et al., 2017: Realising transition pathways for a more electric, low-carbon energy system in the United Kingdom: Challenges, insights and opportunities. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, **231(6)**, 440-477, doi:10.1177/0957650917695448.

Clarke, L. et al., 2009: International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Economics*, **31**, S64-S81, doi:10.1016/j.eneco.2009.10.013.

Clarke, L. et al., 2014: Assessing transformation pathways. 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, United Kingdom and New York, NY, USA, pp. 413-510.

Collins, M. et al., 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1029-1136.

Craxton, M., J. Merrick, C. Makridis, and J. Taggart, 2017: On the climate policy implications of substitutability and flexibility in the economy: An in-depth integrated assessment model diagnostic. *Technological Forecasting and Social Change*, **125**, 289-298, doi:https://doi.org/10.1016/j.techfore.2017.07.003.

Creutzig, F. et al., 2017: The underestimated potential of solar energy to mitigate climate change. *Nature Energy*, **2(9)**, 17140, doi:10.1038/nenergy.2017.140.

Dell, M., B.F. Jones, and B.A. Olken, 2014: What Do We Learn from the Weather ? The New Climate-Economy

Literature. *Journal of Economic Literature*, **52(3)**, 740-798.
Dennig, F., M.B. Budolfson, M. Fleurbaey, A. Siebert, and R.H. Socolow, 2015: Inequality, climate impacts on the future poor, and carbon prices. *Proceedings of the National Academy of Sciences*, **112(52)**, 15827-15832, doi:10.1073/pnas.1513967112.
Dietz, S. and N. Stern, 2008: Why Economic Analysis Supports Strong Action on Climate Change: A Response to the Stern Review's Critics. *Review of Environmental Economics and Policy*, **2(1)**, 94-113, doi:10.1093/reep/ren001.
Edelenbosch, O.Y. et al., 2017a: Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models. *Energy*, **122**, 701-710, doi:10.1016/J.ENERGY.2017.01.017.
Edelenbosch, O.Y. et al., 2017b: Decomposing passenger transport futures: Comparing results of global integrated assessment models. *Transportation Research Part D: Transport and Environment*, **55**, 281-293, doi:10.1016/j.trd.2016.07.003.
Edelenbosch, O.Y. et al., 2017c: Transport fuel demand responses to fuel price and income projections: Comparison of integrated assessment models. *Transportation Research Part D: Transport and Environment*, **55**, 310-321, doi:10.1016/J.TRD.2017.03.005.
Edenhofer, O. and M. Kowarsch, 2015: Cartography of pathways: A new model for environmental policy assessments. *Environmental Science & Policy*, **51**, 56-64, doi:10.1016/j.envsci.2015.03.017.
Edenhofer, O. et al., 2010: The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs. *The Energy Journal*, **31(Special Issue 1)**, 11-48, doi:10.2307/41323490.
Etminan, M., G. Myhre, E.J. Highwood, and K.P. Shine, 2016: Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters*, **43(24)**, 12,614-12,623, doi:10.1002/2016GL071930.
Figueres, C. et al., 2017: Three years to safeguard our climate. *Nature*, **546(7660)**, 593-595, doi:10.1038/546593a.
Forster, P. et al., 2007: Changes in Atmospheric Constituents and in Radiative Forcing. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 129-234.
Frank, S. et al., 2017: Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters*, **12(10)**, 105004, doi:10.1088/1748-9326/aa8c83.
Frank, S. et al., 2018: Structural change as a key component for agricultural non-CO2 mitigation efforts. *Nature Communications*, **9(1)**, 1060, doi:10.1038/s41467-018-03489-1.
Fricko, O. et al., 2016: Energy sector water use implications of a 2 °C climate policy. *Environmental Research Letters*, **11(3)**, 034011, doi:10.1088/1748-9326/11/3/034011.
Geels, F.W., B.K. Sovacool, T. Schwanen, and S. Sorrell, 2017: Sociotechnical transitions for deep decarbonization. *Science*, **357(6357)**.
Grubb, M., J.C. Hourcade, and K. Neuhoff, 2014: *Planetary economics: energy, climate change and the three domains of sustainable development*. Routledge Earthscan, Oxon, New York, 520 pp.
Grubler, A., 2010: The costs of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy*, **38(9)**, 5174-5188, doi:10.1016/J.ENPOL.2010.05.003.
Grubler, A. et al., 2018: A Global Scenario of Low Energy Demand for Sustainable Development below 1.5°C without Negative Emission Technologies. *Nature Energy* (in press), doi:10.1038/s41560-018-0172-6.
Gschrey, B., W. Schwarz, C. Elsner, and R. Engelhardt, 2011: High increase of global F-gas emissions until 2050. *Greenhouse Gas Measurement and Management*, **1(2)**, 85-92, doi:10.1080/20430779.2011.579352.
Guivarch, C., R. Crassous, O. Sassi, and S. Hallegatte, 2011: The costs of climate policies in a second-best world with labour market imperfections. *Climate Policy*, **11(1)**, 768-788, doi:10.3763/cpol.2009.0012.
Haegel, N.M. et al., 2017: Terawatt-scale photovoltaics: Trajectories and challenges. *Science*, **356(6334)**, 141-143, doi:10.1126/science.aal1288.
Hallegatte, S. and J. Rozenberg, 2017: Climate change through a poverty lens. *Nature Climate Change*, **7**, 250.
Havlík, P. et al., 2014: Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences of the United States of America*, **111(10)**, 3709-14, doi:10.1073/pnas.1308044111.
Hejazi, M. et al., 2014: Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. *Technological Forecasting and Social Change*, **81**, 205-226, doi:10.1016/j.techfore.2013.05.006.
Hoesly, R.M. et al., 2018: Historical (1750-2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). *Geoscientific Model Development*, **11(1)**, 369-408, doi:10.5194/gmd-11-369-2018.
Holz, C., L. Siegel, E. Johnston, A.P. Jones, and J. Sterman, 2018: Ratcheting ambition to limit warming to 1.5°C - trade-offs between emission reductions and carbon dioxide removal. *Environmental Research Letters* (in press), doi:10.1088/1748-9326/aac0c1.
Houghton, R. et al., 2012: Carbon emissions from land use and land-cover change. *Biogeosciences*, **9(12)**, 5125-5142, doi:10.5194/bg-9-5125-2012.
Hsiang, S. et al., 2017: Estimating economic damage from climate change in the United States. *Science*, **356(6345)**, 1362 LP - 1369.
Humpenöder, F. et al., 2018: Large-scale bioenergy production: how to resolve sustainability trade-offs? *Environmental*

Research Letters, **13(2)**, 024011, doi:10.1088/1748-9326/aa9e3b.
IEA, 2017: *Energy Technology Perspectives 2017*. International Energy Agency (IEA), Paris, France, 443 pp.
Iyer, G.C. et al., 2015: Improved representation of investment decisions in assessments of CO2 mitigation. *Nature Climate Change*, **5(5)**, 436-440, doi:10.1038/nclimate2553.
Johnson, N. et al., 2017: A reduced-form approach for representing the impacts of wind and solar PV deployment on the structure and operation of the electricity system. *Energy Economics*, **64**, 651-664, doi:10.1016/J.ENECO.2016.07.010.
Knutti, R. and J. Rogelj, 2015: The legacy of our CO2 emissions: a clash of scientific facts, politics and ethics. *Climatic Change*, **133(3)**, 361-373, doi:10.1007/s10584-015-1340-3.
Kolstad, C. et al., 2014: Social, Economic and Ethical Concepts and Methods. 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. Kadne, 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 Univeristy Press, Cambridge, United Kingdom and New York, NY, USA, pp. 207-282.
Krey, V., G. Luderer, L. Clarke, and E. Kriegler, 2014a: Getting from here to there - energy technology transformation pathways in the EMF27 scenarios. *Climatic Change*, **123**, 369-382, doi:10.1007/s10584-013-0947-5.
Krey, V. et al., 2014b: Annex II: Metrics & Methodology. 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, United Kingdom and New York, NY, USA, pp. 1281-1328.
Kriegler, E. et al., 2014: The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change*, **123(3-4)**, 353-367, doi:10.1007/s10584-013-0953-7.
Kriegler, E. et al., 2015a: Diagnostic indicators for integrated assessment models of climate policy. *Technological Forecasting and Social Change*, **90(PA)**, 45-61, doi:10.1016/j.techfore.2013.09.020.
Kriegler, E. et al., 2015b: Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technological Forecasting and Social Change*, **90(PA)**, 24-44, doi:10.1016/j.techfore.2013.09.021.
Kriegler, E. et al., 2016: Will economic growth and fossil fuel scarcity help or hinder climate stabilization?: Overview of the RoSE multi-model study. *Climatic Change*, **136(1)**, 7-22, doi:10.1007/s10584-016-1668-3.
Kriegler, E. et al., 2018: Short term policies to keep the door open for Paris climate goals. *Environ. Res. Lett* (in press), doi:10.1088/1748-9326/aac4f1.
Kunreuther, H. et al., 2014: Integrated Risk and Uncertainty Assessment of Climate Change Response Policies. 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, United Kingdom and New York, NY, USA.
Laitner, J., S. De Canio, and I. Peters, 2000: Incorporating Behavioural, Social, and Organizational Phenomena in the Assessment of Climate Change Mitigation Options. *Society, Behaviour, and Climate Change Mitigation*, 1-64, doi:10.1007/0-306-48160-X_1.
Le Quéré, C. et al., 2016: Global Carbon Budget 2016. *Earth System Science Data*, **8(2)**, 605-649, doi:10.5194/essd-8-605-2016.
Le Quéré, C. et al., 2018: Global Carbon Budget 2017. *Earth Syst. Sci. Data*, **1010333739(10)**, 405-448, doi:10.5194/essd-10-405-2018.
Leach, N.J. et al., 2018: Current level and rate of warming determine emissions budgets under ambitious mitigation. *Nature Geoscience* (in press).
Li, F.G.N. and N. Strachan, 2017: Modelling energy transitions for climate targets under landscape and actor inertia. *Environmental Innovation and Societal Transitions*, **24**, 106-129, doi:10.1016/j.eist.2016.08.002.
Li, F.G.N., E. Trutnevyte, and N. Strachan, 2015: A review of socio-technical energy transition (STET) models. *Technological Forecasting and Social Change*, **100**, 290-305, doi:10.1016/j.techfore.2015.07.017.
Liu, J.–Y. et al., 2017: Socio-economic factors and future challenges of the goal of limiting the increase in global average temperature to 1.5°C. *Carbon Management* (in press).
Löffler, K. et al., 2017: Designing a Model for the Global Energy System-GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS). *Energies*, **10(10)**, 1468, doi:10.3390/en10101468.
Lontzek, T.S., Y. Cai, K.L. Judd, and T.M. Lenton, 2015: Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy. *Nature Climate Change*, **5(5)**, 441-444.
Lucon, O. et al., 2014: Buildings. 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, United Kingdom and New York, NY, USA, pp. 671-738.
Luderer, G., C. Bertram, K. Calvin, E. De Cian, and E. Kriegler, 2016: Implications of weak near-term climate policies on long-term mitigation pathways. *Climatic Change*, **136(1)**, 127-140, doi:10.1007/s10584-013-0899-9.
Luderer, G. et al., 2012: The economics of decarbonizing the energy system - results and insights from the RECIPE model intercomparison. *Climatic Change*, **114(1)**, 9-37, doi:10.1007/s10584-011-0105-x.
Luderer, G. et al., 2013: Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environmental Research Letters*, **8(3)**, 034033, doi:10.1088/1748-9326/8/3/034033.
Luderer, G. et al., 2017: Assessment of wind and solar power in global low-carbon energy scenarios: An introduction. *Energy Economics*, **64**, 542-551, doi:10.1016/J.ENECO.2017.03.027.
Luderer, G. et al., 2018: Residual fossil CO2 emissions in 1.5-2°C pathways. *Nature Climate Change* (in press), doi:10.1038/s41558-018-0198-6.
Marcucci, A., S. Kypreos, and E. Panos, 2017: The road to achieving the long-term Paris targets: Energy transition and the role of direct air capture. *Climatic Change*, **144(2)**, 181-193, doi:10.1007/s10584-017-2051-8.
McCollum, D.L., W. Zhou, C. Bertram, H.–S. de Boer, and V. Bosetti, 2018: Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy* (in press), doi:10.1038/s41560-018-0179-z.
McCollum, D.L. et al., 2016: Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. *Transportation Research Part D: Transport and Environment*, doi:10.1016/j.trd.2016.04.003.
Meinshausen, M., T.M.L. Wigley, and S.C.B. Raper, 2011a: Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 2: Applications. *Atmospheric Chemistry and Physics*, **11(4)**, 1457-1471, doi:10.5194/acp-11-1457-2011.
Meinshausen, M. et al., 2009: Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature*, **458(7242)**, 1158-1162, doi:10.1038/nature08017.
Meinshausen, M. et al., 2011b: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change*, **109(1-2)**, 213-241, doi:10.1007/s10584-011-0156-z.
Mercure, J.–F. et al., 2018: Environmental impact assessment for climate change policy with the simulation-based integrated assessment model E3ME-FTT-GENIE. *Energy Strategy Reviews*, **20**, 195-208, doi:https://doi.org/10.1016/j.esr.2018.03.003.
Mouratiadou, I., A. Biewald, and M. Pehl, 2016: The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways. *Environmental Science & Policy*, **64**, 48-58.
Mouratiadou, I. et al., 2018: Water demand for electricity in deep decarbonisation scenarios: a multi-model assessment. *Climatic Change*, **147(1)**, 91-106, doi:10.1007/s10584-017-2117-7.
Mundaca, L., L. Neij, E. Worrell, and M. McNeil, 2010: Evaluating Energy Efficiency Policies with Energy-Economy Models. *Annual Review of Environment and Resources*, **35(1)**, 305-344, doi:10.1146/annurev-environ-052810-164840.
Mundaca, L., M. Mansoz, L. Neij, and G. Timilsina, 2013: Transaction costs analysis of low-carbon technologies. *Climate Policy*, **13(4)**, 490-513, doi:10.1080/14693062.2013.781452.
Myhre, G. et al., 2013: Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659-740.
Myhre, G. et al., 2017: Multi-model simulations of aerosol and ozone radiative forcing due to anthropogenic emission changes during the period 1990-2015. *Atmospheric Chemistry and Physics*, **17(4)**, doi:10.5194/acp-17-2709-2017.
Nordhaus, W.D., 2005: A Review of The Stern Review on the Economics of Climate Change. *Journal of Economic Literature*, **XLV**, 686-702.
OECD/IEA and IRENA, 2017: *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*. OECD/IEA and IRENA, 204 pp.
Parkinson, S.C., V. Krey, and D. Huppmann, 2017: Quantifying interactions between SDG6 and a 1.5°C climate policy. (in press).
Patt, A.G., 2015: *Transforming energy: Solving climate change with technology policy*. Cambridge University Press, New york, 349 pp.
Patt, A.G. et al., 2010: Adaptation in integrated assessment modeling: where do we stand? *Climatic Change*, **99**, 383-402, doi:10.1007/s10584-009-9687-y.
Pauliuk, S., A. Arvesen, K. Stadler, and E.G. Hertwich, 2017: Industrial ecology in integrated assessment models. *Nature Climate Change*, **7(1)**, 13-20, doi:10.1038/nclimate3148.
Pietzcker, R.C. et al., 2017: System integration of wind and solar power in integrated assessment models: A cross-model evaluation of new approaches. *Energy Economics*, **64**, 583-599, doi:10.1016/j.eneco.2016.11.018.
Pizer, W. et al., 2014: Using and improving the social cost of carbon. *Science*, **346(6214)**, 1189-1190,

doi:10.1126/science.1259774.
Popp, A. et al., 2014: Land-use transition for bioenergy and climate stabilization: Model comparison of drivers, impacts and interactions with other land use based mitigation options. *Climatic Change*, **123(3-4)**, 495-509, doi:10.1007/s10584-013-0926-x.
Popp, A. et al., 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, **42**, 331-345, doi:10.1016/j.gloenvcha.2016.10.002.
Rao, S. et al., 2017: Future air pollution in the Shared Socio-economic Pathways. *Global Environmental Change*, **42**, 346-358, doi:10.1016/j.gloenvcha.2016.05.012.
Revesz, R. et al., 2014: Global warming: Improve economic models of climate change. *Nature*, **508(7495)**, 173-175, doi:10.1038/508173a.
Riahi, K. et al., 2015: Locked into Copenhagen pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change*, **90(PA)**, 8-23, doi:10.1016/j.techfore.2013.09.016.
Riahi, K. et al., 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, **42**, 153-168, doi:10.1016/j.gloenvcha.2016.05.009.
Rockström, J. et al., 2017: A roadmap for rapid decarbonization. *Science*, **355(6331)**, 1269-1271, doi:10.1126/science.aah3443.
Rogelj, J., D.L. McCollum, B.C. O'Neill, and K. Riahi, 2013a: 2020 emissions levels required to limit warming to below 2 C. *Nature Climate Change*, **3(4)**, 405-412, doi:10.1038/nclimate1758.
Rogelj, J., D.L. McCollum, A. Reisinger, M. Meinshausen, and K. Riahi, 2013b: Probabilistic cost estimates for climate change mitigation. *Nature*, **493(7430)**, 79-83, doi:10.1038/nature11787.
Rogelj, J. et al., 2014: Disentangling the effects of CO2 and short-lived climate forcer mitigation. *Proceedings of the National Academy of Sciences*, **111(46)**, 16325-16330, doi:10.1073/pnas.1415631111.
Rogelj, J. et al., 2015: Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nature Climate Change*, **5(6)**, 519-527, doi:10.1038/nclimate2572.
Rogelj, J. et al., 2018: Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, **8(4)**, 325-332, doi:10.1038/s41558-018-0091-3.
Rubin, E.S., J.E. Davison, and H.J. Herzog, 2015: The cost of CO2 capture and storage. *International Journal of Greenhouse Gas Control*, **40**, 378-400, doi:10.1016/J.IJGGC.2015.05.018.
Schneider von Deimling, T. et al., 2012: Estimating the near-surface permafrost-carbon feedback on global warming. *Biogeosciences*, **9(2)**, 649-665, doi:10.5194/bg-9-649-2012.
Schneider von Deimling, T. et al., 2015: Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity. *Biogeosciences*, **12(11)**, 3469-3488, doi:10.5194/bg-12-3469-2015.
Schwanitz, V.J., 2013: Evaluating integrated assessment models of global climate change. *Environmental Modelling & Software*, **50**, 120-131, doi:10.1016/j.envsoft.2013.09.005.
Shah, N., M. Wei, V. Letschert, and A. Phadke, 2015: *Benefits of Leapfrogging to Superefficiency and Low Global Warming Potential Refrigerants in Room Air Conditioning*. LBNL-1003671, 58 pp.
Shell International B.V., 2018: *Shell Scenarios: Sky - Meeting the Goals of the Paris Agreement*. Shell International B.V. 36 pp.
Shindell, D.T. et al., 2012: Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. *Science*, **335(6065)**, 183-189, doi:10.1126/science.1210026.
Smith, C.J. et al., 2018: FAIR v1.3: A simple emissions-based impulse response and carbon cycle model. *Geoscientific Model Development* (in press), doi:10.5194/gmd-2017-266.
Stanton, E.A., F. Ackerman, and S. Kartha, 2009: Inside the integrated assessment models: Four issues in climate economics. *Climate and Development*, **1(2)**, 166, doi:10.3763/cdev.2009.0015.
Stern, N., 2016: Current climate models are grossly misleading. *Nature*, **530**, 407-409, doi:10.1038/530407a.
Stevanović, M. et al., 2016: The impact of high-end climate change on agricultural welfare. *Science Advances*, **2(8)**, e1501452, doi:10.1126/sciadv.1501452.
Stiglitz, J.E. et al., 2017: *Report of the High-Level Commission on Carbon Prices*. Carbon Pricing Leadership Coalition, 68 pp.
Stocker, T.F. et al., 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33-115.
Strefler, J., T. Amann, N. Bauer, E. Kriegler, and J. Hartmann, 2018a: Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters*, **13(3)**, 034010, doi:10.1088/1748-9326/aaa9c4.
Strefler, J., N. Bauer, E. Kriegler, A. Popp, and O. Giannousakis, Anastasis Edenhofer, 2018b: Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. *Environ. Res. Lett*, **13**, 044015.
Sussams, L. and J. Leaton, 2017: *Expect the Unexpected - The Disruptive Power of Low-carbon Technology*. 52 pp.

Tavoni, M., E. De Cian, G. Luderer, J.C. Steckel, and H. Waisman, 2012: The value of technology and of its evolution towards a low carbon economy. *Climatic Change*, **114(1)**, 39-57, doi:10.1007/s10584-011-0294-3.

Tavoni, M. et al., 2015: Post-2020 climate agreements in the major economies assessed in the light of global models. *Nature Climate Change*, **5(2)**, 119-126, doi:10.1038/nclimate2475.

Trutnevyte, E., N. Strachan, P.E. Dodds, D. Pudjianto, and G. Strbac, 2015: Synergies and trade-offs between governance and costs in electricity system transition. *Energy Policy*, **85**, 170-181, doi:10.1016/j.enpol.2015.06.003.

Turnheim, B. et al., 2015: Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Global Environmental Change*, **35**, 239-253, doi:10.1016/j.gloenvcha.2015.08.010.

Ürge-Vorsatz, D., A. Novikova, S. Köppel, and B. Boza-Kiss, 2009: Bottom-up assessment of potentials and costs of CO2 emission mitigation in the buildings sector: insights into the missing elements. *Energy Efficiency*, **2(4)**, 293-316, doi:10.1007/s12053-009-9051-0.

van Marle, M.J.E. et al., 2017: Historic global biomass burning emissions for CMIP6 (BB4CMIP) based on merging satellite observations with proxies and fire models (1750-2015). *Geoscientific Model Development*, **10(9)**, 3329-3357, doi:10.5194/gmd-10-3329-2017.

van Sluisveld, M.A.E., S.H. Martínez, V. Daioglou, and D.P. van Vuuren, 2016: Exploring the implications of lifestyle change in 2 °C mitigation scenarios using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **102**, 309-319, doi:10.1016/J.TECHFORE.2015.08.013.

van Sluisveld, M.A.E. et al., 2015: Comparing future patterns of energy system change in 2 °C scenarios with historically observed rates of change. *Global Environmental Change*, **35**, 436-449, doi:10.1016/j.gloenvcha.2015.09.019.

van Vuuren, D.P. et al., 2011: The representative concentration pathways: An overview. *Climatic Change*, **109(1)**, 5-31, doi:10.1007/s10584-011-0148-z.

van Vuuren, D.P. et al., 2015: Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **98**, 303-323, doi:10.1016/J.TECHFORE.2015.03.005.

van Vuuren, D.P. et al., 2018: Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nature Climate Change*, **8(5)**, 391-397, doi:10.1038/s41558-018-0119-8.

Velders, G.J.M., D.W. Fahey, J.S. Daniel, S.O. Andersen, and M. McFarland, 2015: Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. *Atmospheric Environment*, **123**, 200-209, doi:10.1016/j.atmosenv.2015.10.071.

Vrontisi, Z. et al., 2018: A multi-model assessment of the short-term effectiveness of Paris pledges towards a 1.5-2°C stabilization. *Environ. Res. Lett*, **13**, 044039, doi:10.1088/1748-9326/aab53e.

Warszawski, L. et al., 2014: The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP): Project framework. *Proceedings of the National Academy of Sciences*, **111(9)**, 3228-3232, doi:10.1073/pnas.1312330110.

Weindl, I. et al., 2017: Livestock and human use of land: Productivity trends and dietary choices as drivers of future land and carbon dynamics. *Global and Planetary Change*, **159**, 1-10, doi:10.1016/j.gloplacha.2017.10.002.

Weyant, J., 2017: Some Contributions of Integrated Assessment Models of Global Climate Change. *Review of Environmental Economics and Policy*, **11(1)**, 115-137, doi:10.1093/reep/rew018.

Wilkerson, J.T., B.D. Leibowicz, D.D. Turner, and J.P. Weyant, 2015: Comparison of integrated assessment models: Carbon price impacts on U.S. energy. *Energy Policy*, **76**, 18-31, doi:https://doi.org/10.1016/j.enpol.2014.10.011.

Wilson, C. and H. Dowlatabadi, 2007: Models of Decision Making and Residential Energy Use. *Annual Review of Environment and Resources*, **32(1)**, 169-203, doi:10.1146/annurev.energy.32.053006.141137.

Wilson, C., A. Grubler, K.S. Gallagher, and G.F. Nemet, 2012: Marginalization of end-use technologies in energy innovation for climate protection. *Nature Climate Change*, **2(11)**, 780-788, doi:10.1038/NCLIMATE1576.

Wilson, C., A. Grubler, N. Bauer, V. Krey, and K. Riahi, 2013: Future capacity growth of energy technologies: are scenarios consistent with historical evidence? *Climatic Change*, **118(2)**, 381-395, doi:10.1007/s10584-012-0618-y.

Wilson, C. et al., 2017: Evaluating Process-Based Integrated Assessment Models of Climate Change Mitigation. IIASA Working Paper WP-17-007.

Wong-Parodi, G., T. Krishnamurti, A. Davis, D. Schwartz, and B. Fischhoff, 2016: A decision science approach for integrating social science in climate and energy solutions. *Nature Climate Change*, **6(6)**, 563-569, doi:10.1038/nclimate2917.

Zhang, R., S. Fujimori, and T. Hanaoka, 2018: The contribution of transport policies to the mitigation potential and cost of 2°C and 1.5°C goals. *Environmental Research Letters*, **13(5)**, 054008.

Chapter 2 - Technical Annex – Part II - Mitigation pathways compatible with 1.5°C in the context of sustainable development

Contributing modelling framework reference cards

For each of the contributing modelling frameworks a reference card has been created highlighting the key features of the model. These reference cards are either based on information received from contributing modelling teams upon submission of scenarios to the SR1.5 database, or alternatively drawn from the ADVANCE IAM wiki documentation, available at http://www.fp7-advance.eu/content/model-documentation, and updated. These reference cards are provided in part II of this annex.

Reference card – AIM-CGE

About

⇨ ***Name and version***

AIM-CGE

⇨ ***Institution and users***

National Institute for Environmental Studies (NIES), Japan

Model scope and methods

⇨ ***Objective***

AIM/CGE is developed to analyse the climate mitigation and impact. The energy system is disaggregated to meet this objective in both of energy supply and demand sides. Agricultural sectors have also been disaggregated for the appropriate land use treatment. The model is designed to be flexible in its use for global analysis.

⇨ ***Concept***

General Equilibrium with technology explicit modules in power sectors

⇨ ***Solution method***

Solving a mixed complementarity problem

⇨ ***Anticipation***

Myopic

⇨ ***Temporal dimension***

Base year: 2005**, time steps:** Annual, **horizon:** 2100

⇨ ***Spatial dimension***

Number of regions: 17

1. Japan
2. China
3. India
4. Southeast Asia
5. Rest of Asia
6. Oceania
7. EU25
8. Rest of Europe
9. Former Soviet Union
10. Turkey
11. Canada
12. United States
13. Brazil
14. Rest of South America
15. Middle East
16. North Africa
17. Rest of Africa

⇨ ***Policy implementation***

Climate policy such as emissions target, Emission permits trading and so on. Energy taxes and subsidies

Socio economic drivers

⇨ ***Exogenous drivers***

– Total Factor Productivity

Note: GDP is endogenous, while TFP is exogenous; but TFP can be calibrated so as to reproduce a given GDP pathway

⇨ ***Endogenous drivers***

– GDP (Non-baseline scenarios that take into account either climate change mitigation or impacts.)

⇨ ***Development***

– GDP per capita

Macro economy

⇨ ***Economic sectors***

– Agriculture
– Industry
– Energy
– Transport
– Services

⇨ ***Cost measures***

– GDP loss
– Welfare loss
– Consumption loss

⇨ ***Trade***

– Coal
– Oil
– Gas
– Electricity
– Food crops
– Emissions permits
– Non-energy goods

Energy

⇨ ***Behaviour***

⇨ ***Resource use***

– Coal
– Oil
– Gas
– Biomass

⇨ ***Electricity technologies***

– Coal
– Gas
– Oil
– Nuclear
– Biomass
– Wind
– Solar PV
– CCS

⇨ ***Conversion technologies***

– Oil to liquids
– Biomass to liquids

⇨ ***Grid and infrastructure***
⇨ ***Energy technology substitution***
– Discrete technology choices
⇨ ***Energy service sectors***
– Transportation
– Industry
– Residential and commercial

Land use
⇨ ***Land cover***
– Abandoned land
– Cropland
– Forest
– Grassland
– Extensive Pastures
Note: 6 AEZs (Agro-Ecological Zones) by Crop, pasture, forestry, Other forest, natural grassland and others
There is a land competition under multi-nominal logit selection.

Other resources

Emissions and climate
⇨ ***Greenhouse gases***
– CO_2
– CH_4
– N_2O
– HFCs
– CFCs
– SF_6
⇨ ***Pollutants***
– NO_X
– SO_X
– BC
– OC
– VOC
– CO
⇨ ***Climate indicators***
– CO_2e concentration (ppm)
– Radiative Forcing (W/m^2)
– Temperature change (°C)

Reference card – BET

About

⇨ ***Name and version***

BET EMF33

⇨ ***Institution and users***

CRIEPI

University of Tokyo

Role of end-use technologies in long-term GHG reduction scenarios developed with the BET model
doi: 10.1007/s10584-013-0938-6

Model scope and methods

⇨ ***Objective***

The model is used for climate change studies on long-term mitigation scenarios. Typical application is to examine the role of electrification and advanced end-use technologies in climate change mitigation in a more systematic fashion, ranging from changes in usage of end-use technologies to power generation mix.

⇨ ***Concept***

General equilibrium (closed economy)

⇨ ***Solution method***

Optimization

⇨ ***Anticipation***

Inter-temporal (foresight)

⇨ ***Temporal dimension***

Base year: 2010**, time steps:** 10, **horizon:** 2010-2230

⇨ ***Spatial dimension***

Number of regions: 13

1. BRA Brazil
2. CAZ Canada, Australia, and New Zealand
3. CHA China incl. Hong Kong
4. EUR EU27+3 (Switzerland, Norway, and Iceland)
5. IND India
6. JPN Japan
7. MNA Middle East and North Africa
8. OAS Other Asia
9. OLA Other Latin America
10. ORF Other Reforming Economies
11. RUS Russia
12. SSA Sub-Saharan Africa
13. USA United States

⇨ ***Policy implementation***

Emission Tax/Pricing, Cap and Trade, Pricing Carbon Stocks

Socio economic drivers

⇨ ***Exogenous drivers***

– Population
– Total Factor Productivity
– Autonomous Energy Efficiency Improvements

⇨ ***Endogenous drivers***

– GDP

Macro economy

- ⇨ ***Economic sectors***
- ⇨ ***Cost measures***

– GDP loss
– Consumption loss
– Energy system costs

- ⇨ ***Trade***

– Coal
– Oil
– Gas
– Food crops
– Emissions permits
– Non-energy goods

Energy

- ⇨ ***Behaviour***
- ⇨ ***Resource use***

– Coal
– Conventional Oil
– Unconventional Oil
– Conventional Gas
– Unconventional Gas
– Uranium
– Bioenergy

- ⇨ ***Electricity technologies***

– Coal w/o CCS
– Coal w/ CCS
– Gas w/o CCS
– Gas w/ CCS
– Oil w/o CCS
– Bioenergy w/o CCS
– Bioenergy w/ CCS
– Geothermal Power
– Nuclear Power
– Solar Power|Central PV
– Wind Power|Onshore
– Wind Power|Offshore
– Hydroelectric Power

- ⇨ ***Conversion technologies***

– Coal to Hydrogen w/ CCS
– Electrolysis
– Coal to Liquids w/o CCS
– Bioliquids w/o CCS
– Oil Refining
– Biomass to Gas w/o CCS

- ⇨ ***Grid and infrastructure***

– Electricity
– Gas

- ⇨ ***Energy technology substitution***

– Linear choice (lowest cost)
– Expansion and decline constraints
– System integration constraints

⇨ ***Energy service sectors***
- Transportation
- Industry
- Residential and commercial

Land use

⇨ ***Land cover***
- Cropland Food Crops
- Cropland Feed Crops
- Cropland Energy Crops
- Managed Forest
- Natural Forest
- Pasture

Other resources

Emissions and climate

⇨ ***Greenhouse gases***
- CO_2

⇨ ***Pollutants***

⇨ ***Climate indicators***
- CO_2e concentration (ppm)
- Radiative Forcing (W/m^2)

Reference card – C-ROADS

About

⇨ ***Name and version***

C-ROADS v5 005

⇨ ***Institution and users***

Climate Interactive, US, https://www.climateinteractive.org/.

Model scope and methods

⇨ ***Objective***

The purpose of C-ROADS is to improve public and decision-maker understanding of the long-term implications of international emissions and sequestration futures with a rapid-iteration, interactive tool as a path to effective action that stabilizes the climate.

⇨ ***Concept***

C-ROADS takes future population, economic growth and GHG emissions as scenario inputs specified by the user and currently omits the costs of policy options and climate change damage.

⇨ ***Solution method***

Recursive dynamic solution method (myopic)

⇨ ***Anticipation***

Simulation modelling framework, without foresight.

⇨ ***Temporal dimension***

Base year: 1850**, time steps:** 0.25 year time step, **horizon:** 2100

⇨ ***Spatial dimension***

Number of regions: 20

1. USA
2. European Union (EU) 27 (EU27) (plus Iceland, Norway and Switzerland)
3. Russia (includes fraction of former USSR)
4. Other Eastern Europe
5. Canada
6. Japan
7. Australia
8. New Zealand
9. South Korea
10. Mexico
11. China
12. India
13. Indonesia
14. Philippines, Thailand, Taiwan, Hong Kong, Malaysia, Pakistan, Singapore
15. Brazil
16. Latin America excluding Mexico and Brazil
17. Middle East
18. South Africa
19. Africa excluding South Africa
20. Asia excluding China, India, Indonesia, and those included in Other Large Asia

⇨ ***Policy implementation***

The model does not include explicit representation of policies.

Socio economic drivers

⇨ ***Exogenous drivers***

– Exogenous population
– Exogenous GDP

⇨ ***Endogenous drivers***

– None

⇨ ***Development***
– None

Macro economy
⇨ ***Economic sectors***
– Not represented by the model
⇨ ***Cost measures***
– Not represented by the model
⇨ ***Trade***
– Not represented by the model

Energy

⇨ ***Behaviour***
– Not represented by the model
⇨ ***Resource use***
– Not represented by the model
⇨ ***Electricity technologies***
– Not represented by the model
⇨ ***Conversion technologies***
– Not represented by the model
⇨ ***Grid and infrastructure***
– Not represented by the model
⇨ ***Energy technology substitution***
– Not represented by the model
⇨ ***Energy service sectors***
– Not represented by the model

Land use
⇨ ***Land cover***
– Not represented by the model

Other resources
– None

Emissions and climate
⇨ ***Greenhouse gases***
– CO_2
– CH_4
– N_2O
– HFCs
– CFCs
– SF_6
– PFCs
⇨ ***Pollutants***
– Not covered by the model
⇨ ***Climate indicators***
– CO_2e concentration (ppm)
– Radiative Forcing (W/m^2)
– Temperature change (°C)
– Sea level rise
– Ocean acidification

Reference card – DNE21

About

⇨ ***Name and version***

DNE21+ V.14C

⇨ ***Institution and users***

Research Institute of Innovative Technology for the Earth (RITE), 9-2 Kizugawadai, Kizugawa-shi, Kyoto 619-0292

http://www.rite.or.jp/Japanese/labo/sysken/about-global-warming/download-data/RITE_GHGMitigationAssessmentModel_20150130.pdf

Model scope and methods

⇨ ***Objective***

⇨ ***Concept***

Minimizing Energy Systems Cost

⇨ ***Solution method***

Optimization

⇨ ***Anticipation***

Inter-temporal (foresight)

⇨ ***Temporal dimension***

Base year: 2000**, time steps:** 5 year steps (2000 - 2030); 10 year-steps (2030 - 2050), **horizon:** 2000-2050

⇨ ***Spatial dimension***

Number of regions: 54

1. ARG+ Argentina, Paraguay, Uruguay
2. AUS Australia
3. BRA Brazil
4. CAN Canada
5. CHN China
6. EU15 EU-15
7. EEU Eastern Europe (Other EU-28)
8. IND India
9. IDN Indonesia
10. JPN Japan
11. MEX Mexico
12. RUS Russia
13. SAU Saudi Arabia
14. SAF South Africa
15. ROK South Korea
16. TUR Turkey
17. USA United States of America
18. OAFR Other Africa
19. MEA Middle East & North Africa
20. NZL New Zealand
21. OAS Other Asia
22. OFUE Other FUSSR (Eastern Europe)
23. OFUA Other FUSSR (Asia)
24. OLA Other Latin America
25. OWE Other Western Europe

⇨ ***Policy implementation***

Emission Tax/Pricing, Cap and Trade; Fuel Taxes; Fuel Subsidies; Feed-in-Tariff; Portfolio Standard; Capacity Targets; Emission Standards; Energy Efficiency Standards; Land Protection; Pricing Carbon Stocks

Socio economic drivers

⇨ ***Exogenous drivers***

- Population
- Population Age Structure
- Education Level
- Urbanization Rate
- GDP
- Income Distribution
- Labour Participation Rate
- Labour Productivity

Macro economy

⇨ ***Economic sectors***

- Agriculture
- Industry
- Energy
- Services

⇨ ***Cost measures***

- Energy system costs

⇨ ***Trade***

- Coal
- Oil
- Gas
- Electricity
- Emissions permits

Energy

⇨ ***Behaviour***

- Transportation
- Industry
- Residential & Commercial
- Technology Adoption

⇨ ***Resource use***

- Coal
- Conventional Oil
- Unconventional Oil
- Conventional Gas
- Unconventional Gas

⇨ ***Electricity technologies***

- Coal w/o CCS
- Coal w/ CCS
- Gas w/o CCS
- Gas w/ CCS
- Oil w/o CCS
- Oil w/ CCS
- Bioenergy w/o CCS
- Bioenergy w/ CCS
- Geothermal Power
- Nuclear Power
- Solar Power
- Wind Power
- Hydroelectric Power

⇨ ***Conversion technologies***
- Coal to Hydrogen w/o CCS
- Coal to Hydrogen w/ CCS
- Natural Gas to Hydrogen w/o CCS
- Natural Gas to Hydrogen w/ CCS
- Biomass to Hydrogen w/o CCS
- Biomass to Hydrogen w/ CCS
- Electrolysis
- Coal to Liquids w/o CCS
- Bioliquids w/o CCS
- Oil Refining
- Coal to Gas w/o CCS

⇨ ***Grid and infrastructure***
- Electricity
- Gas
- CO_2
- H_2

⇨ ***Energy technology substitution***
- Linear choice (lowest cost)
- System integration constraints

⇨ ***Energy service sectors***
- Transportation
- Industry
- Residential and commercial

Land use

⇨ ***Land cover***
- Cropland Food Crops
- Cropland Feed Crops
- Cropland Energy Crops
- Managed Forest
- Natural Forest
- Pasture

Other resources

⇨ ***Other resources***
- Water

Emissions and climate

⇨ ***Greenhouse gases***
- CO_2
- CH_4
- N_2O
- HFCs
- CFCs
- SF6

⇨ ***Pollutants***
- NO_X
- SO_X
- BC
- OC

⇨ ***Climate indicators***
- CO_2e concentration (ppm)

- Radiative Forcing (W/m^2)
- Temperature change (°C)

Reference card – FARM 3.2

About

⇨ ***Name and version***

Future Agricultural Resources Model 3.2

⇨ ***Institution and users***

United States Department of Agriculture, Economic Research Service; Öko-Institut Germany – https://www.ers.usda.gov/webdocs/publications/81903/err-223.pdf?v=42738

Model scope and methods

⇨ ***Objective***

The Future Agricultural Resources Model (FARM) was originally designed as a static CGE model to simulate land use and climate impacts at a global scale. It has since been extended to simulate energy and agricultural systems through 2100 to enable participation in EMF and AgMIP model comparison studies.

⇨ ***Concept***

FARM models land use shifts among crops, pasture, and forests in response to population growth, changes in agricultural productivity, and policies such as a renewable portfolio standard or greenhouse gas cap-and-trade.

⇨ ***Solution method***

General equilibrium recursive-dynamic simulation

⇨ ***Anticipation***

Myopic

⇨ ***Temporal dimension***

Base year: 2011**, time steps:** 5 years, **horizon:** 2101

⇨ ***Spatial dimension***

Number of regions: 15

1. United States
2. Japan
3. European Union west (EU-15)
4. European Union east
5. Other OECD90
6. Russian Federation
7. Other Reforming Economies
8. China region
9. India
10. Indonesia
11. Other Asia
12. Middle East and North Africa
13. Sub-Saharan Africa
14. Brazil
15. Other Latin America

⇨ ***Policy implementation***

Emissions Tax/Pricing, Cap and Trade, Fuel Taxes and Subsidies, Portfolio Standards, Agricultural Producer, Subsidies, Agricultural Consumer Subsidies, Land Protection

Socio economic drivers

⇨ ***Exogenous drivers***

– Population
– Labour Productivity
– Land Productivity
– Autonomous Energy Efficiency Improvements
– Other input-specific productivity

⇨ ***Endogenous drivers***

- none

⇨ ***Development***

- none

Macro economy

⇨ ***Economic sectors***

- Agriculture
- Industry
- Energy
- Services

⇨ ***Cost measures***

- GDP loss
- Welfare loss
    - Equivalent Variation
- Consumption loss

⇨ ***Trade***

- Coal
- Oil
- Gas
- Electricity
- Food crops
- Non-energy goods

Energy

⇨ ***Behaviour***

- Substitution between energy and non-energy inputs in response to changes in relative prices

⇨ ***Resource use***

- Coal (supply Curve)
- Conventional Oil (Supply Curve)
- Conventional Gas (Supply Curve)
- Biomass (Supply Curve)

⇨ ***Electricity technologies***

- Coal (w/o and w/ CCS)
- Gas (w/o and w/ CCS)
- Oil (w/o and w/ CCS)
- Nuclear
- Biomass (w/o and w/ CCS)
- Wind
- Solar PV

⇨ ***Conversion technologies***

- Fuel to liquid, Oil Refining

⇨ ***Grid and infrastructure***

- Electricity (aggregate)
- Gas (aggregate)
- CO_2 (aggregate)

⇨ ***Energy technology substitution***

- Discrete technology choices with mostly high substitutability through production functions

⇨ ***Energy service sectors***

- Transportation (land, water, air)
- Buildings

Land use

- ⇨ ***Land cover***
  - Crop Land
    - Food Crops
    - Feed Crops
    - Energy Crops
  - Managed Forest
  - Pastures

Other resources

- ⇨ ***Other resources***
- none

Emissions and climate

- ⇨ ***Greenhouse gases***
- CO_2
  - Fossil Fuels
  - Cement
  - Land Use
- ⇨ ***Pollutants***
- none
- ⇨ ***Climate indicators***
- none

Reference card – GCAM 4.2

About

⇨ ***Name and version***

Global Change Assessment Model 4.2

⇨ ***Institution and users***

Joint Global Change Research Institute – http://jgcri.github.io/gcam-doc/v4.2/toc.html

Model scope and methods

⇨ ***Objective***

GCAM is a global integrated assessment model that represents the behaviour of, and complex interactions between five systems: the energy system, water, agriculture and land use, the economy, and the climate.

⇨ ***Concept***

The core operating principle for GCAM is that of market equilibrium. Representative agents in GCAM use information on prices, as well as other information that might be relevant, and make decisions about the allocation of resources. These representative agents exist throughout the model, representing, for example, regional electricity sectors, regional refining sectors, regional energy demand sectors, and land users who have to allocate land among competing crops within any given land region. Markets are the means by which these representative agents interact with one another. Agents pass goods and services along with prices into the markets. Markets exist for physical flows such as electricity or agricultural commodities, but they also can exist for other types of goods and services, for example tradable carbon permits.

⇨ ***Solution method***

Partial equilibrium (price elastic demand) recursive-dynamic

⇨ ***Anticipation***

Myopic

⇨ ***Temporal dimension***

Base year: 2010**, time steps:** 5 years, **horizon:** 2100

⇨ ***Spatial dimension***

Number of regions: 32 (For CD-Links scenarios, GCAM included 82 regions)

1. USA (For CD-Links scenarios, the USA was subdivided into 50 states plus the District of Columbia)
2. Eastern Africa
3. Northern Africa
4. Southern Africa
5. Western Africa
6. Australia and New Zealand
7. Brazil
8. Canada
9. Central America and Caribbean
10. Central Asia
11. China
12. EU-12
13. EU-15
14. Eastern Europe
15. Non-EU Europe
16. European Free Trade Association
17. India
18. Indonesia
19. Japan
20. Mexico
21. Middle East
22. Pakistan
23. Russia
24. South Africa

25. Northern South America
26. Southern South America
27. South Asia
28. South Korea
29. Southeast Asia
30. Taiwan
31. Argentina
32. Colombia

⇨ ***Policy implementation***

- Climate Policies
    - Emission Tax/Pricing
    - Cap and Trade
- Energy Policies
    - Fuel Taxes
    - Fuel Subsidies
    - Portfolio Standard
- Energy Technology Policies
    - Capacity Targets
    - Energy Efficiency Standards
- Land Use Policies
    - Land Protection
    - Afforestation

Socio economic drivers

⇨ ***Exogenous drivers***

- Population
- GDP
- Labour Participation Rate
- Labour Productivity

⇨ ***Endogenous drivers***

- none

⇨ ***Development***

- none

Macro economy

⇨ ***Economic sectors***

- Agriculture
- Industry
- Energy
- Transport
- Services
- Residential and Commercial

⇨ ***Cost measures***

- Area under MAC

⇨ ***Trade***

- Coal
- Oil
- Gas
- Uranium
- Bioenergy crops
- Food crops
- Emissions permits

Energy

⇨ ***Behaviour***

- none

⇨ ***Resource use***

- Coal (Supply Curve)
- Conventional Oil (Supply Curve)
- Unconventional Oil (Supply Curve)
- Conventional Gas (Supply Curve)
- Unconventional Gas (Supply Curve)
- Uranium (Supply Curve)
- Biomass (Process Model)
- Land

⇨ ***Electricity technologies***

- Coal (w/ o and w/ CCS)
- Gas (w/o and w/ CCS)
- Oil (w/o and w/ CCS)
- Nuclear
- Biomass (w/o and w/ CCS)
- Wind (Onshore)
- Solar PV (Central PV, Distributed PV, and Concentrating Solar Power)
- CCS

⇨ ***Conversion technologies***

- CHP
- Hydrogen
  - from Coal, Oil, Gas, and biomass, w/o and w/ CCS
  - Nuclear and Solar Thermochemical
- Fuel to gas
  - Coal to Gas w/o CCS
  - Biomass (w/o and w/ CCS)
- Fuel to liquid
  - Coal to Liquids (w/o and w/ CCS)
  - Gas to Liquids (w/o and w/ CCS)
  - Biomass to Liquids (w/o and w/ CCS)

⇨ ***Grid and infrastructure***

- none

⇨ ***Energy technology substitution***

- Discrete technology choices with usually high substitutability through logit-choice model

⇨ ***Energy service sectors***

- Transportation
- Residential and commercial
- Industry

Land use

⇨ ***Land cover***

- Cropland
  - Food Crops
  - Feed Crops
  - Energy Crops
- Forest
  - Managed Forest
  - Natural Forest
- Pasture
- Shrubland

  - Tundra
  - Urban
  - Rock, Ice, Desert

Other resources

⇨ ***Other resources***

- Water
- Cement

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2 (Fossil Fuels, Cement, Land Use)
- CH_4 (Energy, Land Use, Other)
- N_2O (Energy, Land Use, Other)
- HFCs
- CFCs
- SF6

⇨ ***Pollutants***

- NO_X (Energy, Land Use)
- SO_X (Energy, Land Use)
- BC (Energy, Land Use)
- OC (Energy, Land Use)
- NH3 (Energy, Land Use)

⇨ ***Climate indicators***

- Kyoto-Gases Concentration
- Radiative Forcing (W/m^2)
- Temperature change (°C)

Reference card – GEM-E3

About

⇨ ***Name and version***

GEM-E3

⇨ ***Institution and users***

Institute of Communication and Computer Systems (ICCS), Greece

Model scope and methods

⇨ ***Objective***

The model puts emphasis on: i) The analysis of market instruments for energy-related environmental policy, such as taxes, subsidies, regulations, emission permits etc., at a degree of detail that is sufficient for national, sectoral and World-wide policy evaluation. ii) The assessment of distributional consequences of programmes and policies, including social equity, employment and cohesion for less developed regions.

⇨ ***Concept***

General equilibrium

⇨ ***Solution method***

The model is formulated as a simultaneous system of equations with an equal number of variables. The system is solved for each year following a time-forward path. The model uses the GAMS software and is written as a mixed non-linear complementarity problem solved by using the PATH algorithm using the standard solver options.

⇨ ***Anticipation***

Myopic

⇨ ***Temporal dimension***

Base year: 2011, **time steps:** Five year time steps, **horizon:** 2050

⇨ ***Spatial dimension***

Different spatial dimension depending on application. Main applications feature one of the two regional disaggregation below.

Number of regions: 38

1. Austria
2. Belgium
3. Bulgaria
4. Croatia
5. Cyprus
6. Czech Republic
7. Germany
8. Denmark
9. Spain
10. Estonia
11. Finland
12. France
13. United Kingdom
14. Greece
15. Hungary
16. Ireland
17. Italy
18. Lithuania
19. Luxembourg
20. Latvia
21. Malta
22. Netherlands
23. Poland

24. Portugal
25. Slovakia
26. Slovenia
27. Sweden
28. Romania
29. USA
30. Japan
31. Canada
32. Brazil
33. China
34. India
35. Oceania
36. Russian federation
37. Rest of Annex I
38. Rest of the World

Or

Number of regions: 19

1. EU28
2. USA
3. Japan
4. Canada
5. Brazil
6. China
7. India
8. South Korea
9. Indonesia
10. Mexico
11. Argentina
12. Turkey
13. Saudi Arabia
14. Oceania
15. Russian federation
16. Rest of energy producing countries
17. South Africa
18. Rest of Europe
19. Rest of the World

⇨ ***Policy implementation***

Taxes, Permits trading, Subsidies, Energy efficiency standards, CO2 standards, Emission reduction targets, Trade agreements, R&D, adaptation.

Socio economic drivers

⇨ ***Exogenous drivers***

- Total Factor Productivity
- Labour Productivity
- Capital Technical progress
- Energy Technical progress
- Materials Technical progress
- Active population growth

⇨ ***Endogenous drivers***

- Learning-by-doing

⇨ ***Development***

- GDP per capita
- Labour participation rate

Macro economy

⇨ ***Economic sectors***

- Agriculture
- Industry
- Energy
- Transport
- Services
- Other

Note: GEM-E3 represents the sectors below: Agriculture, Coal, Crude Oil, Oil, Gas, Electricity supply, Ferrous metals, Non-ferrous metals, Chemical Products, Paper&Pulp, Non-metallic minerals, Electric Goods, Conventional Transport Equipment, Other Equipment Goods, Consumer Goods Industries, Construction, Air Transport, Land Transport - passenger, Land Transport – freight, Water Transport – passenger, Water Transport – freight, Biofuel feedstock, Biomass, Ethanol, Biodiesel, Advanced electric appliances, Electric vehicles, Equipment for Wind, Equipment for PV, Equipment for CCS, Market Services, Non-Market Services, Coal fired, Oil fired, Gas fired, Nuclear, Biomass, Hydroelectric, Wind, PV, CCS coal, CCS Gas

⇨ ***Cost measures***

- GDP loss
- Welfare loss
- Consumption loss

⇨ ***Trade***

- Coal
- Oil
- Gas
- Electricity
- Emissions permits
- Non-energy goods
- Agriculture
- Ferrous and non-ferrous metals
- Chemical products
- Other energy intensive
- Electric goods
- Transport equipment
- Other equipment goods
- Consumer goods industries

Energy

⇨ ***Behaviour***

The GEM-E3 model endogenously computes energy consumption, depending on energy prices, realised energy efficiency expenditures and autonomous energy efficiency improvements. Each agent decides how much energy it will consume in order to optimise its behaviour (i.e. to maximise profits for firms and utility for households) subject to technological constraints (i.e. a production function). At a sectoral level, energy consumption is derived from profit maximization under a nested CES (Constant Elasticity of Substitution) specification. Energy enters the production function together with other production factors (capital, labour, materials). Substitution of energy and the rest of the production factors is imperfect (energy is considered an essential input to the production process) and it is induced by changes in the relative prices of each input. Residential energy consumption is derived from the utility maximization problem of households. Households allocate their income between different consumption categories and savings to maximize their utility subject to their budget constraint. Consumption is split between durable (i.e. vehicles, electric appliances) and non-durable goods. For durable goods, stock accumulation depends on new purchases and scrapping. Durable goods consume (non-durable) goods and services, including energy products. The latter are endogenously determined depending on the stock of durable goods and on relative energy prices.

⇨ ***Resource use***

- Coal
- Oil
- Gas
- Biomass

⇨ ***Electricity technologies***

- Coal
- Gas
- Oil
- Nuclear
- Biomass
- Wind
- Solar PV
- CCS

⇨ ***Conversion technologies***

⇨ ***Grid and infrastructure***

- Electricity

⇨ ***Energy technology substitution***

- Discrete technology choices

⇨ ***Energy service sectors***

- Transportation
- Industry
- Residential and commercial

Land use

⇨ ***Land cover***

No land-use is simulated in the current version of GEM-E3.

Other resources

⇨ ***Other resources***

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2
- CH_4
- N_2O
- HFCs
- CFCs
- SF_6

⇨ ***Pollutants***

- NO_X
- SO_X

⇨ ***Climate indicators***

Reference card – GENeSYS-MOD 1.0

About

⇨ ***Name and version***

GENeSYS-MOD 1.0

⇨ ***Institution and users***

Technische Universität (TU) Berlin, Germany / German Institute for Economic Research (DIW Berlin), Germany

Model scope and methods

⇨ ***Objective***

The Global Energy System Model (GENeSYS-MOD) is an open-source energy system model, based on the Open-Source Energy Modelling System (OSeMOSYS). The aim is to analyse potential pathways and scenarios for the future energy system, e.g. for an assessment of climate targets. It incorporates the sectors power, heat, and transportation and specifically considers sector-coupling aspects between these traditionally segregated sectors.

⇨ ***Concept***

The model minimizes the total discounted system costs by choosing the cost-optimal mix of generation and sector-coupling technologies for the sectors power, heat, and transportation.

⇨ ***Solution method***

Linear program optimization (minimizing total discounted system costs)

⇨ ***Anticipation***

Perfect Foresight

⇨ ***Temporal dimension***

Base year: 2015, **time steps:** 2015, 2020, 2030, 2035, 2040, 2045, 2050, **horizon:** 2015-2050

⇨ ***Spatial dimension***

Number of regions: 10

1. Europe
2. Africa
3. North America
4. South America
5. Oceania
6. China and Mongolia
7. India
8. Middle East
9. Former Soviet Union
10. Remaining Asian countries (mostly South-East-Asia)

⇨ ***Policy implementation***

Emission Tax/Pricing, Emissions Budget, Fuel Taxes, Fuel Subsidies, Capacity Targets, Emission Standards, Energy Efficiency Standards

Socio economic drivers

⇨ ***Exogenous drivers***

– Technical progress (such as efficiency measures)
– GDP per capita
– Population

⇨ ***Endogenous drivers***
⇨ ***Development***

Macro economy

⇨ ***Economic sectors***
⇨ ***Cost measures***
⇨ ***Trade***

Energy

⇨ ***Behaviour***
⇨ ***Resource use***

- Coal
- Oil
- Gas
- Uranium
- Biomass

⇨ ***Electricity technologies***

- Coal
- Gas
- Oil
- Nuclear
- Biomass
- Wind (onshore & offshore)
- Solar PV (utility PV & rooftop PV)
- CSP
- Geothermal
- Hydropower
- Wave & Tidal power

⇨ ***Conversion technologies***

- CHP
- Hydrogen (Electrolysis & Fuel Cells)
- Electricity & Gas storages

⇨ ***Grid and infrastructure***

- Electricity

⇨ ***Energy technology substitution***

- Discrete technology choices
- Expansion and decline constraints
- System integration constraints

⇨ ***Energy service sectors***

- Transportation (split up in passenger & freight)
- Total Power Demand
- Heat (divided up in warm water / space heating & process heat)

Land use

⇨ ***Land cover***

Other resources

⇨ ***Other resources***

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2

- ⇨ ***Pollutants***
- ⇨ ***Climate indicators***

Reference card – GRAPE-15 1.0

About

⇨ ***Name and version***

GRAPE-15 1.0

⇨ ***Institution and users***

The Institute of Applied Energy, Japan – https://doi.org/10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI3-13

Model scope and methods

⇨ ***Objective***

GRAPE is an integrated assessment model with inter-temporal optimization model, which consists of modules of energy, macro economy, climate, land use and environmental impacts.

⇨ ***Concept***

⇨ ***Solution method***

Partial equilibrium (fixed demand) inter-temporal optimisation

⇨ ***Anticipation***

Perfect foresight

⇨ ***Temporal dimension***

Base year: 2005**, time steps:** 5 years, **horizon:** 2110

⇨ ***Spatial dimension***

Number of regions: 15

1. Canada
2. USA
3. Western Europe
4. Japan
5. Oceania
6. China
7. Southeast Asia
8. India
9. Middle East
10. Sub-Sahara Africa
11. Brazil
12. Other Latin America
13. Central Europe
14. Eastern Europe
15. Russia

⇨ ***Policy implementation***

Emissions Taxes/Pricing, Cap and Trade, Land Protection

Socio economic drivers

⇨ ***Exogenous drivers***

- Population
- Population age Structure
- Education Level
- Urbanisation Rate
- GDP
- Income Distribution
- Total Factor Productivity
- Autonomous Energy Efficiency Improvements

⇨ ***Endogenous drivers***

- none

⇨ ***Development***

- Income distribution in a region (exogenous)

- Urbanisation rate (exogenous)
- Education level (exogenous)

Macro economy

⇨ ***Economic sectors***

- Agriculture
- Industry
- Energy
- Transport
- Services

⇨ ***Cost measures***

- GDP loss
- Welfare loss
- Consumption loss
- Energy system costs

⇨ ***Trade***

- Coal
- Oil
- Gas
- Electricity
- Bioenergy crops
- Food crops
- Non-energy goods

Energy

⇨ ***Behaviour***

- none

⇨ ***Resource use***

- Coal (Supply Curve)
- Conventional Oil (Supply Curve)
- Unconventional Oil (Supply Curve)
- Conventional Gas (Supply Curve)
- Unconventional Gas (Supply Curve)
- Uranium (Supply Curve)
- Biomass (Supply Curve)
- Water (Process Model)
- Land

⇨ ***Electricity technologies***

- Coal (w/o and w/ CCS)
- Gas (w/o and w/ CCS)
- Oil (w/o and w/ CCS)
- Nuclear
- Biomass (w/o and w/ CCS)
- Wind (Onshore and Offshore)
- Solar PV (Central and Distributed)
- Geothermal
- Hydroelectric

⇨ ***Conversion technologies***

- CHP
- Coal/Oil/Gas/Biomass-to-Heat
- Hydrogen
    - Coal-to-H2 (w/o and w/ CCS)
    - Oil-to-H2 (w/o and w/ CCS)

  - Gas-to-H2 (w/o and w/ CCS)
  - Biomass-to-H2 (w/o CCS)
  - Nuclear and Solar Thermochemical
  - Electrolysis
- Fuel to gas
  - Coal-to-Gas (w/o and w/ CCS)
- Fuel to liquid
  - Coal-to-liquids (w/o and w/ CCS)
  - Gas-to-liquids (w/o and w/ CCS)
  - Biomass-to-liquids (w/o and w/ CCS)
  - Oil Refining

⇨ ***Grid and infrastructure***

- Electricity
- Gas
- Heat
- CO_2
- H_2

⇨ ***Energy technology substitution***

- Discrete technology choices with mostly high substitutability through linear choice (lowest cost)
- Expansion and decline constraints

⇨ ***Energy service sectors***

- Transportation
- Industry
- Residential and commercial

Land use

⇨ ***Land cover***

- Energy Cropland
- Forest
- Pastures
- Built-up Area

Other resources

⇨ ***Other resources***

- Water

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2
  - Fossil Fuels
  - Land Use
- CH_4
  - Energy
  - Land Use
- N_2O
  - Energy
- HFCs
- CFCs
- SF6
- CO
  - Energy Use

⇨ ***Pollutants***

Only for energy

– NO_X
– SO_X
– BC
– OC
– Ozone

⇨ ***Climate indicators***

– CO_2e concentration (ppm)
– Radiative Forcing (W/m^2)
– Temperature change (°C)

Reference card – ETP Model

About

⇨ ***Name and version***

ETP Model, version 3

⇨ ***Institution and users***

International Energy Agency – http://www.iea.org/etp/etpmodel/

Model scope and methods

⇨ ***Objective***

The analysis and modelling aim to identify an economical way for society to reach the desired outcomes of reliable, affordable and clean energy. For a variety of reasons the scenario results do not necessarily reflect the least-cost ideal. The ETP analysis takes into account those policies that have already been implemented or decided. In the short term, this means that deployment pathways may differ from what would be most cost-effective. In the longer term, the analysis emphasises a normative approach, and fewer constraints governed by current political objectives apply in the modelling. The objective of this methodology is to provide a model for a cost-effective transition to a sustainable energy system.

⇨ ***Concept***

Partial equilibrium (fixed energy service and material demands), with the exception for the transport sector where avoid and shift policies are being considered.

⇨ ***Solution method***

Optimization for power, other transformation and industry sectors; simulation for agriculture, residential, services and transport sectors

⇨ ***Anticipation***

Inter-temporal (foresight)

⇨ ***Temporal dimension***

Base year: 2014**, time steps:** 5 years, **horizon:** 2060

⇨ ***Spatial dimension***

Number of regions: differs between energy sectors (28-39 model regions)

1. Asian countries except Japan
2. Countries of the Middle East and Africa
3. Latin American countries
4. OECD90 and EU (and EU candidate) countries
5. Countries from the Reforming Economies of the Former Soviet Union
6. World
7. OECD countries
8. Non-OECD countries
9. Brazil
10. China
11. South Africa
12. Russia
13. India
14. ASEAN region countries
15. USA
16. European Union (28 member countries)
17. Mexico

⇨ ***Policy implementation***

Emission Tax/Pricing, Cap and Trade, Fuel Taxes, Fuel Subsidies, Feed-in-Tariff, Portfolio Standards, Capacity Targets, Emission Standards, Energy Efficiency Standards

Socio economic drivers

⇨ ***Exogenous drivers***

– Population

- Urbanisation rate
- GDP
- Autonomous Energy Efficiency Improvements

⇨ ***Endogenous drivers***

- none

⇨ ***Development***

- none

Macro economy

⇨ ***Economic sectors***

- Agriculture
- Industry
- Residential
- Services
- Transport
- Power
- Other transformation

⇨ ***Cost measures***

- None

⇨ ***Trade***

- Coal
- Oil
- Gas
- Electricity - Yes

Energy

⇨ ***Behaviour***

- none

⇨ ***Resource use***

- Coal - Supply Curve
- Conventional Oil - Process Model
- Unconventional Oil - Supply Curve
- Conventional Gas - Process Model
- Unconventional Gas - Supply Curve
- Bioenergy - Supply Curve

⇨ ***Electricity technologies***

- Coal (w/o and w/ CCS)
- Gas (w/o and w/ CCS)
- Oil (w/o and w/ CCS)
- Nuclear
- Biomass (w/o and w/ CCS)
- Solar Power (Central PV, Distributed PV, and CSP)
- Wind Power (Onshore and Offshore)
- Hydroelectric Power
- Ocean Power

⇨ ***Conversion technologies***

- Coal to Hydrogen (w/o CCS and w/ CCS)
- Natural Gas to Hydrogen (w/o CCS and w/ CCS)
- Oil to Hydrogen (w/o CCS)
- Biomass to Hydrogen (w/o CCS and w/ CCS)
- Coal to Liquids (w/o CCS and w/ CCS)
- Gas to Liquids(w/o CCS and w/ CCS)
- Bioliquids (w/o CCS and w/ CCS)

- Oil Refining
- Coal to Gas (w/o CCS and w/ CCS)
- Oil to Gas (w/o CCS and w/ CCS)
- Biomass to Gas (w/o CCS and w/ CCS)
- Coal Heat
- Natural Gas Heat
- Oil Heat
- Biomass Heat
- Geothermal Heat
- Solarthermal Heat
- CHP (coupled heat and power)

⇨ ***Grid and infrastructure***

- Electricity (spatially explicit)
- Gas (aggregate)
- Heat (aggregate)
- Hydrogen (aggregate)
- CO_2 (spatially explicit)
- Gas spatially explicit for gas pipelines and LNG infrastructure between model regions

⇨ ***Energy technology substitution***

- Lowest cost with adjustment penalties. Discrete technology choices with mostly high substitutability in some sectors and mostly low substitutability in other sectors
- Expansion and decline constraints
- System integration constraints

⇨ ***Energy service sectors***

- Transportation
- Industry
- Residential & Commercial

Land use

⇨ ***Land cover***

- Not represented by the model

Other resources

⇨ ***Other resources***

- none

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2 Fossil Fuels (endogenous & controlled)
- CO_2 Cement (endogenous & controlled)

⇨ ***Pollutants***

- none

⇨ ***Climate indicators***

- none

Reference card – IEA World Energy Model

About

⇨ ***Name and version***

IEA World Energy Model (version 2016)

⇨ ***Institution and users***

International Energy Agency - https://www.iea.org/weo/
http://www.iea.org/media/weowebsite/2017/WEM_Documentation_WEO2017.pdf

Model scope and methods

⇨ ***Objective***

The model is a large-scale simulation model designed to replicate how energy markets function and is the principal tool used to generate detailed sector-by-sector and region-by-region projections for the World Energy Outlook (WEO) scenarios.

⇨ ***Concept***

Partial equilibrium (price elastic demand)

⇨ ***Solution method***

Simulation

⇨ ***Anticipation***

Mix of "Inter-temporal (foresight)" and "Recursive-dynamic (myopic)"

⇨ ***Temporal dimension***

Base year: 2014, time steps: 1 year steps, horizon: 2050

⇨ ***Spatial dimension***

Number of regions:

11. United States
12. Canada
13. Mexico
14. Chile
15. Japan
16. Korea
17. OECD Oceania
18. Other OECD Europe
19. France, Germany, Italy, United Kingdom
20. Europe 21 excluding EUG4
21. Europe 7
22. Eurasia
23. Russia
24. Caspian
25. China
26. India
27. Indonesia
28. South East Asia (excluding Indonesia)
29. Rest of Other Developing Asia
30. Brazil
31. Other Latin America
32. North Africa
33. Other Africa
34. South Africa
35. Middle East

⇨ ***Policy implementation***

Emission Tax/Pricing, Cap and Trade (global and regional), Fuel Taxes, Fuel Subsidies, Feed-in-Tariff, Portfolio Standard, Capacity Targets, Emission Standards, Energy Efficiency Standards

Socio economic drivers

⇨ ***Exogenous drivers***

– Population (exogenous)
– Urbanization Rate (exogenous)
– GDP (exogenous)

⇨ ***Endogenous drivers***

– Autonomous Energy Efficiency Improvements (endogenous)

⇨ ***Development***

Macro economy

⇨ ***Economic sectors***

– Agriculture (economic)
– Industry (physical & economic)
– Services (economic)
– Energy (physical & economic)

⇨ ***Cost measures***

– Energy System Cost Mark-Up

⇨ ***Trade***

– Coal
– Oil
– Gas
– Bioenergy crops
– Emissions permits

Energy

⇨ ***Behaviour***

⇨ ***Resource use***

– Coal (Process Model)
– Conventional Oil (Process Model)
– Unconventional Oil (Process Model)
– Conventional Gas (Process Model)
– Unconventional Gas (Process Model)
– Bioenergy (Process Model)

⇨ ***Electricity technologies***

– Coal
– Gas
– Oil
– Nuclear
– Geothermal
– Biomass
– Wind (Onshore and Offshore)
– Solar PV (Central and distributed)
– CCS
– CSP
– Hydropower
– Ocean power

Note: CCS can be combined with coal, gas and biomass power generation technologies

⇨ ***Conversion technologies***

– Natural Gas to Hydrogen w/o CCS
– Coal to Liquids w/o CCS
– Coal to Gas w/o CCS
– Coal Heat

- Natural Gas Heat
- Oil Heat
- Biomass Heat
- Geothermal Heat
- Solarthermal Heat
- CHP (coupled heat and power)

⇨ ***Grid and infrastructure***

- Electricity (aggregate)
- Gas (aggregate)

⇨ ***Energy technology substitution***

- Logit choice model
- Weibull function
- Discrete technology choices with mostly high substitutability in some sectors and mostly low substitutability in other sectors
- Expansion and decline constraints
- System integration constraints

⇨ ***Energy service sectors***

- Transportation
- Industry
- Residential and commercial

Land use

⇨ ***Land cover***

- Not covered by the model

Other resources

⇨ ***Other resources***

Emissions and climate

⇨ ***Greenhouse gases****

- CO_2
- CH_4
- N_2O
- HFCs
- CFCs
- SF_6

⇨ ***Pollutants****

- NOx
- SOx
- BC
- OC
- CO
- NH_3
- VOC

*NOTE: Non-energy CO_2, non-energy CH_4, non-energy N_2O, CFC, HFC, SF_6, CO, NOx, VOC, SO_2, are assumptions-based and not disaggregated (only total emissions are available).

⇨ ***Climate indicators***

- CO_2e concentration (ppm)
- Radiative Forcing (W/m^2)
- Temperature change (°C)

Reference card – IMACLIM

About

⇨ ***Name and version***

IMACLIM 1.1 (Advance), IMACLIM-NLU 1.0 (EMF33)

⇨ ***Institution and users***

Centre international de recherche sur l'environnement et le développement (CIRED), France, http://www.centre-cired.fr.

Societe de Mathematiques Appliquees et de Sciences Humaines (SMASH), France, http://www.smash.fr.

Model scope and methods

⇨ ***Objective***

Imaclim-R is intended to study the interactions between energy systems and the economy, to assess the feasibility of low carbon development strategies and the transition pathway towards low carbon future.

⇨ ***Concept***

Hybrid: general equilibrium with technology explicit modules. Recursive dynamics: each year the equilibrium is solved (system of non-linear equations), in between two years parameters to the equilibrium evolve according to specified functions.

⇨ ***Solution method***

Imaclim-R is implemented in Scilab, and uses the function fsolve from a shared C++ library to solve the static equilibrium system of non-linear equations.

⇨ ***Anticipation***

Recursive dynamics: each year the equilibrium is solved (system of non-linear equations), in between two years parameters to the equilibrium evolve according to specified functions.

⇨ ***Temporal dimension***

Base year: 2001**, time steps:** Annual, **horizon:** 2050 or 2100

⇨ ***Spatial dimension***

Number of regions: 12

1. USA
2. Canada
3. Europe
4. China
5. India
6. Brazil
7. Middle East
8. Africa
9. Commonwealth of Independent States
10. OECD Pacific
11. Rest of Asia
12. Rest of Latin America

⇨ ***Policy implementation***

Baseline do not include explicit climate policies. Climate/energy policies can be implemented in a number of ways, depending on the policy. A number of general or specific policy choices can be modelled including: Emissions or energy taxes, permit trading, specific technology subsidies, regulations, technology and/or resource constraints

Socio economic drivers

⇨ ***Exogenous drivers***

– Labour Productivity
– Energy Technical progress
– Population
– Active population

Note: Our model growth engine is composed of exogenous trends of active population growth and exogenous trends of labour productivity growth. The two sets of assumptions on demography and labour productivity, although exogenous, only prescribe natural growth. Effective growth results endogenously from the interaction of these driving forces with short-term constraints: (i) available capital flows for investments and (ii) rigidities, such as fixed technologies, immobility of the installed capital across sectors or rigidities in real wages, which may lead to partial utilization of production factors (labour and capital).

⇨ ***Endogenous drivers***

⇨ ***Development***

– GDP per capita

Macro economy

⇨ ***Economic sectors***

– Agriculture
– Industry
– Energy
– *Transport*
– *Services*
– *Construction*

Note: The energy sector is divided into five sub-sectors: oil extraction, gas extraction, coal extraction, refinery, power generation. The transport sector is divided into three sub-sectors: terrestrial transport, air transport, water transport. The industry sector has one sub-sector: Energy intensive industry.

⇨ ***Cost measures***

– GDP loss
– Welfare loss
– Consumption loss
– Energy system costs

⇨ ***Trade***

– Coal
– Oil
– Gas
– Electricity
– Bioenergy crops
– Capital
– Emissions permits
– Non-energy goods
– Refined Liquid Fuels

Energy

⇨ ***Behaviour***

Price response (via elasticities), and non-price drivers (infrastructure and urban forms conditioning location choices, different asymptotes on industrial goods consumption saturation levels with income rise, speed of personal vehicle ownership rate increase, speed of residential area increase).

⇨ ***Resource use***

– Coal
– Oil
– Gas
– Biomass

⇨ ***Electricity technologies***

– Coal
– Gas
– Oil
– Nuclear
– Biomass

- Wind
- Solar PV
- CCS

⇨ ***Conversion technologies***

- Fuel to liquid

⇨ ***Grid and infrastructure***

- Electricity

⇨ ***Energy technology substitution***

- Discrete technology choices
- Expansion and decline constraints
- System integration constraints

⇨ ***Energy service sectors***

- Transportation
- Industry
- Residential and commercial
- Agriculture

Land use

⇨ ***Land cover***

- Cropland
- Forest
- Extensive Pastures
- Intensive Pastures
- Inaccessible Pastures
- Urban Areas
- Unproductive Land

Note:
IMACLIM 1.1 (Advance) : Bioenergy production is determined by the fuel and electricity modules of Imaclim-R using supply curves from Hoogwijk et al. (2009) (bioelectricity) and IEA (biofuel).
IMACLIM-NLU 1.0 (EMF33) : In this version the Imaclim-R model in linked to the land use mode Nexus Land use. Bioenergy demand level is determined by the fuel and electricity modules of Imaclim-R. The Nexus Land use gives the corresponding price of biomass feedstock, taking into account the land constaints and food production The production of biomass for electricity and ligno-cellulosic fuels is located on marginal lands (i.e., less fertile or accessible lands). By increasing the demand for land, and spurring agricultural intensification, Bioenergy propels land and food prices.

Other resources

⇨ ***Other resources***

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2

⇨ ***Pollutants***

⇨ ***Climate indicators***

Reference card – IMAGE

About

⇨ ***Name and version***

IMAGE framework 3.0

⇨ ***Institution and users***

Utrecht University (UU), Netherlands, http://www.uu.nl.
PBL Netherlands Environmental Assessment Agency (PBL), Netherlands, http://www.pbl.nl.

Model scope and methods

⇨ ***Objective***

IMAGE is an ecological-environmental model framework that simulates the environmental consequences of human activities worldwide. The objective of the IMAGE model is to explore the long- term dynamics and impacts of global changes that result. More specifically, the model aims

1. to analyse interactions between human development and the natural environment to gain better insight into the processes of global environmental change;
2. to identify response strategies to global environmental change based on assessment of options and
3. to indicate key inter-linkages and associated levels of uncertainty in processes of global environmental change.

⇨ ***Concept***

The IMAGE framework can best be described as a geographically explicit assessment, integrated assessment simulation model, focusing a detailed representation of relevant processes with respect to human use of energy, land and water in relation to relevant environmental processes.

⇨ ***Solution method***

Recursive dynamic solution method

⇨ ***Anticipation***

Simulation modelling framework, without foresight. However, a simplified version of the energy/climate part of the model (called FAIR) can be run prior to running the framework to obtain data for climate policy simulations.

⇨ ***Temporal dimension***

Base year: 1970**, time steps:** 1-5 year time step, **horizon:** 2100

⇨ ***Spatial dimension***

Number of regions: 26

21. Canada
22. USA
23. Mexico
24. Rest of Central America
25. Brazil
26. Rest of South America
27. Northern Africa
28. Western Africa
29. Eastern Africa
30. South Africa
31. Western Europe
32. Central Europe
33. Turkey
34. Ukraine +
35. Asian-Stan
36. Russia +
37. Middle East
38. India +
39. Korea
40. China +

41. Southeastern Asia
42. Indonesia +
43. Japan
44. Oceania
45. Rest of South Asia
46. Rest of Southern Africa

⇨ ***Policy implementation***

Key areas where policy responses can be introduced in the model are:

– Climate policy
– Energy policies (air pollution, access and energy security)
– Land use policies (food)
– Specific policies to project biodiversity
– Measures to reduce the imbalance of the nitrogen cycle

Socio economic drivers

⇨ ***Exogenous drivers***

– Exogenous GDP
– GDP per capita
– Population

⇨ ***Endogenous drivers***

– Energy demand
– Renewable price
– Fossil fuel prices
– Carbon prices
– Technology progress
– Energy intensity
– Preferences
– Learning by doing
– Agricultural demand
– Value added

⇨ ***Development***

– GDP per capita
– Income distribution in a region
– Urbanisation rate

Note: GDP per capita and income distribution are exogenous

Macro economy

⇨ ***Economic sectors***

Note: No explicit economy representation in monetary units. Explicit economy representation in terms of energy is modelled (for the agriculture, industry, energy, transport and built environment sectors)

⇨ ***Cost measures***

– Area under MAC
– Energy system costs

⇨ ***Trade***

– Coal
– Oil
– Gas
– Uranium
– Bioenergy crops
– Food crops
– Emissions permits
– Non-energy goods
– Bioenergy products

– Livestock products

Energy

⇨ ***Behaviour***

In the energy model, substitution among technologies is described in the model using the multinomial logit formulation. The multinomial logit model implies that the market share of a certain technology or fuel type depends on costs relative to competing technologies. The option with the lowest costs gets the largest market share, but in most cases not the full market. We interpret the latter as a representation of heterogeneity in the form of specific market niches for every technology or fuel.

⇨ ***Resource use***

– Coal
– Oil
– Gas
– Uranium
– Biomass

Note: Distinction between traditional and modern biomass

⇨ ***Electricity technologies***

– Coal w/ CCS
– Coal w/o CCS
– Gas w/ CCS
– Gas w/o CCS
– Oil w/ CCS
– Oil w/o CCS
– Nuclear
– Biomass w/ CCS
– Biomass w/o CCS
– Wind
– Solar PV
– CSP
– Hydropower
– Geothermal

Note: wind: onshore and offshore; coal: conventional, IGCC, IGCC + CCS, IGCC + CHP, IGCC + CHP + CCS; oil: conventional, OGCC, OGCC + CCS, OGCC + CHP, OGCC + CHP + CCS); natural gas: conventional, CC, CC + CCS, CC + CHP, CC + CHP + CCS; biomass: conventional, CC, CC + CCS, CC + CHP, CC + CHP + CCS
hydropower and geothermal: exogenous

⇨ ***Conversion technologies***

– CHP
– Hydrogen

⇨ ***Grid and infrastructure***

– Electricity

⇨ ***Energy technology substitution***

– Discrete technology choices
– Expansion and decline constraints
– System integration constraints

⇨ ***Energy service sectors***

– Transportation
– Industry
– Residential and commercial

Land use

⇨ ***Land cover***

– Forest
– Cropland

- Grassland
- Abandoned land
- Protected land

Other resources

⇨ ***Other resources***

- Water
- Metals
- Cement

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2
- CH_4
- N_2O
- HFCs
- CFCs
- SF_6
- PFCs

⇨ ***Pollutants***

- NO_X
- SO_X
- BC
- OC
- Ozone
- VOC
- NH3
- CO

⇨ ***Climate indicators***

- CO_2e concentration (ppm)
- Radiative Forcing (W/m^2)
- Temperature change (°C)

Reference card – MERGE-ETL 6.0

About

⇨ ***Name and version***

MERGE-ETL 6.0

⇨ ***Institution and users***

Paul Scherrer Institut

https://www.psi.ch/eem/ModelsEN/2012MergeDescription.pdf

https://www.psi.ch/eem/ModelsEN/2014MergeCalibration.pdf

Model scope and methods

⇨ ***Objective***

MERGE (Model for Evaluating Regional and Global Effects of GHG reductions policies) is an integrated assessment model originally developed by Manne et al. (1995). It divides the world in geopolitical regions, each one represented by two coupled submodels describing the energy and economic sectors, respectively. MERGE acts as a global social planner with perfect foresight and determines the economic equilibrium in each region that maximizes global welfare, defined as a linear combination of the current and future regional welfares. Besides these regional energy-economic submodels, and linked to them, MERGE includes global submodels of greenhouse gas emissions and the climate to allow the analysis of the effectiveness and impacts of climate policies and the role of technologies to realize climate targets. The model is sufficiently flexible to explore views on a wide range of contentious issues: costs of abatement, damages of climate change, valuation and discounting.

⇨ ***Concept***

The MERGE-ETL model is a hard-linked hybrid model as the energy sectors are fully integrated with the rest of the economy. The model combines a bottom-up description of the energy system disaggregated into electric and non-electric sectors, a top-down economic model based on macroeconomic production functions, and a simplified climate cycle model. The energy sectors endogenously accounts for technological change with explicit representation of two-factor learning curves.

⇨ ***Solution method***

General equilibrium (closed economy). Two different solutions can be produced: a cooperative globally optimal solution and a non-cooperative solution equivalent to Nash equilibrium. It is programmed in GAMS and uses the CONOPT solver.

⇨ ***Anticipation***

Inter-temporal (foresight) or myopic.

⇨ ***Temporal dimension***

Base year: 2015**, time steps:** 10 years, **horizon:** 2015-2100

⇨ ***Spatial dimension***

Number of regions: 10

1. EUP European Union
2. RUS Russia
3. MEA Middle East
4. IND India
5. CHI China
6. JPN Japan
7. CANZ Canada, Australia and New Zealand
8. USA United States of America
9. ROW Rest of the World
10. SWI Switzerland

⇨ ***Policy implementation***

Emission Tax/Pricing, Cap and Trade, Fuel Taxes, Fuel Subsidies, Feed-in-Tariff, Portfolio Standard, Capacity Targets

Socio economic drivers

⇨ ***Exogenous drivers***

Population, Population Age Structure, Autonomous Energy Efficiency Improvements

⇨ ***Development***

GDP

Macro economy

⇨ ***Economic sectors***

– One final good
– Electric and non-electric demand sectors

⇨ ***Cost measures***

– GDP loss
– Welfare loss
– Consumption loss
– Area under MAC
– Energy system costs

⇨ ***Trade***

– Non-Energy goods
– Coal
– Oil
– Gas
– Uranium
– Bioenergy crops
– Emissions permits

Energy

⇨ ***Behaviour***

– Considered in side-constraints controlling technology deployment rates

⇨ ***Resource use***

– Coal
– Conventional Oil
– Unconventional Oil
– Conventional Gas
– Unconventional Gas
– Uranium
– Bioenergy

Note: Cost-supply curves for the different resources are considered

⇨ ***Electricity technologies***

– Coal
– Gas
– Oil
– Nuclear
– Biomass
– Wind
– Solar PV
– Hydrogen

Note: CCS can be combined with coal, gas and biomass power generation technologies

⇨ ***Conversion technologies***

– Hydrogen
– Fuel to liquids

Note: CCS can be combined with coal, gas and biomass technologies

⇨ ***Grid and infrastructure***

– Electricity

- Gas
- CO_2
- H_2

⇨ ***Energy technology substitution***

- Expansion and decline constraints
- System integration constraints
- Early technology retirement

⇨ ***Energy service sectors***

- Electric and non-electric demand that is further disaggregated to seven energy sectors/fuels, namely coal, oil, gas, biofuels, hydrogen, solar and heat

Land use

⇨ ***Land cover***

Other resources

⇨ ***Other resources***

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2
- CH_4
- N_2O
- HFCs
- SF6

⇨ ***Pollutants***

⇨ ***Climate indicators***

- CO_2e concentration (ppm)
- Radiative Forcing (W/m^2)
- Temperature change (°C)
- Climate damages $ or equivalent

Reference card – MESSAGE(ix)-GLOBIOM

About

⇨ ***Name and version***

MESSAGE-GLOBIOM 1.0 and MESSAGE*ix*-GLOBIOM 1.0

⇨ ***Institution and users***

International Institute for Applied Systems Analysis (IIASA), Austria, global model description: http://data.ene.iiasa.ac.at/message-globiom/. Model documentation and code (MESSAGE*ix*) http://messageix.iiasa.ac.at

main users: IIASA, the MESSAGE model is distributed via the International Atomic Energy Agency (IAEA) to member countries, the new MESSAGE*ix* model is available as an open source tool via GitHub (https://github.com/iiasa/message_ix)

Model scope and methods

⇨ ***Objective***

MESSAGE-GLOBIOM is an integrated assessment framework designed to assess the transformation of the energy and land systems vis-a-vis the challenges of climate change and other sustainability issues. It consists of the energy model MESSAGE, the land use model GLOBIOM, the air pollution and GHG model GAINS, the aggregated macro-economic model MACRO and the simple climate model MAGICC.

⇨ ***Concept***

Hybrid model (energy engineering and land use partial equilibrium models soft-linked to macro-economic general equilibrium model)

⇨ ***Solution method***

Hybrid model (linear program optimization for the energy systems and land use modules, non-linear program optimization for the macro-economic module)

⇨ ***Anticipation***

Myopic/Perfect Foresight (MESSAGE can be run both with perfect foresight and myopically, while GLOBIOM runs myopically)

⇨ ***Temporal dimension***

Base year: 2010, **time steps:** 1990, 1995, 2000, 2005, 2010, 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100, 2110, **horizon:** 1990-2110

⇨ ***Spatial dimension***

Number of regions: 11+1

36. AFR (Sub-Saharan Africa)
37. CPA (Centrally Planned Asia & China)
38. EEU (Eastern Europe)
39. FSU (Former Soviet Union)
40. LAM (Latin America and the Caribbean)
41. MEA (Middle East and North Africa)
42. NAM (North America)
43. PAO (Pacific OECD)
44. PAS (Other Pacific Asia)
45. SAS (South Asia)
46. WEU (Western Europe)
47. GLB (international shipping)

⇨ ***Policy implementation***

GHG and energy taxes; GHG emission cap and permits trading; energy taxes and subsidies; micro-financing (for energy access analysis); regulation: generation capacity, production and share targets

Socio economic drivers

⇨ ***Exogenous drivers***

– Labour Productivity
– Energy Technical progress

- GDP per capita
- Population

⇨ ***Endogenous drivers***

⇨ ***Development***

- GDP per capita
- Income distribution in a region
- Number of people relying on solid cooking fuels

Macro economy

⇨ ***Economic sectors***

Note: MACRO represents the economy in a single sector with the production function including capital, labour and energy nests

⇨ ***Cost measures***

- GDP loss
- Consumption loss
- Area under MAC
- Energy system costs

⇨ ***Trade***

- Coal
- Oil
- Gas
- Uranium
- Electricity
- Food crops
- Emissions permits

Note: bioenergy is only traded after processing to a secondary fuel (e.g., liquid biofuel)

Energy

⇨ ***Behaviour***

Non-monetary factors of decision making (e.g., behavioural impacts) are represented in MESSAGE via so-called inconvenience costs. These are generally included in the consumer-dominated energy end-use sectors (transportation sector, residential and commercial sector) and are particularly relevant in the modelling of energy access in developing countries.

⇨ ***Resource use***

- Coal
- Oil
- Gas
- Uranium
- Biomass

Note: modern and traditional applications of biomass are distinguished

⇨ ***Electricity technologies***

- Coal w /o CCS
- Coal w/ CCS
- Gas w/o CCS
- Gas w/ CCS
- Oil w/o CCS
- Biomass w/o CCS
- Biomass w/ CCS
- Nuclear
- Wind Onshore
- Wind Offshore
- Solar PV
- *CSP*

– *Geothermal*
– *Hydropower*

Note: CCS can be combined with coal, gas and biomass power generation technologies

⇨ ***Conversion technologies***

– CHP
– Hydrogen
– Fuel to gas
– Fuel to liquid

Note: CHP can be combined with all thermal power plant types, Hydrogen can be produced from coal, gas and biomass feedstocks and electricity, Fuel to liquids is represented for coal, gas and biomass feedstocks, Fuel to gas is represented for coal and biomass feedstocks

⇨ ***Grid and infrastructure***

– Electricity
– Gas
– Heat
– CO_2
– Hydrogen

⇨ ***Energy technology substitution***

– Discrete technology choices
– Expansion and decline constraints
– System integration constraints

⇨ ***Energy service sectors***

– Transportation
– Industry
– Residential and commercial

Note: non-energy use (feedstock) of energy carriers is separately represented, but generally reported under industry

Land use

⇨ ***Land cover***

- Forest (natural/managed)
- Short-rotation plantations
- Cropland
- Grassland
- Other natural land

Other resources

⇨ ***Other resources***

– Water
– Cement

Note: cement is not modelled as a separate commodity, but process emissions from cement production are represented

Emissions and climate

⇨ ***Greenhouse gases***

– CO_2
– CH_4
– N_2O
– HFCs
– CFCs
– SF_6

⇨ ***Pollutants***

– NOx

– SOx
– BC
– OC
– *CO*
– *NH3*
– *VOC*

⇨ ***Climate indicators***

– CO_2e concentration (ppm)
– Radiative Forcing (W/m^2)
– Temperature change (°C)

Reference card – POLES

About

⇨ ***Name and version***

POLES ADVANCE (other versions are in use in other applications)

⇨ ***Institution and users***

JRC - Joint Research Centre - European Commission (EC-JRC), Belgium, http://ec.europa.eu/jrc/en/poles. main users: - European Commission, JRC - Université de Grenoble UPMF, France - Enerdata

Model scope and methods

⇨ ***Objective***

POLES was originally developed to assess energy markets, combining a detailed description of energy demand, transformation and primary supply for all energy vectors. It provides full energy balances on a yearly basis using frequent data updates to as to deliver robust forecasts for both short and long-term horizons. It has quickly been used, in the late 90s, to assess energy-related CO2 mitigation policies. Over time other GHG emissions have been included (energy and industry non-CO2 from the early 2000s), and linkages with agricultural and land use models have been progressively implemented.

⇨ ***Concept***

Partial equilibrium

⇨ ***Solution method***

Recursive simulation

⇨ ***Anticipation***

Myopic

⇨ ***Temporal dimension***

Base year: 1990-2015 (data up to current time -1/-2)**, time steps:** yearly, **horizon:** 2050-2100

⇨ ***Spatial dimension***

Number of regions: 66

⇨ ***Policy implementation***

- Energy taxes per sector and fuel, carbon pricing - Feed-in tariffs, green certificates, low interest rates, investment subsidies - Fuel efficiency standards in vehicles and buildings, white certificates

Socio economic drivers

⇨ ***Exogenous drivers***

– Exogenous GDP
– Population

⇨ ***Endogenous drivers***

– Value added
– Mobility needs
– Fossil fuel prices
– Buildings surfaces

⇨ ***Development***

– GDP per capita
– Urbanisation rate

Macro economy

⇨ ***Economic sectors***

– Agriculture
– Industry
– Services

⇨ ***Cost measures***

– Area under MAC
– Energy system costs

Note: Investments: supply-side only

⇨ ***Trade***
- Coal
- Oil
- Gas
- Bioenergy crops
- Emissions permits
- Liquid biofuels

Energy

⇨ ***Behaviour***

Activity drivers depend on income per capita and energy prices via elasticities. Energy demand depends on activity drivers, energy prices and technology costs. Primary energy supply depends on remaining resources, production cost and price effects.

⇨ ***Resource use***
- Coal
- Oil
- Gas
- Uranium
- Biomass

⇨ ***Electricity technologies***
- Coal
- Gas
- Oil
- Nuclear
- Biomass
- Wind
- Solar PV
- CCS
- Hydropower
- Geothermal
- Solar CSP
- Ocean

⇨ ***Conversion technologies***
- CHP
- Hydrogen
- Fuel to liquid

⇨ ***Grid and infrastructure***
- Gas
- H_2

⇨ ***Energy technology substitution***

⇨ ***Energy service sectors***
- Transportation
- Industry
- Residential and commercial

Land use

⇨ ***Land cover***
- Cropland
- Forest
- Grassland
- Urban Areas
- Desert

Other resources

⇨ ***Other resources***

– Metals

Note: Steel tons

Emissions and climate

⇨ ***Greenhouse gases***

– CO_2
– CH_4
– N_2O
– HFCs
– SF_6
– PFCs

⇨ ***Pollutants***

⇨ ***Climate indicators***

Reference card – REMIND - MAgPIE

About

⇨ ***Name and version***

REMIND 1.7 – MAgPIE 3.0

⇨ ***Institution and users***

Potsdam Institut für Klimafolgenforschung (PIK), Germany,
https://www.pik-potsdam.de/research/sustainable-solutions/models/remind
https://redmine.pik-potsdam.de/projects/magpie/wiki/Overview

Model scope and methods

⇨ ***Objective***

REMIND (Regionalized model of investment and development) is a global multi-regional model incorporating the economy, the climate system and a detailed representation of the energy sector. It allows analysing technology options and policy proposals for climate mitigation, and models regional energy investments and interregional trade in goods, energy carriers and emissions allowances.

MAgPIE (Model of Agricultural Production and its Impact on the Environment) is a global land use allocation model. MAgPIE derives future projections of spatial land use patterns, yields and regional costs of agricultural production.

⇨ ***Concept***

- REMIND: Hybrid model that couples an economic growth model with a detailed energy system model and a simple climate model.
- MAgPIE: Gridded land use model with economic regions. Coupled to the grid-based dynamic vegetation model LPJmL providing gridded input on potential crop yields, water availabiility and terrestrial carbon content under various climate conditions.

⇨ ***Solution method***

- REMIND: Inter-temporal optimization that maximizes cumulated discounted global welfare: Ramsey-type growth model with Negishi approach to regional welfare aggregation.
- MAgPIE: Partial equilibrium model with recursive-dynamic optimization. Optimal spatial patterns of land allocation and use are based on regional production cost minimization to meet a given amount of regional bioenergy and price-inelastic food and other agricultural demand.

⇨ ***Anticipation***

- REMIND: Perfect Foresight
- MAgPIE: Myopic

⇨ ***Temporal dimension***

- REMIND: Base year:2005**, time steps:** flexible time steps, default is 5-year time steps until 2050 and 10-year time steps until 2100; period from 2100-2150 is calculated to avoid distortions due to end effects, but typically only the time span 2005-2100 is used for model applications.
- MAgPIE: Base year: 1995, time steps: 5 and/or 10 years, horizon: 1995-2100

⇨ ***Spatial dimension***

Number of regions: 11

1. AFR - Sub-Saharan Africa (excluding South Africa)
2. CHN - China
3. EUR - European Union
4. JPN - Japan
5. IND - India
6. LAM - Latin America
7. MEA - Middle East, North Africa, and Central Asia
8. OAS - other Asian countries (mainly South-East Asia)
9. RUS - Russia
10. ROW - rest of the World (Australia, Canada, New Zealand, Non-EU Europe, South Africa)
11. USA - United States of America

Note: MAgPIE operates on 10 socio-economic world regions which are mapped into REMIND-defined regions.

⇨ ***Policy implementation***

- REMIND: Pareto-optimal achievement of policy targets on temperature, radiative forcing, GHG concentration, or cumulative carbon budgets. Alternatively, calculation of Nash equilibrium without internalized technology spillovers. Possibility to analyse changes in expectations about climate policy goals as well as pre-specified policy packages until 2030/2050, including e.g. energy capacity and efficiency targets, renewable energy quotas, carbon and other taxes, and energy subsidies
- MAgPIE: Pricing of land carbon and agricultural emissions, land use regulation, REDD+ policies, afforestation, agricultural trade policies

Socio economic drivers

⇨ ***Exogenous drivers***

– REMIND: Labour productivity, energy efficiency parameters of the production function, population
– MAgPIE: Demand for bioenergy, food, feed, and material demand from the agricultural sector

⇨ ***Endogenous drivers***

- REMIND: Investments in industrial capital stock. Endogenous learning-by-doing for wind and solar power as well as electric and fuel cell vehicle technologies (global learning curve, internalized spillovers).
- MAgPIE: Investments in agricultural productivity, land conversion and (re)allocation of agricultural production.

⇨ ***Development***

– REMIND: GDP per capita

Macro economy (REMIND)

⇨ ***Economic sectors***

Note: The macro-economic part contains a single sector representation of the entire economy. A generic final good is produced from capital, labour, and different final energy types

⇨ ***Cost measures***

– GDP loss
– Welfare loss
– Consumption loss

⇨ ***Trade***

– Coal
– Oil
– Gas
– Uranium
– Bioenergy crops
– Capital
– Emissions permits
– Non-energy goods

Energy (REMIND)

⇨ ***Behaviour***

Price response through CES production function. No explicit modelling of behavioural change. Baseline energy demands are calibrated in such a way that the energy demand patterns in different regions slowly converge when displayed as per capita energy demand over per capita GDP"

⇨ ***Resource use***

– Coal
– Oil
– Gas
– Uranium
– Biomass

⇨ ***Electricity technologies***
- Coal (with and w/o CCS)
- Gas (with and w/o CCS)
- Oil (with and w/o CCS)
- Nuclear
- Biomass (with and w/o CCS)
- Wind
- Solar PV
- CCS
- *Solar CSP*
- *Hydropower*
- *Geothermal*

⇨ ***Conversion technologies***
- CHP
- Heat pumps
- Hydrogen (from fossil fuels and biomass with and w/o CCS; electrolytic hydrogen)
- Fuel to gas
- Fuel to liquid (from fossil fuels and biomass with and w/o CCS)
- *Heat plants*

⇨ ***Grid and infrastructure***
- Electricity
- Gas
- Heat
- CO_2
- H_2

Note: Generalized transmission and distribution costs are included, but not modelled on an explicit spatial level. Regionalized additional grid and storage costs for renewable integration are included.

⇨ ***Energy technology substitution***
- Discrete technology choices
- Expansion and decline constraints
- System integration constraints

Note: Expansion and decline, and system integration are influenced though cost markups rather than constraints.

⇨ ***Energy service sectors***
- Transportation
- Industry
- Residential and commercial

Note: In older versions of REMIND (REMIND 1.6 and earlier), the industry and residential and commercial sectors are not treated separately but represented jointly by one Stationary sector (referred to as 'Other Sector').

Land use (MAgPIE)

MAgPIE allocates land use to fulfil competing demands for commodities, feed, carbon storage, land conservation and environmental protection. Land use is broadly categorized in cropland, forest land, pasture land, and other natural land. Regional food energy demand is defined for an exogenously given population in 16 food energy categories, based on regional diets. Future trends in food demand are derived from a cross-country regression analysis, based on future scenarios on GDP and population growth. MAgPIE takes technological development and production costs as well as spatially explicit data on potential crop yields, land and water constraints (from LPJmL) into account. It includes agricultural trade with different levels of regional self-sufficiency constraints. Changes in soil and plant carbon from land conversion are accounted for. MAgPIE models the full suite of AFOLU emissions.

REMIND and MAgPIE are coupled by exchanging greenhouse gas prices and bioenergy demand from REMIND to MAgPIE, and bioenergy prices and AFOLU greenhouse gas emissions from MAgPIE to REMIND, and iterating until an equilibrium of prices and quantities is established.

Other resources

⇨ ***Other resources***

– Cement

Note: Cement production is not explicitly modelled, but emissions from cement production are accounted for.

Emissions and climate

⇨ ***Greenhouse gases***

– CO_2
– CH_4
– N_2O
– HFCs
– CFCs
– SF_6

⇨ ***Pollutants***

– NO_X
– SO_X
– BC
– OC
– Ozone
– *CO*
– *VOC*

Note: Ozone is not modelled as emission, but is an endogenous result of atmospheric chemistry.

⇨ ***Climate indicators***

– CO_2e concentration (ppm)
– Radiative Forcing (W/m^2)
– Temperature change (°C)

Note: Different emissions are accounted for with different levels of detail depending on the types and sources of emissions (directly by source, via MAC curves, by econometric estimates, exogenous).

Reference card – Shell - World Energy Model

About

⇨ ***Name and version***

Shell World Energy Model 2018

2018 Edition (Version 2.10 series)

⇨ ***Institution and users***

Shell Corporation B.V., www.shell.com/scenariosenergymodels

Model scope and methods

⇨ ***Objective***

Exploratory simulations of plausible scenarios, covering both short-term drivers and momentum, together with the capability for long-term transformation of the energy system.

⇨ ***Concept***

Partial equilibrium (price elastic demand)

⇨ ***Solution method***

Simulation

⇨ ***Anticipation***

Recursive-dynamic (myopic)

⇨ ***Temporal dimension***

Base year: 2017, time steps: 1 year steps, horizon: 2100

⇨ ***Spatial dimension***

Number of regions: 100 (= 82 top countries + 18 rest of the world regions)

⇨ ***Policy implementation***

Emission Tax/Pricing, Cap and Trade, Fuel Taxes, Fuel Subsidies, Energy Efficiency Standards

Socio economic drivers

⇨ ***Exogenous drivers***

- Population
- Autonomous Energy Efficiency Improvements

⇨ ***Endogenous drivers***

⇨ ***Development***

Macro economy

⇨ ***Economic sectors***

Number of sectors: 14

- Industry
- Services
- Energy
- Energy service (sector-specific) and energy demand (in EJ) for each sector

⇨ ***Cost measures***

⇨ ***Trade***

- Coal
- Oil
- Gas
- Bioenergy crops

Energy

⇨ ***Behaviour***

⇨ ***Resource use***

- Coal
- Conventional Oil (Process Model)
- Unconventional Oil (Process Model)

- Conventional Gas (Process Model)
- Unconventional Gas (Process Model)
- Bioenergy (Fixed)

⇨ ***Electricity technologies***

- Coal (w/o CCS and w/ CCS)
- Gas (w/o CCS and w/ CCS)
- Oil (w/o CCS and w/ CCS)
- Bioenergy (w/o CCS and w/ CCS)
- Geothermal Power
- Nuclear Power
- Solar Power (Central PV, Distributed PV, CSP)
- Wind Power
- Hydroelectric Power
- Ocean Power

⇨ ***Conversion technologies***

- Coal to Hydrogen (w/o CCS and w/ CCS)
- Natural Gas to Hydrogen (w/o CCS and w/ CCS)
- Oil to Hydrogen (w/o CCS and w/ CCS)
- Biomass to Hydrogen (w/o CCS and w/ CCS)
- Nuclear Thermochemical Hydrogen
- Electrolysis
- Coal to Liquids (w/o CCS and w/ CCS)
- Gas to Liquids (w/o CCS and w/ CCS)
- Bioliquids (w/o CCS and w/ CCS)
- Oil Refining
- Coal to Gas (w/o CCS and w/ CCS)
- Oil to Gas (w/o CCS and w/ CCS)
- Biomass to Gas (w/o CCS and w/ CCS)
- Coal Heat
- Natural Gas Heat
- Oil Heat
- Biomass Heat
- Geothermal Heat
- Solarthermal Heat

⇨ ***Grid and infrastructure***

⇨ ***Energy technology substitution***

- Logit choice model
- Discrete technology choices with mostly high substitutability
- Mostly a constrained logit model; some derivative choices (e.g. refinery outputs) have pathway dependent choices
- Constraints are imposed both endogenously and after off-model analysis

⇨ ***Energy service sectors***

- Transportation
- Industry
- Residential and commercial

Land use

⇨ ***Land cover***

Other resources

⇨ ***Other resources***

Emissions and climate

⇨ ***Greenhouse gases***

– CO_2 Fossil Fuels (endogenous & uncontrolled)

⇨ ***Pollutants***

⇨ ***Climate indicators***

Reference card – WITCH

About

⇨ ***Name and version***

WITCH

⇨ ***Institution and users***

Fondazione Eni Enrico Mattei (FEEM), Italy, http://www.feem.it.
Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Italy, http://www.cmcc.it.

Model scope and methods

⇨ ***Objective***

WITCH evaluates the impacts of climate policies on global and regional economic systems and provides information on the optimal responses of these economies to climate change. The model considers the positive externalities from leaning-by-doing and learning-by-researching in the technological change.

⇨ ***Concept***

Hybrid: Economic optimal growth model, including a bottom-up energy sector and a simple climate model, embedded in a `game theory` framework.

⇨ ***Solution method***

Regional growth models solved by non-linear optimization and game theoretic setup solved by tatonnement algorithm (cooperative solution: Negishi welfare aggregation, non-cooperative solution: Nash equilibrium)

⇨ ***Anticipation***

Perfect foresight

⇨ ***Temporal dimension***

Base year: 2005**, time steps:5**, **horizon:** 2150

⇨ ***Spatial dimension***

Number of regions: 14

1. cajaz: Canada, Japan, New Zealand
2. china: China, including Taiwan
3. easia: South East Asia
4. india: India
5. kosau: South Korea, South Africa, Australia
6. laca: Latin America, Mexico and Caribbean
7. indo: Indonesia
8. mena: Middle East and North Africa
9. neweuro: EU new countries + Switzerland + Norway
10. oldeuro: EU old countries (EU-15)
11. sasia: South Asia
12. ssa: Sub Saharan Africa
13. te: Non-EU Eastern European countries, including Russia
14. usa: United States of America

⇨ ***Policy implementation***

Quantitative climate targets (temperature, radiative forcing, concentration), carbon budgets, emissions profiles as optimization constraints. Carbon taxes. Allocation and trading of emission permits, banking and borrowing. Subsidies, taxes and penalty on energies sources.

Socio economic drivers

⇨ ***Exogenous drivers***

– Total Factor Productivity
– Labour Productivity
– Capital Technical progress

⇨ ***Development***

Macro economy

⇨ ***Economic sectors***

– Energy
– Other

Note: A single economy sector is represented. Production inputs are capital, labour and energy services, accounting for the Energy sector split into 8 energy technologies sectors (coal, oil, gas, wind & solar, nuclear, electricity and biofuels).

⇨ ***Cost measures***

– GDP loss
– Welfare loss
– Consumption loss
– Energy system costs

⇨ ***Trade***

– Coal
– Oil
– Gas
– Emissions permits

Energy

⇨ ***Resource use***

– Coal
– Oil
– Gas
– Uranium
– Biomass

⇨ ***Electricity technologies***

– Coal
– Gas
– Oil
– Nuclear
– Biomass
– Wind
– Solar PV
– CCS

⇨ ***Conversion technologies***

⇨ ***Grid and infrastructure***

– Electricity
– CO_2

⇨ ***Energy technology substitution***

– Expansion and decline constraints
– System integration constraints

⇨ ***Energy service sectors***

– Transportation

Land use

⇨ ***Land cover***

– Cropland
– Forest

Note: Bioenergy related cost and emissions are obtained by soft linking with the GLOBIOM model.

Other resources

➪ ***Other resources***

– Water

Emissions and climate

➪ ***Greenhouse gases***

– CO_2
– CH_4
– N_2O
– HFCs
– CFCs
– SF_6

➪ ***Pollutants***

– NO_X
– SO_X
– BC
– OC

➪ ***Climate indicators***

– CO_2e concentration (ppm)
– Radiative Forcing (W/m^2)
– Temperature change (°C)
– Climate damages $ or equivalent