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Mitigation Pathways Compatible with Long-term Goals

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Executive Summary

Chapter 3 assesses the emissions pathways literature in order to identify their key characteristics (both in commonalities and differences) and to understand how societal choices may steer the system into a particular direction (*high confidence*). More than 2000 quantitative emissions pathways were submitted to the IPCC's Sixth Assessment Report AR6 scenarios database, out of which 1202 scenarios included sufficient information for assessing the associated warming consistent with WGI. Five Illustrative Mitigation Pathways (IMPs) were selected, each emphasising a different scenario element as its defining feature: heavy reliance on renewables (IMP-Ren), strong emphasis on energy demand reductions (IMP-LD), extensive use of carbon dioxide removal (CDR) in the energy and the industry sectors to achieve net negative emissions (IMP-Neg), mitigation in the context of broader sustainable development (IMP-SP), and the implications of a less rapid and gradual strengthening of near-term mitigation actions (IMP-GS). {3.2, 3.3}

Pathways consistent with the implementation and extrapolation of countries' implemented policies until the end of 2020 see greenhouse gas (GHG) emissions reaching 54–61 $GtCO_2$-eq yr^{-1} by 2030 and to 47–67 $GtCO_2$-eq yr^{-1} by 2050, leading to a median global warming of 2.2°C to 3.5°C by 2100 (*medium confidence*). These pathways consider policies at the time that they were developed. The Shared Socio-economic Pathways (SSPs) permit a more systematic assessment of future GHG emissions and their uncertainties than was possible in AR5. The main emissions drivers include growth in population, reaching 8.5–9.7 billion by 2050, and an increase in global GDP of 2.7–4.1% per year between 2015 and 2050. Final energy demand in the absence of any new climate policies is projected to grow to around 480–750 EJ yr^{-1} in 2050 (compared to around 390 EJ in 2015) (*medium confidence*). The highest emissions scenarios in the literature result in global warming of >5°C by 2100, based on assumptions of rapid economic growth and pervasive climate policy failures (*high confidence*). {3.3}

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

Cost-effective mitigation pathways assuming immediate action[1] to limit warming to 2°C (>67%) are associated with net global GHG emissions of 30–49 $GtCO_2$-eq yr^{-1} by 2030 and 14–26 $GtCO_2$-eq yr^{-1} by 2050 (*medium confidence*). This corresponds to reductions, relative to 2019 levels, of 13–45% by 2030 and 52–76% by 2050. Pathways that limit global warming to below 1.5°C with no or limited overshoot require a further acceleration in the pace of the transformation, with net GHG emissions typically around 21–36 $GtCO_2$-eq yr^{-1} by 2030 and 1–15 $GtCO_2$-eq yr^{-1} by 2050; thus, reductions of 34–60% by 2030 and 73–98% by 2050 relative to 2019 levels. {3.3}

Pathways following Nationally Determined Contributions (NDCs) announced prior to COP26[2] until 2030 reach annual emissions of 47–57 $GtCO_2$-eq by 2030, thereby making it impossible to limit warming to 1.5°C with no or limited overshoot and strongly increasing the challenge to limit warming to 2°C (>67%) (*high confidence*). A high overshoot of 1.5°C increases the risks from climate impacts and increases the dependence on large-scale carbon dioxide removal from the atmosphere. A future consistent with NDCs announced prior to COP26 implies higher fossil fuel deployment and lower reliance on low-carbon alternatives until 2030, compared to mitigation pathways with immediate action to limit warming to 2°C (>67%) or lower. To limit warming to 2°C (>67%) after following the NDCs to 2030, the pace of global GHG emission reductions would need to accelerate rapidly from 2030 onward: to an average of 1.4–2.0 $GtCO_2$-eq yr^{-1} between 2030 and 2050, which is around two-thirds of the global CO_2 emission reductions in 2020 due to the COVID-19 pandemic, and around 70% faster than in immediate action pathways that limit warming to 2°C (>67%). Accelerating emission reductions after following an NDC pathway to 2030 would be particularly challenging because of the continued buildup of fossil fuel infrastructure that would be expected to take place between now and 2030. {3.5, 4.2}

Pathways accelerating actions compared to NDCs announced prior to COP26 that reduce annual GHG emissions to 48 (38–52) $GtCO_2$-eq by 2030, or 2–9 $GtCO_2$-eq below projected emissions from fully implementing NDCs announced prior to COP26, reduce the mitigation challenge for limiting warming to 2°C (>67%) after 2030 (*medium confidence*). The accelerated action pathways are characterised by a global, but regionally differentiated, roll out of regulatory and pricing policies. Compared to NDCs, they see less fossil fuels and more low-carbon fuels until 2030, and narrow, but do not close the gap to pathways assuming immediate global action using all available least-cost abatement options. All delayed or accelerated action pathways that limit warming to 2°C (>67%) converge to a global mitigation regime at some point after 2030 by putting a significant value on reducing carbon and other GHG emissions in all sectors and regions. {3.5}

1 Immediate action in modelled global pathways refers to the adoption between 2020 and at latest before 2025 of climate policies intended to limit global warming to a given level. Modelled pathways that limit warming to 2°C (>67%) based on immediate action are summarised in category C3a in Table SPM.2. All assessed modelled global pathways that limit warming to 1.5°C (>50%) with no or limited overshoot assume immediate action as defined here (Category C1 in Table SPM.2).

2 NDCs announced prior to COP26 refer to the most recent nationally determined contributions submitted to the UNFCCC up to the literature cut-off date of this report, 11 October 2021, and revised NDCs announced by China, Japan and the Republic of Korea prior to October 2021 but only submitted thereafter.

Mitigation pathways limiting warming to 1.5°C (>50%) with no or limited overshoot reach 50% reductions of CO_2 in the 2030s, relative to 2019, then reduce emissions further to reach net zero CO_2 emissions in the 2050s. Pathways limiting warming to 2°C (>67%) reach 50% reductions in the 2040s and net zero CO_2 by 2070s (*medium confidence*). {3.3, Cross-Chapter Box 3 in this chapter}

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

Rapid reductions in non-CO_2 GHGs, particularly methane, would lower the level of peak warming (*high confidence*). Residual non-CO_2 emissions at the time of reaching net zero CO_2 range between 5 and 11 $GtCO_2$-eq yr^{-1} in pathways limiting warming to 2°C (>67%) or lower. Methane (CH_4) is reduced by around 19% (4–46%) in 2030 and 45% (29–64%) in 2050, relative to 2019. Methane emission reductions in pathways limiting warming to 1.5°C (>50%) with no or limited overshoot are substantially higher by 2030, 34% (21–57%), but only moderately so by 2050, 51% (35–70%). Methane emissions reductions are thus attainable at relatively lower GHG prices but are at the same time limited in scope in most 1.5°C–2°C pathways. Deeper methane emissions reductions by 2050 could further constrain the peak warming. N_2O emissions are reduced too, but similar to CH_4, emission reductions saturate for more stringent climate goals. In the mitigation pathways, the emissions of cooling aerosols are reduced due to reduced use of fossil fuels. The overall impact on non-CO_2-related warming combines these factors. {3.3}

Net zero GHG emissions imply net negative CO_2 emissions at a level compensating residual non-CO_2 emissions. Only 30% of the pathways limiting warming to 2°C (>67%) or lower reach net zero GHG emissions in the 21st century (*high confidence*). In those pathways reaching net zero GHGs, it is achieved around 10 to 40 years later than for net zero CO_2 (*medium confidence*). The reported quantity of residual non-CO_2 emissions depends on accounting: the choice of GHG metric. Reaching and sustaining global net zero GHG emissions, measured in terms of GWP-100, results in a gradual decline of temperature (*high confidence*). {Cross-Chapter Box 2 in Chapter 2, 3.3, Cross-Chapter Box 3 in this chapter}

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

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

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

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

The measures required to limit warming to 2°C (>67%) or lower can result in large-scale transformation of the land surface (*high confidence*). Pathways limiting warming to 2°C (>67%) or lower are projected to reach net zero CO_2 emissions in the AFOLU sector between the 2020s and 2070, with an increase of forest cover of about 322 million ha (–67 to 890 million ha) in 2050 in pathways limiting warming to 1.5°C (>50%) with no or limited overshoot. Cropland area to supply biomass for bioenergy (including bioenergy with carbon capture and storage – BECCS) is around 199 (56–482) million ha in 2050 in pathways limiting warming to 1.5°C (>50%) with no or limited overshoot. The use of bioenergy can lead to either increased or reduced emissions, depending on the scale of deployment, conversion technology, fuel displaced, and how/where the biomass is produced (*high confidence*). {3.4}

Anthropogenic land CO_2 emissions and removals in Integrated Assessment Model (IAM) pathways cannot be directly compared with those reported in national GHG inventories (*high confidence*). Methodologies enabling a more like-for-like comparison between models' and countries' approaches would support more accurate assessment of the collective progress achieved under the Paris Agreement. {3.4, 7.2.2.5}

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

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

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

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

Mitigation pathways that limit warming to 2°C (>67%) entail losses in global GDP with respect to reference scenarios of between 1.3% and 2.7% in 2050; and in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, losses are between 2.6% and 4.2%. Yet, these estimates do not account for the economic benefits of avoided climate change impacts (*medium confidence*). In mitigation pathways that limit warming to 2°C (>67%), marginal abatement costs of carbon are about 90 (60–120) USD2015 tCO_2 in 2030 and about 210 (140–340) USD2015 tCO_2 in 2050; in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, they are about 220 (170–290) USD2015 tCO_2 in 2030 and about 630 (430–990) USD2015 tCO_2 in 2050.[3] {3.6.1}

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

The economic benefits on human health from air quality improvement arising from mitigation action can be of the same order of magnitude as mitigation costs, and potentially even larger (*medium confidence*). {3.6.3}

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

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

[3] Numbers in parenthesis represent the interquartile range of the scenario samples.

The timing of mitigation actions and their effectiveness will have significant consequences for broader sustainable development outcomes in the longer term (*high confidence*). Ambitious mitigation can be considered a precondition for achieving the Sustainable Development Goals (SDGs), especially for vulnerable populations and ecosystems with little capacity to adapt to climate impacts. Dimensions with anticipated co-benefits include health, especially regarding air pollution, clean energy access and water availability. Dimensions with potential trade-offs include food, employment, water stress, and biodiversity, which come under pressure from large-scale CDR deployment, energy affordability/access, and mineral-resource extraction (*high confidence*). {3.7}

Many of the potential trade-offs of mitigation measures for other sustainable development outcomes depend on policy design and can thus be compensated or avoided with additional policies and investments or through policies that integrate mitigation with other SDGs (*high confidence*). Targeted SDG policies and investments, for example in the areas of healthy nutrition, sustainable consumption and production, and international collaboration, can support climate change mitigation policies and resolve or alleviate trade-offs. Trade-offs can be addressed by complementary policies and investments, as well as through the design of cross-sectoral policies integrating mitigation with the Sustainable Development Goals of health, nutrition, sustainable consumption and production, equity and biodiversity. {3.7}

Decent living standards, which encompass many SDG dimensions, are achievable at lower energy use than previously thought (*high confidence*). Mitigation strategies that focus on lower demands for energy and land-based resources exhibit reduced trade-offs and negative consequences for sustainable development relative to pathways involving either high emissions and climate impacts or those with high consumption and emissions that are ultimately compensated by large quantities of BECCS. {3.7}

Different mitigation pathways are associated with different feasibility challenges, though appropriate enabling conditions can reduce these challenges (*high confidence*). Feasibility challenges are transient and concentrated in the next two to three decades (*high confidence*). They are multidimensional, context-dependent and malleable to policy, technological and societal trends. {3.8}

Mitigation pathways are associated with significant institutional and economic feasibility challenges rather than technological and geophysical feasibility challenges (*medium confidence*). The rapid pace of technological development and deployment in mitigation pathways is not incompatible with historical records. Institutional capacity is rather a key limiting factor for a successful transition. Emerging economies appear to have the highest feasibility challenges in the short to medium term. {3.8}

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

3.1 Introduction

3.1.1 Assessment of Mitigation Pathways and Their Compatibility With Long-term Goals

Chapter 3 takes a long-term perspective on climate change mitigation pathways. Its focus is on the implications of long-term targets for the required short- and medium-term system changes and associated greenhouse gas (GHG) emissions. This focus dictates a more global view and on issues related to path-dependency and up-scaling of mitigation options necessary to achieve different emissions trajectories, including particularly deep mitigation pathways that require rapid and fundamental changes.

Stabilising global average-temperature change requires reducing CO_2 emissions to net zero. Thus, a central cross-cutting topic within the chapter is the timing of reaching net zero CO_2 emissions and how a 'balance between anthropogenic emissions by sources and removals by sinks' could be achieved across time and space. This includes particularly the increasing body of literature since the *IPCC Special Report on Global Warming of 1.5°C* (SR1.5) which focuses on net zero CO_2 emissions pathways that avoid temperature overshoot and hence do not rely on net negative CO_2 emissions. The chapter conducts a systematic assessment of the associated economic costs as well as the benefits of mitigation for other societal objectives, such as the Sustainable Development Goals (SDGs). In addition, the chapter builds on SR1.5 and introduces a new conceptual framing for the assessment of possible social, economic, technical, political, and geophysical 'feasibility' concerns of alternative pathways, including the enabling conditions that would need to fall into place so that stringent climate goals become attainable.

The structure of the chapter is as follows: Section 3.2 introduces different types of mitigation pathways as well as the available modelling. Section 3.3 explores different emissions trajectories given socio-economic uncertainties and consistent with different long-term climate outcomes. A central element in this section is the systematic categorisation of the scenario space according to key characteristics of the mitigation pathways (including e.g., global average-temperature change, socio-economic development, technology assumptions, etc.). In addition, the section introduces selected Illustrative Mitigation Pathways (IMPs) that are used across the whole report. Section 3.4 conducts a sectoral analysis of the mitigation pathways, assessing the pace and direction of systems changes across sectors. Among others, this section aims at the integration of the sectoral information across AR6 WGIII chapters through a comparative assessment of the sectoral dynamics in economy-wide systems models compared to the insights from bottom-up sectoral models (from Chapters 6 to 11). Section 3.5 focuses on the required timing of mitigation actions, and the implication of near-term choices for the attainability of a range of long-term climate goals. After having explored the underlying systems transitions and the required timing of the mitigation actions, Section 3.6 assesses the economic implications, mitigation costs and benefits; and Section 3.7 assesses related co-benefits, synergies, and possible trade-offs for sustainable development and other societal (non-climate) objectives. Section 3.8 assumes a central role in the chapter and introduces a multidimensional feasibility metric that permits the evaluation of mitigation pathways across a range of feasibility concerns. Finally, methods of the assessment and knowledge gaps are discussed in Section 3.9, followed by Frequently Asked Questions (FAQs).

3.1.2 Linkages to Other Chapters in the Report

Chapter 3 is linked to many other chapters in the report. The most important connections exist with Chapter 4 on mitigation and development pathways in the near to mid-term; with the sectoral chapters (Chapters 6–11); with the chapters dealing with cross-cutting issues (Chapters 12 and 17, e.g., feasibility); and finally also with AR6 WGI and WGII.

Within the overall framing of the AR6 report, Chapter 3 and Chapter 4 provide important complementary views of the required systems transitions across different temporal and spatial scales. While Chapter 3 focuses on the questions concerning the implications of the long-term objectives for the medium-to-near-term transformations, Chapter 4 comes from the other direction, and focuses on current near-term trends and policies (such as the Nationally Determined Contributions – NDCs) and their consequences with regards to GHG emissions. The latter chapter naturally focuses much more on the regional and national dimensions, and the heterogeneity of current and planned policies. Bringing together the information from these two chapters enables the assessment of whether current and planned actions are consistent with the required systems changes for the long-term objectives of the Paris Agreement.

Important other linkages comprise the collaboration with the 'sectoral' Chapters 6 to 11 to provide an integrated cross-sectoral perspective. This information (including information also from the sectoral chapters) is taken up ultimately also by Chapter 5 on demand/services and Chapter 12 for a further assessment of sectoral potential and costs.

Linkages to other chapters exist also on the topic of feasibility, which are informed by the policy, the sectoral and the demand chapters, the technology and finance chapters, as well as Chapter 4 on national circumstances.

Close collaboration with WGI permitted the use of AR6-calibrated emulators, which assure full consistency across the different working groups. Linkages to WGII concern the assessment of macroeconomic benefits of avoided impacts that are put into the context of mitigation costs as well as co-benefits and trade-offs for sustainable development.

3.1.3 Complementary Use of Large Scenario Ensembles and a Limited Set of Illustrative Mitigation Pathways (IMPs)

The assessment of mitigation pathways explores a wide scenario space from the literature within which seven Illustrative Pathways (IPs) are explored. The overall process is indicated in Figure 3.5a.

For a comprehensive assessment, a large ensemble of scenarios is collected and made available through an interactive AR6 Scenarios Database[4]. The collected information is shared across the chapters of AR6 and includes more than 3000 different pathways from a diverse set of studies. After an initial screening and quality control, scenarios were further vetted to assess if they sufficiently represented historical trends (Annex III.II.3.1). Subsequently, the climate consequences of each scenario were assessed using the climate emulator (leading to further classification). The assessment in Chapter 3 is, however, not limited to the scenarios from the database, and wherever necessary other literature sources are also assessed in order to bring together multiple lines of evidence.

In parallel, based on the overall AR6 assessment, seven illustrative pathways (IP) were defined representing critical mitigation strategies discussed in the assessment. The seven pathways are composed of two sets: (i) one set of five Illustrative Mitigation Pathways (IMPs) and (ii) one set of two reference pathways illustrative for high emissions. The IMPs are on the one hand representative of the scenario spac but also help to communicate archetypes of distinctly different systems transformations and related policy choices. Subsequently, seven scenarios were selected from the full database that fitted these storylines of each IP best. For these scenarios more strict vetting criteria were applied. The selection was done by first applying specific filters based on the storyline followed by a final selection (Box 3.1 and Figure 3.5a).

3.2 Which Mitigation Pathways are Compatible With Long-term Goals?

3.2.1 Scenario and Emission Pathways

Scenario and emission pathways are used to explore possible long-term trajectories, the effectiveness of possible mitigation strategies, and to help understand key uncertainties about the future. A **scenario** is an integrated description of a possible future of the human–environment system (Clarke et al. 2014), and could be a qualitative narrative, quantitative projection, or both. Scenarios typically capture interactions and processes that change key driving forces such as population, GDP, technology, lifestyles, and policy, and the consequences on energy use, land use, and emissions. Scenarios are not predictions or forecasts. An emission pathway is a modelled trajectory of anthropogenic emissions (Rogelj et al. 2018a) and, therefore, a part of a scenario.

There is no unique or preferred method to develop scenarios, and future pathways can be developed from diverse methods, depending on user needs and research questions (Turnheim et al. 2015; Trutnevyte et al. 2019a; Hirt et al. 2020). The most comprehensive scenarios in the literature are qualitative narratives that are translated into quantitative pathways using models (Clarke et al. 2014; Rogelj et al. 2018a). Schematic or illustrative pathways can also be used to communicate specific features of more complex scenarios (Allen et al. 2018). Simplified models can be used to explain the mechanisms operating in more complex models (e.g., Emmerling et al. 2019). Ultimately, a diversity of scenario and modelling approaches can lead to more robust findings (Schinko et al. 2017; Gambhir et al. 2019).

3.2.1.1 Reference Scenarios

It is common to define a reference scenario (also called a baseline scenario). Depending on the research question, a reference scenario could be defined in different ways (Grant et al. 2020): (i) a hypothetical world with no climate policies or climate impacts (Kriegler et al. 2014b), (ii) assuming current policies or pledged policies are implemented (Roelfsema et al. 2020), or (iii) a mitigation scenario to compare sensitivity with other mitigation scenarios (Kriegler et al. 2014a; Sognnaes et al. 2021).

No-climate-policy reference scenarios have often been compared with mitigation scenarios (Clarke et al. 2014). A no-climate-policy scenario assumes that no future climate policies are implemented, beyond what is in the model calibration, effectively implying that the carbon price is zero. No-climate-policy reference scenarios have a broad range depending on socio-economic assumptions and model characteristics, and consequently are important when assessing mitigation costs (Riahi et al. 2017; Rogelj et al. 2018b). As

Box 3.1 | Illustrative Mitigation Pathways (IMPs)

The literature shows a wide range of possible emissions trajectories, depicting developments in the absence of new climate policies or showing pathways consistent with the Paris Agreement. From the literature, a set of five Illustrative Mitigation Pathways (IMPs) was selected to denote implications of choices on socio-economic development and climate policies, and the associated transformations of the main GHG-emitting sectors (Figure 3.5b). The IMPs include a set of transformative pathways that illustrate how choices may lead to distinctly different transformations that may keep temperature increase to below 2°C (>67%) or 1.5°C. These pathways illustrate the implications of a focus on renewable energy such as solar and wind; reduced energy demand; extensive use of CDR in the energy and the industry sectors to achieve net negative emissions and reliance on other supply-side measures; strategies that avoid net negative carbon emissions, and gradual strengthening. In addition, one IMP explores how climate policies consistent with keeping limit warming to 1.5C (>50%) can be combined with a broader shift towards sustainable development. These IMPs are used in various chapters, exploring for instance their implications for different sectors, regions, and innovation characteristics (Figure 3.5b).

[4] Available at: https://doi.org/10.5281/zenodo.5886911. All figures and tables in this chapter source data from the AR6 Scenarios Database, unless otherwise stated.

3

countries move forward with climate policies of varying stringency, no-climate-policy baselines are becoming increasingly hypothetical (Hausfather and Peters 2020). Studies clearly show current policies are having an effect, particularly when combined with the declining costs of low-carbon technologies (IEA 2020a; Roelfsema et al. 2020; Sognnaes et al. 2021; UNEP 2020), and, consequently, realised trajectories begin to differ from earlier no-climate-policy scenarios (Burgess et al. 2020). High-end emission scenarios, such as RCP8.5 and SSP5-8.5, are becoming less likely with climate policy and technology change (Box 3.3), but high-end concentration and warming levels may still be reached with the inclusion of strong carbon or climate feedbacks (Hausfather and Peters 2020; Pedersen et al. 2020).

3.2.1.2 Mitigation Scenarios

Mitigation scenarios explore different strategies to meet climate goals and are typically derived from reference scenarios by adding climate or other policies. Mitigation pathways are often developed to meet a predefined level of climate change, often referred to as a backcast. There are relatively few IAMs that include an endogenous climate model or emulator due to the added computational complexity, though exceptions do exist. In practice, models implement climate constraints by either iterating carbon-price assumptions (Strefler et al. 2021b) or by adopting an associated carbon budget (Riahi et al. 2021). In both cases, other GHGs are typically controlled by CO_2-equivalent pricing. A large part of the AR5 literature has focused on forcing pathways towards a target at the end of the century (van Vuuren et al. 2007, 2011; Clarke et al. 2009; Blanford et al. 2014; Riahi et al. 2017), featuring a temporary overshoot of the warming and forcing levels (Geden and Löschel 2017). In comparison, many recent studies explore mitigation strategies that limit overshoot (Johansson et al. 2020; Riahi et al. 2021). An increasing number of IAM studies also explore climate pathways that limit adverse side effects with respect to other societal objectives, such as food security (van Vuuren et al. 2019; Riahi et al. 2021) or larger sets of sustainability objectives (Soergel et al. 2021a).

3.2.2 The Utility of Integrated Assessment Models

Integrated Assessment Models (IAMs) are critical for understanding the implications of long-term climate objectives for the required near-term transition. For doing so, an integrated systems perspective including the representation of all sectors and GHGs is necessary. IAMs are used to explore the response of complex systems in a formal and consistent framework. They cover a broad range of modelling frameworks (Keppo et al. 2021). Given the complexity of the systems under investigation, IAMs necessarily make simplifying assumptions and therefore results need to be interpreted in the context of these assumptions. IAMs can range from economic models that consider only carbon dioxide emissions through to detailed process-based representations of the global energy system, covering separate regions and sectors (such as energy, transport, and land use), all GHG emissions and air pollutants, interactions with land and water, and a reduced representation of the climate system. IAMs are generally driven by economics and can have a variety of characteristics such as partial-, general- or non-equilibrium; myopic or perfect foresight; be based on optimisation or simulation; have exogenous or endogenous technological change amongst many other characteristics. IAMs take as input socio-economic and technical variables and parameters to represent various systems. There is no unique way to integrate this knowledge into a model, and due to their complexity, various simplifications and omissions are made for tractability. IAMs therefore have various advantages and disadvantages which need to be weighed up when interpreting IAM outcomes. Annex III.I contains an overview of the different types of models and their key characteristics.

Most IAMs are necessarily broad as they capture long-term dynamics. IAMs are strong in showing the key characteristics of emission pathways and are most suited to questions related to short- versus long-term trade-offs, key interactions with non-climate objectives, long-term energy and land-use characteristics, and implications of different overarching technological and policy choices (Clarke et al. 2014; Rogelj et al. 2018a). While some IAMs have a high level of regional and sectoral detail, for questions that require higher levels of granularity (e.g., local policy implementation) specific region and sector models may be better suited. Utility of the IAM pathways increases when the quantitative results are contextualized through qualitative narratives or other additional types of knowledge to provide deeper insights (Geels et al. 2016a; Weyant 2017; Gambhir et al. 2019).

IAMs have a long history in addressing environmental problems, particularly in the IPCC assessment process (van Beek et al. 2020). Many policy discussions have been guided by IAM-based quantifications, such as the required emission reduction rates, net zero years, or technology deployment rates required to meet certain climate outcomes. This has led to the discussion about whether IAM scenarios have become performative, meaning that they act upon, transform or bring into being the scenarios they describe (Beck and Mahony 2017, 2018). Transparency of underlying data and methods is critical for scenario users to understand what drives different scenario results (Robertson 2020). A number of community activities have thus focused on the provision of transparent and publicly accessible databases of both input and output data (Riahi et al. 2012; Huppmann et al. 2018; Krey et al. 2019; Daioglou et al. 2020), as well as the provision of open-source code, and increased documentation (Annex III.I.9). Transparency is needed to reveal conditionality of results on specific choices in terms of assumptions (e.g., discount rates) and model architecture. More detailed explanations of underlying model dynamics would be critical to increase the understanding of what drives results (Bistline et al. 2020; Butnar et al. 2020; Robertson 2020).

Mitigation scenarios developed for a long-term climate constraint typically focus on cost-effective mitigation action towards a long-term climate goal. Results from IAM as well as sectoral models depend on model structure (Mercure et al. 2019), economic assumptions (Emmerling et al. 2019), technology assumptions (Pye et al. 2018), climate/emissions target formulation (Johansson et al. 2020), and the extent to which pre-existing market distortions are considered (Guivarch et al. 2011). The vast majority of IAM pathways do not consider climate impacts (Schultes et al. 2021). Equity hinges upon ethical and normative choices. As most IAM pathways follow the cost-effectiveness approach, they do not make any additional equity assumptions. Notable exceptions include Tavoni et al. (2015), Pan et al. (2017), van den Berg et al. (2020), and Bauer et al. (2020). Regional IAM results therefore need to be assessed with care, considering that emissions reductions are happening where it is most cost-effective, which needs to be separated from who is ultimately paying for the mitigation costs. Cost-effective pathways can provide a useful benchmark, but may not reflect real-world developments (Calvin et al. 2014a; Trutnevyte 2016). Different modelling frameworks may lead to different outcomes (Mercure et al. 2019). Recent studies have shown that other desirable outcomes can evolve with only minor deviations from cost-effective pathways (Bauer et al. 2020; Neumann and Brown 2021). IAM and sectoral models represent social, political, and institutional factors only in a rudimentary way. This assessment is thus relying on new methods for the *ex post* assessment of feasibility concerns (Jewell and Cherp 2020; Brutschin et al. 2021). A literature is emerging that recognises and reflects on the diversity and strengths/weaknesses of model-based scenario analysis (Keppo et al. 2021).

The climate constraint implementation can have a meaningful impact on model results. The literature so far includes many temperature overshoot scenarios with heavy reliance on long-term CDR and net negative CO_2 emissions to bring back temperatures after the peak (Rogelj et al. 2019b; Johansson et al. 2020). New approaches have been developed to avoid temperature overshoot. The new generation of scenarios show that CDR is important beyond its ability to reduce temperature, but is essential also for offsetting residual emissions to reach net zero CO_2 emissions (Rogelj et al. 2019b; Johansson et al. 2020; Riahi et al. 2021; Strefler et al. 2021b).

Many factors influence the deployment of technologies in the IAMs. Since AR5, there has been fervent debate on the large-scale deployment of bioenergy with carbon capture and storage (BECCS) in scenarios (Fuss et al. 2014; Geden 2015; Anderson and Peters 2016; Smith et al. 2016; van Vuuren et al. 2017; Galik 2020; Köberle 2019). Hence, many recent studies explore mitigation pathways with limited BECCS deployment (Grubler et al. 2018; van Vuuren et al. 2019; Riahi et al. 2021; Soergel et al. 2021a). While some have argued that technology diffusion in IAMs occurs too rapidly (Gambhir et al. 2019), others argued that most models prefer large-scale solutions resulting in a relatively slow phase-out of fossil fuels (Carton 2019). While IAMs are particularly strong on supply-side representation, demand-side measures still lag in detail of representation despite progress since AR5 (Grubler et al. 2018; Lovins et al. 2019; van den Berg et al. 2019; O'Neill et al. 2020b; Hickel et al. 2021; Keyßer and Lenzen 2021). The discount rate has a significant impact on the balance between near-term and long-term mitigation. Lower discount rates <4% (than used in IAMs) may lead to more near-term emissions reductions – depending on the stringency of the target (Emmerling et al. 2019; Riahi et al. 2021). Models often use simplified policy assumptions (O'Neill et al. 2020b) which can affect the deployment of technologies (Sognnaes et al. 2021). Uncertainty in technologies can lead to more or less short-term mitigation (Grant et al. 2021; Bednar et al. 2021). There is also a recognition to put more emphasis on what drives the results of different IAMs (Gambhir et al. 2019) and suggestions to focus more on what is driving differences in result across IAMs (Nikas et al. 2021). As noted by Weyant (2017, p. 131), 'IAms can provide very useful information, but this information needs to be carefully interpreted and integrated with other quantitative and qualitative inputs in the decision-making process.'

3.2.3 The Scenario Literature and Scenario Databases

IPCC reports have often used voluntary submissions to a scenario database in its assessments. The database is an ensemble of opportunity, as there is not a well-designed statistical sampling of the hypothetical model or scenario space: the literature is unlikely to cover all possible models and scenarios, and not all scenarios in the literature are submitted to the database. Model intercomparisons are often the core of scenario databases assessed by the IPCC (Cointe et al. 2019; Nikas et al. 2021). Single-model studies may allow more detailed sensitivity analyses or address specific research questions. The scenarios that are organised within the scientific community are more likely to enter the assessment process via the scenario database (Cointe et al. 2019), while scenarios from different communities, in the emerging literature, or not structurally consistent with the database may be overlooked. Scenarios in the grey literature may not be assessed even though they may have greater weight in a policy context.

One notable development since AR5 is the Shared Socio-economic Pathways (SSPs), conceptually outlined in Moss et al. (2010) and subsequently developed to support integrated climate research across the IPCC Working Groups (O'Neill et al. 2014). Initially, a set of SSP narratives were developed, describing worlds with different challenges to mitigation and adaptation (O'Neill et al. 2017a): SSP1 (sustainability), SSP2 (middle of the road), SSP3 (regional rivalry), SSP4 (inequality) and SSP5 (rapid growth). The SSPs have now been quantified in terms of energy, land-use, and emission pathways (Riahi et al. 2017), for both no-climate-policy reference scenarios and mitigation scenarios that follow similar radiative-forcing pathways as the Representative Concentration Pathways (RCPs) assessed in AR5 WGI. Since then the SSPs have been successfully applied in thousands of studies (O'Neill et al. 2020b) including some critiques on the use and application of the SSP framework (Pielke and Ritchie 2021; Rosen 2021). A selection of the quantified SSPs are used prominently in AR6 WGI as they were the basis for most climate modelling since AR5 (O'Neill et al. 2016). Since 2014, when the first set of SSP data was made available, there has been a divergence between scenario and historic trends (Burgess et al. 2020). As a result, the SSPs require updating (O'Neill et al. 2020b). Most of the scenarios in the AR6 database are SSP-based and consider various updates compared to the first release (Riahi et al. 2017).

3.2.4 The AR6 Scenario Database

To facilitate this assessment, a large ensemble of scenarios has been collected and made available through an interactive AR6 WGIII scenario database. The collection of the scenario outputs is coordinated by Chapter 3 and expands upon the IPCC SR1.5 scenario explorer (Huppmann et al. 2018; Rogelj et al. 2018a). A complementary database for national pathways has been established by Chapter 4. Annex III.II.3 contains full details on how the scenario database was compiled.

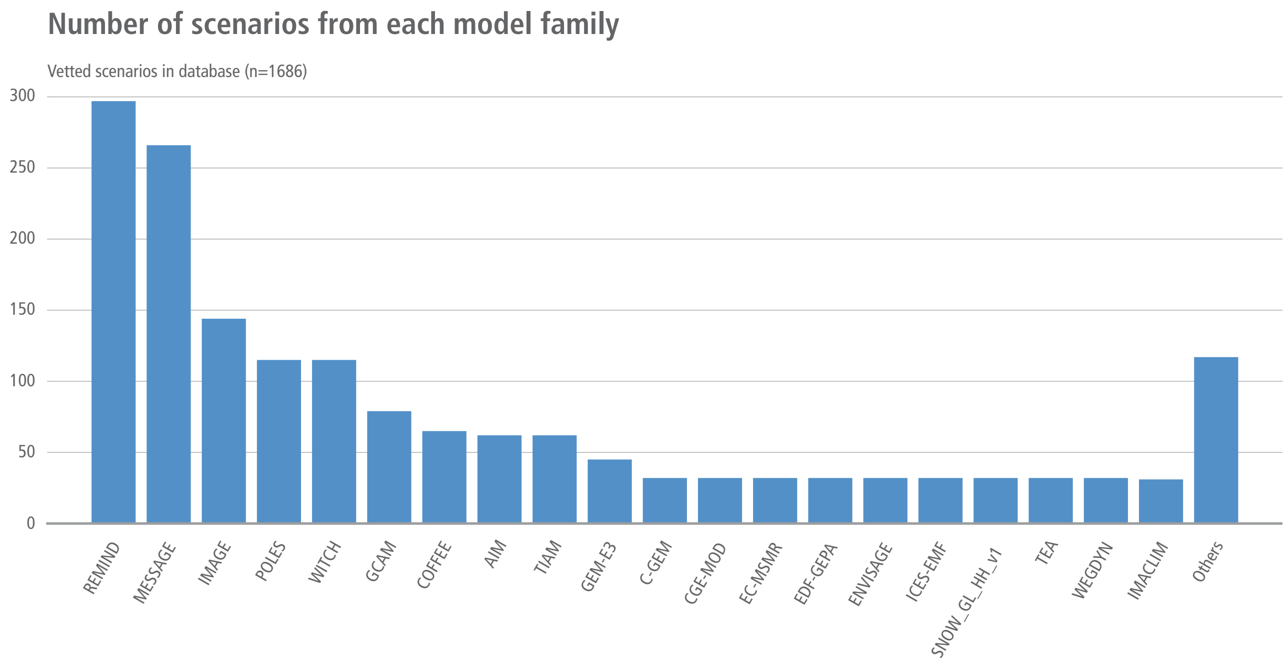


Figure 3.1 | Scenario counts from each model family defined as all versions under the same model's name.

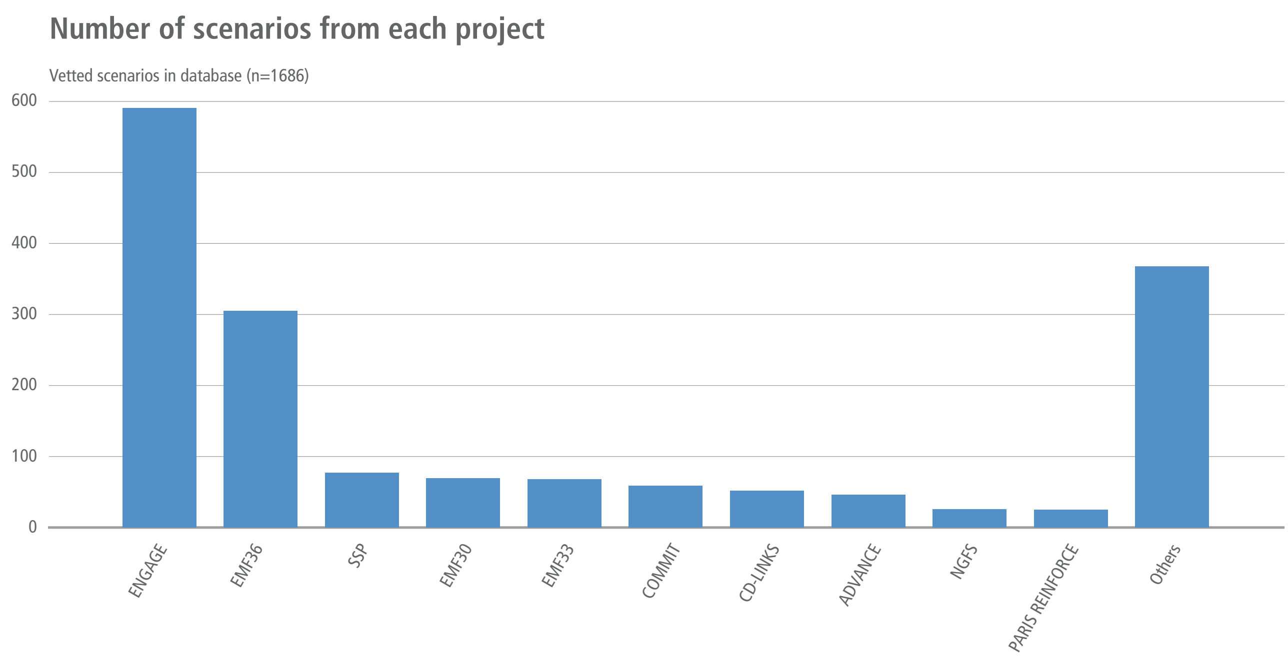


Figure 3.2 | Scenario counts from each named project.

The AR6 scenario database contains 3131 scenarios (Figure 3.5a). After an initial screening and quality control, scenarios were further vetted to assess if they sufficiently represented historical trends (Annex III.II.3.1). Of the initial 2266 scenarios with global scope, 1686 scenarios passed the vetting process and are assessed in this chapter. The scenarios that did not pass the vetting are still available in the database. The vetted scenarios were from over 50 different model families, or over 100 when considering all versions of the same family (Figure 3.1). The scenarios originated from over 15 different model intercomparison projects, with around one-fifth originating from individual studies (Figure 3.2). Because of the uneven distribution of scenarios from different models and projects, uncorrected statistics from the database can be misleading.

Each scenario with sufficient data is given a temperature classification using climate model emulators. Three emulators were used in the assessment: FAIR (Smith et al. 2018), CICERO-SCM (Skeie et al. 2021), MAGICC (Meinshausen et al. 2020). Only the

Table 3.1 | Classification of emissions scenarios into warming levels using MAGICC

Category	Description	WGI SSP	WGIII IP/IMP	Scenarios
C1: Limit warming to 1.5°C (>50%) with no or limited overshoot	Reach or exceed 1.5°C during the 21st century with a likelihood of ≤67%, and limit warming to 1.5°C in 2100 with a likelihood >50%. Limited overshoot refers to exceeding 1.5°C by up to about 0.1°C and for up to several decades.	SSP1-1.9	IMP-SP, IMP-LD, IMP-Ren	**97**
C2: Return warming to 1.5°C (>50%) after a high overshoot	Exceed warming of 1.5°C during the 21st century with a likelihood of >67%, and limit warming to 1.5°C in 2100 with a likelihood of >50%. High overshoot refers to temporarily exceeding 1.5°C global warming by 0.1°C–0.3°C for up to several decades.		IMP-Neg[a]	**133**
C3: ***Limit warming to 2°C (>67%)***	Limit peak warming to 2°C throughout the 21st century with a likelihood of >67%.	SSP1-2.6	IMP-GS	**311**
C4: Limit warming to 2°C (>50%)	Limit peak warming to 2°C throughout the 21st century with a likelihood of >50%.			**159**
C5: Limit warming to 2.5°C (>50%)	Limit peak warming to 2.5°C throughout the 21st century with a likelihood of >50%.			**212**
C6: Limit warming to 3°C (>50%)	Limit peak warming to 3°C throughout the 21st century with a likelihood of >50%.	SSP2-4.5	ModAct	**97**
C7: Limit warming to 4°C (>50%)	Limit peak warming to 4°C throughout the 21st century with a likelihood of >50%.	SSP3-7.0	CurPol	**164**
C8: Exceed warming of 4°C (≥50%)	Exceed warming of 4°C during the 21st century with a likelihood of ≥50%.	SSP5-8.5		**29**
C1, C2, C3: limit warming to 2°C (>67%) or lower	All scenarios in Categories C1, C2 and C3			**541**

[a] The Illustrative Mitigation Pathway 'Neg' has extensive use of carbon dioxide removal (CDR) in the AFOLU, energy and the industry sectors to achieve net negative emissions. Warming peaks around 2060 and declines to below 1.5°C (50% likelihood) shortly after 2100. Whilst technically classified as C3, it strongly exhibits the characteristics of C2 high-overshoot pathways, hence it has been placed in the C2 category. See Box SPM.1 for an introduction of the IPs and IMPs.

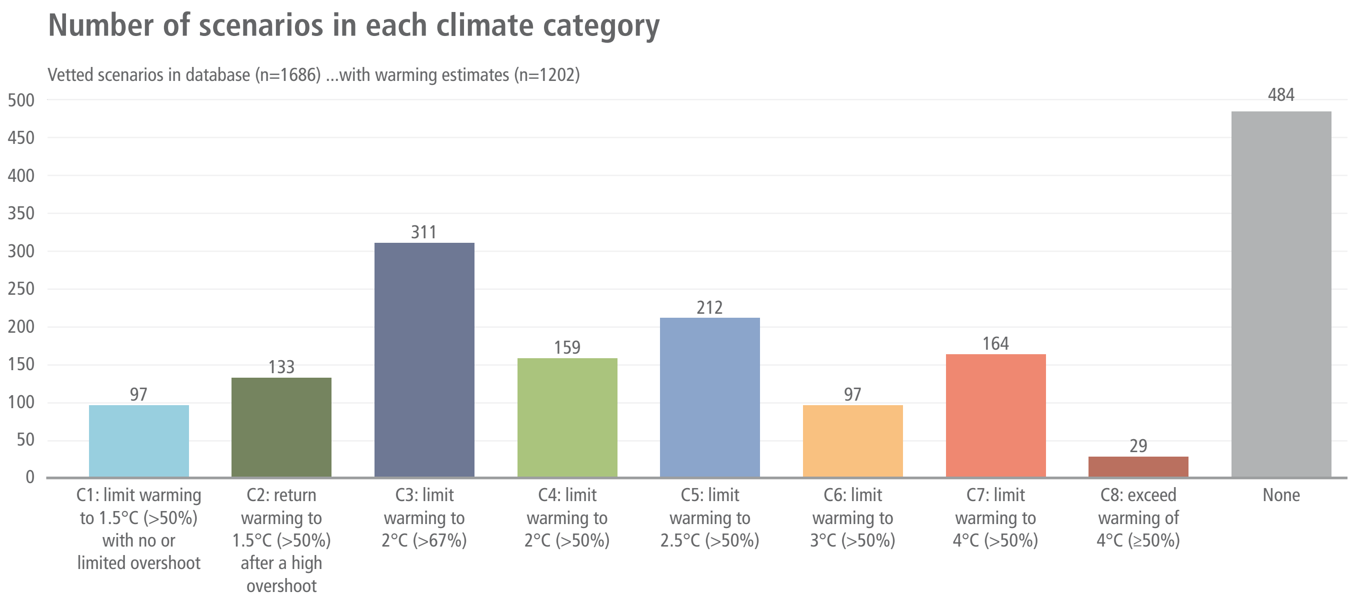


Figure 3.3 | Of the 1686 scenarios that passed vetting, 1202 had sufficient data available to be classified according to temperature, with an uneven distribution across warming levels.

results of MAGICC are shown in this chapter as it adequately covers the range of outcomes. The emulators are calibrated against the behaviour of complex climate models and observation data, consistent with the outcomes of AR6 WGI (Cross-Chapter Box 7.1). The climate assessment is a three-step process of harmonisation, infilling and a probabilistic climate model emulator run (Annex III.II.2.5). Warming projections until the year 2100 were derived for 1574 scenarios, of which 1202 passed vetting, with the remaining scenarios having insufficient information (Figure 3.3 and Table 3.1). For scenarios that limit warming to 2°C or lower, the SR1.5 classification was adopted in AR6, with more disaggregation provided for higher warming levels (Table 3.1).

These choices can be compared with the selection of common global warming levels (GWLs) of 1.5°C, 2°C, 3°C and 4°C to classify climate change impacts in the WGII assessment.

In addition to the temperature classification, each scenario is assigned to one of the following policy categories: (P0) diagnostic scenarios – 99 of 1686 vetted scenarios; (P1) scenarios with no globally coordinated policy (500) and (P1a) no climate mitigation efforts – 124, (P1b) current national mitigation efforts – 59, (P1c) Nationally Determined Contributions (NDCs) – 160, or (P1d) other non-standard assumptions – 153; (P2) globally coordinated climate policies with immediate

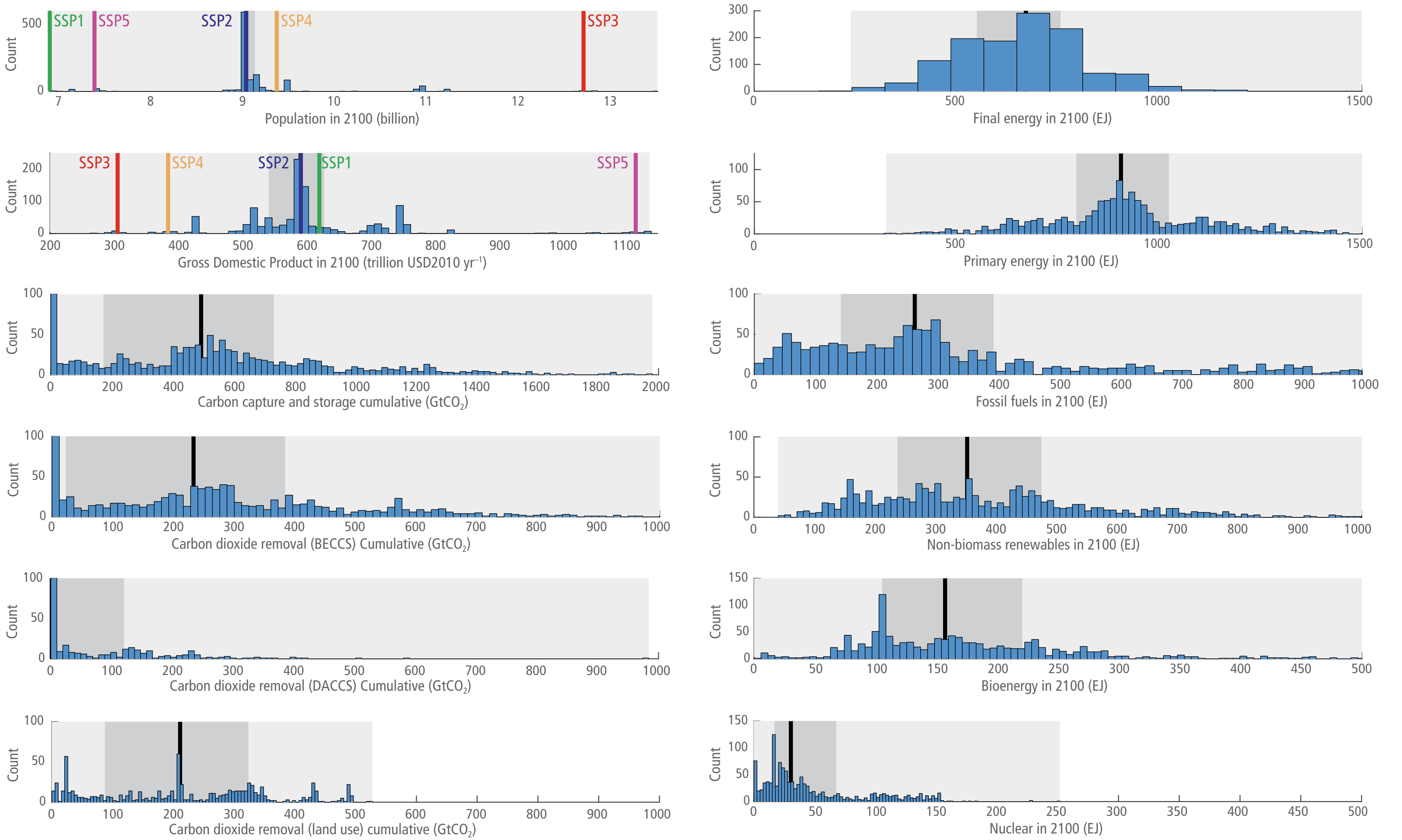


Figure 3.4 | Histograms for key categories in the AR6 scenario database. Only scenarios that passed vetting are shown. For population and GDP, the SSP input data are also shown. The grey shading represents the 0–100% range (light grey), 25–75% range (dark grey), and the median is a black line. The figures with white areas are outside of the scenario range, but the axis limits are retained to allow comparability with other categories. Each sub-figure potentially has different x- and y-axis limits. Each figure also potentially contains different numbers of scenarios, depending on what was submitted to the database. Source: AR6 scenarios database.

action (634) and (P2a) without any transfer of emission permits – 435, (P2b) with transfers – 70; or (P2c) with additional policy assumptions – 55; (P3) globally coordinated climate policies with delayed (i.e., from 2030 onwards or after 2030) action (451), preceded by (P3a) no mitigation commitment or current national policies – 7, (P3b) NDCs – 426, (P3c) NDCs and additional policies – 18; (P4) cost-benefit analysis (CBA) – 2. The policy categories were identified using text pattern matching on the scenario metadata and calibrated on the best-known scenarios from model intercomparisons, with further validation against the related literature, reported emission and carbon price trajectories, and exchanges with modellers. If the information available is enough to qualify a policy category number but not sufficient for a subcategory, then only the number is retained (e.g., P2 instead of P2a/b/c). A suffix added after P0 further qualifies a diagnostic scenario as one of the other policy categories. To demonstrate the diversity of the scenarios, the vetted scenarios were classified into different categories along the dimensions of population, GDP, energy, and cumulative emissions (Figure 3.4). The number of scenarios in each category provides some insight into the current literature, but this does not indicate a higher probability of that category occurring in reality. For population, the majority of scenarios are consistent with the SSP2 'middle of the road' category, with very few scenarios exploring the outer extremes. GDP has a slightly larger variation, but overall most scenarios are around the SSP2 socio-economic assumptions. The level of CCS and CDR is expected to change depending on the extent of mitigation, but there remains extensive use of both CDR and CCS in scenarios. CDR is dominated by bioenergy with CCS (BECCS) and sequestration on land, with relatively few scenarios using direct air capture with carbon storage (DACCS) and even less with enhanced weathering (EW) and other technologies (not shown). In terms of energy consumption, final energy has a much smaller range than primary energy as conversion losses are not included in final energy. Both mitigation and reference scenarios are shown, so there is a broad spread in different energy carriers represented in the database. Bioenergy has a number of scenarios at around 100 EJ, representing a constraint used in many model intercomparisons.

3.2.5 Illustrative Mitigation Pathways

Successive IPCC Assessment Reports (ARs) have used scenarios to illustrate key characteristics of possible climate (policy) futures. In AR5 four RCPs made the basis of climate modelling in WGI and WGII, with WGIII assessing over 1000 scenarios spanning those RCPs (Clarke et al. 2014). Of the over 400 scenarios assessed in SR1.5, four scenarios were selected to highlight the trade-off between short-term emission reductions and long-term deployment of BECCS (Rogelj et al. 2018a), referred to as 'Illustrative Pathways' (IPs). AR6 WGI and WGII rely on the scenarios selected for CMIP6, called ScenarioMIP (O'Neill et al. 2016), to assess warming levels. In addition to the full set of scenarios, AR6 WGIII also uses selected Illustrative Mitigation Pathways (IMPs).

In WGIII, IMPs were selected to denote the implications of different societal choices for the development of future emissions and associated transformations of main GHG-emitting sectors (Figure 3.5a and Box 3.1). The most important function of the IMPs is to illustrate key themes that form a common thread in the report, both with a storyline and a quantitative illustration. The storyline describes the key characteristics that define an IMP. The quantitative versions of the IMPs provide numerical values that are internally consistent and comparable across chapters of the report. The quantitative IMPs have been selected from the AR6 scenario database. No assessment of the likelihood of each IMP has been made.

The selected scenarios (IPs) are divided into two sets (Figures 3.5 and 3.6): two reference pathways illustrative of high emissions and five Illustrative Mitigation Pathways (IMPs). The narratives are explained in full in Annex III.II.2.4. The two reference pathways explore the consequences of current policies and pledges: Current Policies (*CurPol*) and Moderate Action (*ModAct*). The *CurPol* pathway explores the consequences of continuing along the path of implemented climate policies in 2020 and only a gradual strengthening after that. The scenario illustrates the outcomes of many scenarios in the literature that project the trend from implemented policies until the end of 2020. The *ModAct* pathway explores the impact of implementing the Nationally Determined Contributions (NDCs) as formulated in 2020 and some further strengthening after that. In line with current literature, these two reference pathways lead to an increase in global mean temperature of more than 2°C (Section 3.3).

The Illustrative Mitigation Pathways (IMPs) properly explore different pathways consistent with meeting the long-term temperature goals of the Paris Agreement. They represent five different pathways that emerge from the overall assessment. The IMPs differ in terms of their focus, for example, placing greater emphasis on renewables (IMP-Ren), deployment of carbon dioxide removal that results in net negative global GHG emissions (IMP-Neg), and efficient resource use and shifts in consumption patterns, leading to low demand for resources, while ensuring a high level of services (IMP-LD). Other IMPs illustrate the implications of a less rapid introduction of mitigation measures followed by a subsequent gradual strengthening (IMP-GS), and how shifting global pathways towards sustainable development, including by reducing inequality, can lead to mitigation (IMP-SP) In the IMP framework, *IMP-GS* is consistent with limiting warming to 2°C (>67%) (C3), *IMP-Neg* shows a strategy that also limits warming to 2°C (>67%) but returns to nearly 1.5°C (>50%) by the end of the century (hence indicated as C2*). The other variants that can limit warming to 1.5°C (>50%) (C1) were selected. In addition to these IMPs, sensitivity cases that explore alternative warming levels (C3) for *IMP-Neg* and *IMP-Ren* are assessed (*IMP-Neg-2.0* and *IMP-Ren-2.0*).

The IMPs are selected to have different mitigation strategies, which can be illustrated looking at the energy system and emission pathways (Figure 3.7 and Figure 3.8). The mitigation strategies show the different options in emission reduction (Figure 3.7). Each panel shows the key characteristics leading to total GHG emissions, consisting of residual (gross) emissions (fossil CO_2 emissions, CO_2 emissions from industrial processes, and non-CO_2 emissions) and removals (net land-use change, bioenergy with carbon capture and storage – BECCS, and direct air carbon capture and storage – DACCS), in addition to avoided emissions through the use of carbon capture and storage on fossil fuels. The *IMP-Neg* and *IMP-GS* scenarios were shown to illustrate scenarios with a significant role of CDR. The energy supply (Figure 3.8) shows the phase-out of fossil fuels in the *IMP-LD*, *IMP-Ren* and *IMP-SP* cases, but a less substantial decrease in the *IMP-Neg* case. The *IMP-GS* case

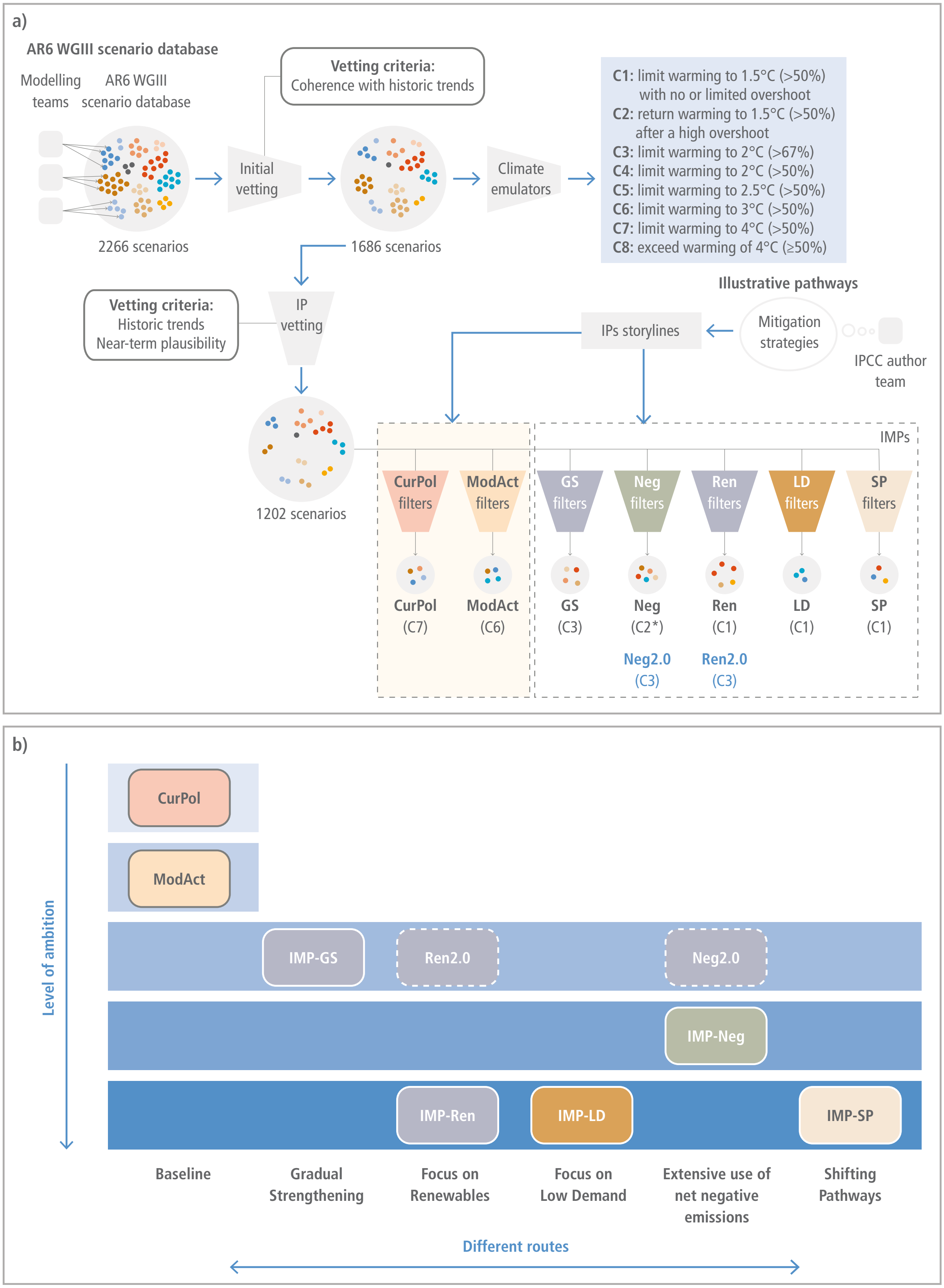


Figure 3.5 | (a) Process for creating the AR6 scenario database and selecting the illustrative (mitigation) pathways. The compiled scenarios in the AR6 scenarios database were vetted for consistency with historical statistics and subsequently a temperature classification was added using climate model emulators. The illustrative (mitigation) pathways were selected from the full set of pathways based on storylines of critical mitigation strategies that emerged from the assessment. **(b)** An overview of the Illustrative Pathways selected for use in IPCC AR6 WGIII, consisting of pathways illustrative of higher emissions, Current Policies (*CurPol*) and Moderate Action (*ModAct*), and Illustrative Mitigation Pathways (IMPs): gradual strengthening of current policies (*IMP-GS*), extensive use of net negative emissions (*IMP-Neg*), renewables (*IMP-Ren*), low demand (*IMP-LD*), and shifting pathways (*IMP-SP*). The Ren2.0 and Neg2.0 scenarios are alternative scenarios to the IMPs. These pathways are based on renewables and extensive use of negative emissions, respectively, but leading to temperature levels comparable to the C3 category and have sometimes been used for comparison.

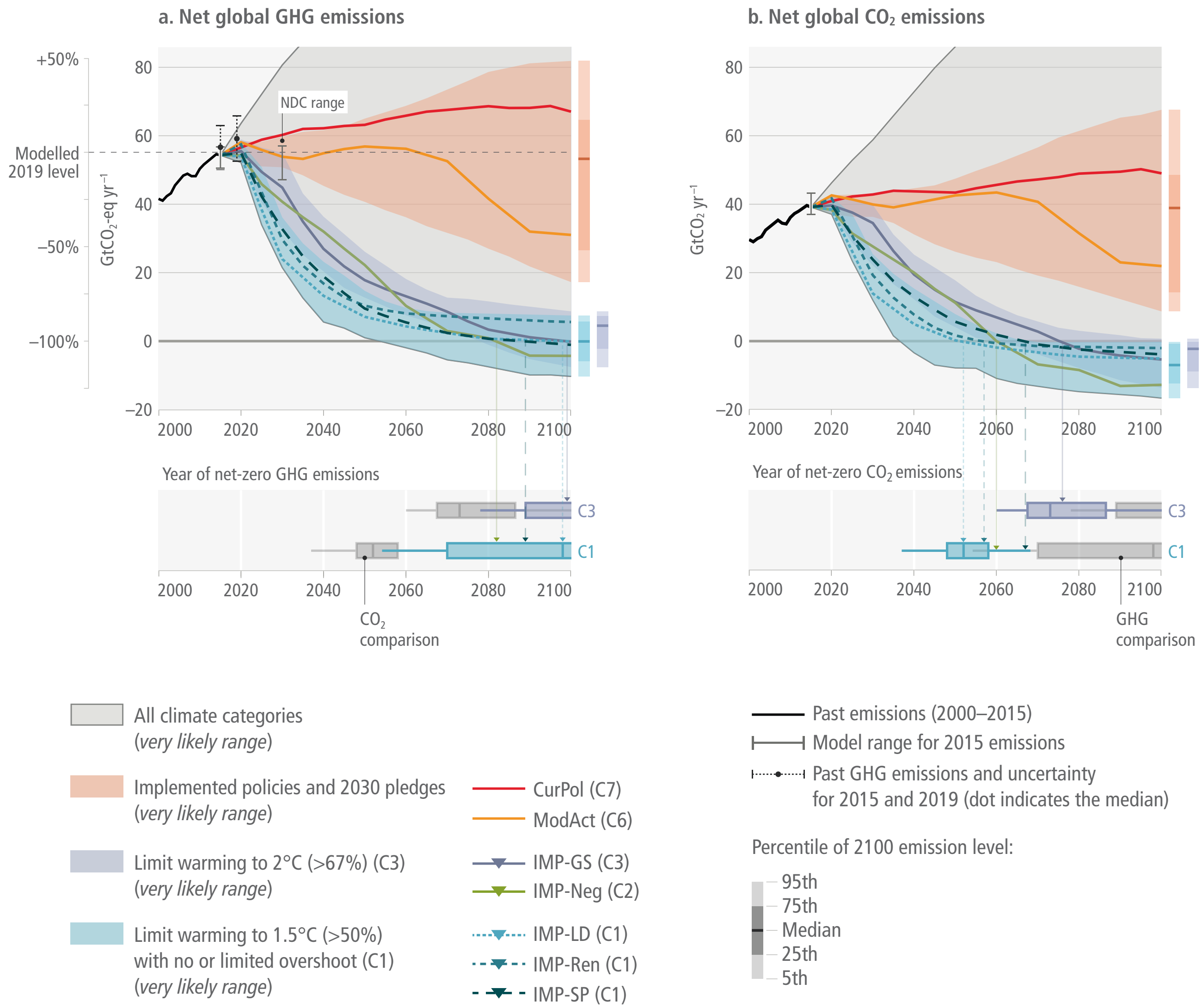


Figure 3.6 | Overview of the net CO_2 emissions and Kyoto greenhouse gas (GHG) emissions for each Illustrative Mitigation Pathway (IMP).

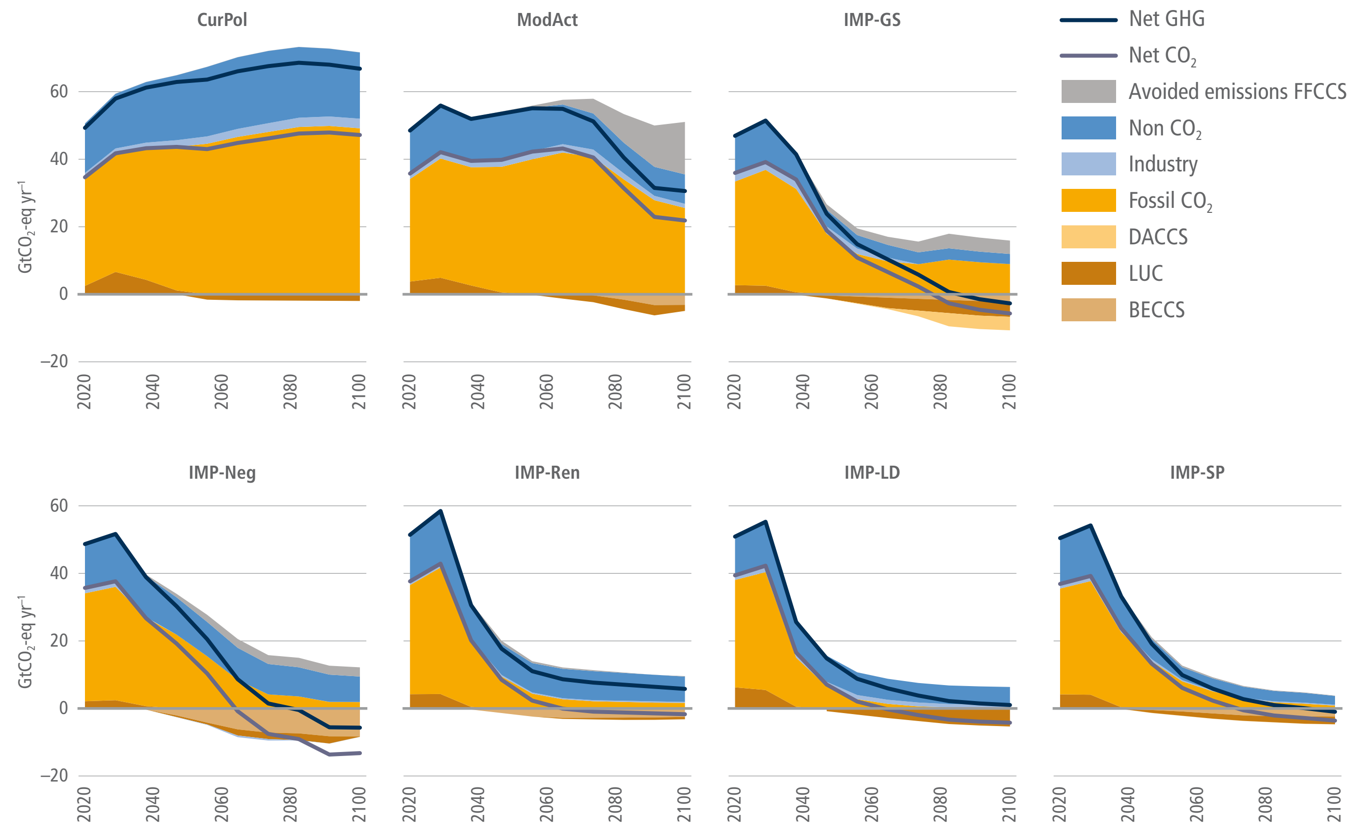


Figure 3.7 | The residual fossil fuel and industry emissions, carbon dioxide removal (CDR) {LUC, DACCS, BECCS}, and non-CO_2 emissions (using AR6 GWP-100) for each of the seven illustrative pathways (IPs). Fossil CCS is also shown, though this does not lead to emissions to the atmosphere (Section 3.2.5).

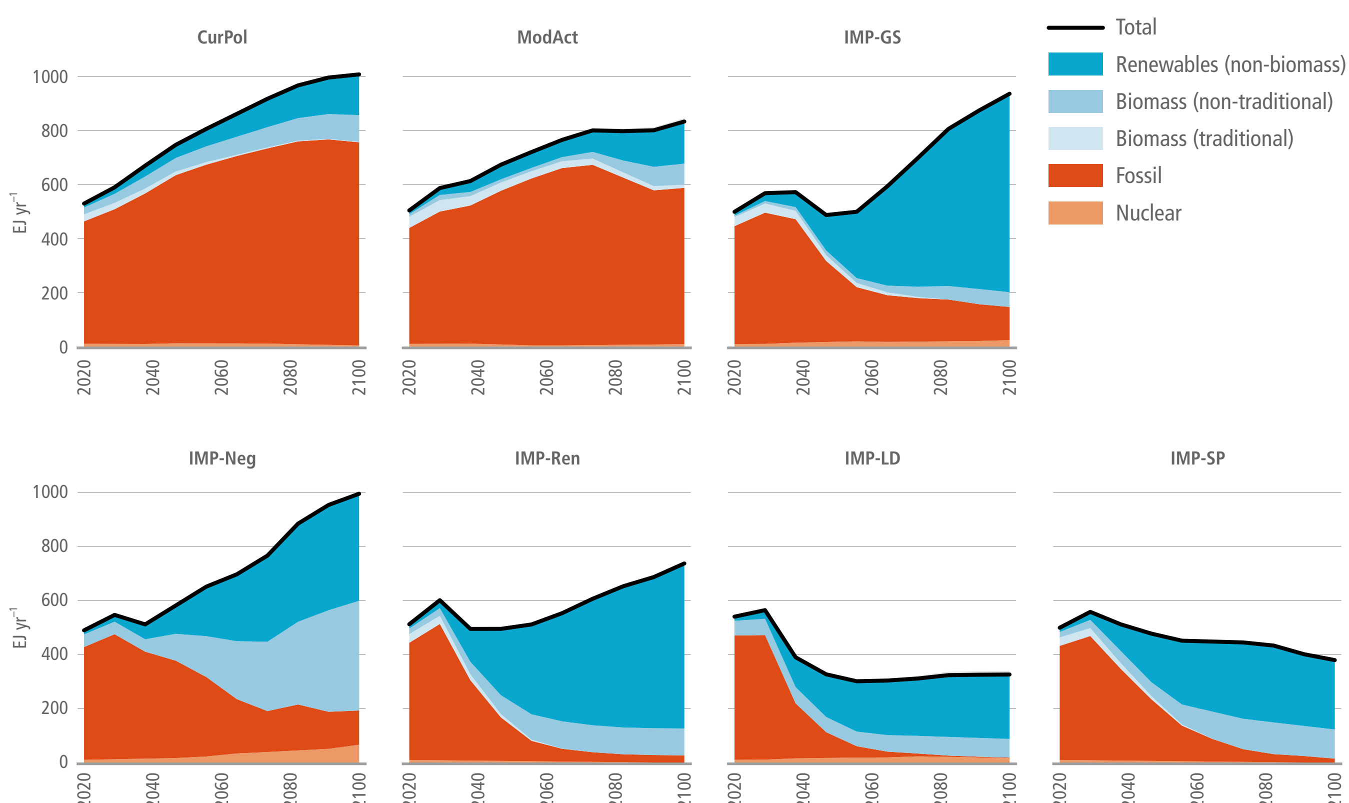


Figure 3.8 | The energy system in each of the illustrative pathways (IPs).

needs to make up its slow start by (i) rapid reductions mid-century and (ii) massive reliance on net negative emissions by the end of the century. The *CurPol* and *ModAct* cases both result in relatively high emissions, showing a slight increase and stabilisation compared to current emissions, respectively.

3.3 Emission Pathways, Including Socio-economic, Carbon Budget and Climate Responses Uncertainties

3.3.1 Socio-economic Drivers of Emissions Scenarios

Greenhouse gas (GHG) emissions mainly originate from the use and transformation of energy, agriculture, land use (change) and industrial activities. The future development of these sources is influenced by trends in socio-economic development, including population, economic activity, technology, politics, lifestyles, and climate policy. Trends for these factors are not independent, and scenarios provide a consistent outlook for these factors together (Section 3.2). Marangoni et al. (2017) show that in projections, assumptions influencing energy intensity (e.g., structural change, lifestyle and efficiency) and economic growth are the most important determinants of future CO_2 emissions from energy combustion. Other critical factors include technology assumptions, preferences, resource assumptions and policy (van Vuuren et al. 2008). As many of the factors are represented differently in specific models, the model itself is also an important factor – providing a reason for the importance of model diversity (Sognnaes et al. 2021). For land use, Stehfest et al. (2019) show that assumptions on population growth are more dominant given that variations in per capita consumption of food are smaller than for energy. Here, we only provide a brief overview of some key drivers. We focus first on so-called reference scenarios (without stringent climate policy) and look at mitigation scenarios in detail later. We use the SSPs to discuss trends in more detail. The SSPs were published in 2017, and by now, some elements will have to be updated (O'Neill et al. 2020b). Still, the ranges represent the full literature relatively well.

Historically, population and GDP have been growing over time. Scenario studies agree that further global population growth is likely up to 2050, leading to a range of possible outcomes of around 8.5–11 billion people (Figure 3.9a). After 2050, projections show a much wider range. If fertility drops below replacement levels, a decline in the global population is possible (as illustrated by SSP1 and SSP5). This typically includes scenarios with rapid development and investment in education. However, median projections mostly show a stabilisation of the world population (e.g., SSP2), while high-end projections show a continued growth (e.g., SSP3). The UN Population Prospects include considerably higher values for both the medium projection and the high end of the range than the SSP scenarios (KC and Lutz 2017; UN 2019). The most recent median UN projection reaches almost 11 billion people in 2100. The key differences are in Africa and China: here, the population projections are strongly influenced by the rate of fertility change (faster drop in SSPs). Underlying these differences, the UN approach is more based on current demographic trends while the SSPs assume a broader range of factors (including education) driving future fertility.

Economic growth is even more uncertain than the population projections (Figure 3.9c). The average growth rate of GDP was about 2.8% per year (constant USD) in the 1990–2019 period (The World Bank 2021). In 2020, the COVID-19 crisis resulted in a considerable drop in GDP (estimated around 4–5%) (IMF 2021). After a recovery period, most economic projections assume growth rates to converge back to previous projections, although at a lower level (IMF 2021; OECD 2021) (see also Box 3.2). In the long term, assumptions on future growth relate to political stability, the role of the progress of the technology frontier and the degree to which countries can catch up (Johansson et al. 2013). The SSP scenarios cover an extensive range, with low per-capita growth in SSP3 and SSP4 (mostly in developing countries) and rapid growth in SSP1 and SSP5. At the same, however, also scenarios outside the range have some plausibility – including the option of economic decline (Kallis et al. 2012) or much faster economic development (Christensen et al. 2018). The OECD long-term projection is at the global level reasonably consistent with SSP2. Equally important economic parameters include income distribution (inequity) and the type of growth (structural change, i.e., services vs manufacturing industries). Some projections (like SSP1) show a considerable convergence of income levels within and across countries, while in other projections, this does not occur (e.g., SSP3). Most scenarios reflect the suggested inverse relationship between the assumed growth rate for income and population growth (Figure 3.9e). SSP1 and SSP5 represent examples of scenarios with relatively low population increase and relatively high-income increase over the century. SSP3 represents an example of the opposite – while SSP2 and SSP4 are placed more in the middle. Nearly all scenarios assessed here do not account for climate impacts on growth (mostly for methodological reasons). As discussed in Section 3.5 these impacts can be considerable. An emerging area of literature emphasises the possibility of stabilisation (or even decline) of income levels in developed countries, arguing that such a trend would be preferred or even needed for environmental reasons (Anderson and Larkin 2013; Hickel and Kallis 2020; Kallis et al. 2020; Hickel et al. 2021; Keyßer and Lenzen 2021) (see also Chapter 5). Such scenarios are not common among IAM outcomes, that are more commonly based on the idea that decarbonisation can be combined with economic growth by a combination of technology, lifestyle and structural economic changes. Still, such scenarios could result in a dramatic reduction of energy and resource consumption.

Scenarios show a range of possible energy projections. In the absence of climate policy, most scenarios project the final energy demand to continue to grow to around 650–800 EJ yr^{-1} in 2100 (based on the AR6 Scenarios Database, Figure 3.9b). Some projections show a very high energy demand up to 1000 EJ yr^{-1} (comparable to SSP5). The scenario of the IEA lies within the SSP range but near the SSP1 projection. However, it should be noted that the IEA scenario includes current policies (most reference scenarios do not) and many scenarios published before 2021 did not account for the COVID-19 crisis. Several researchers discuss the possibility of decoupling material and energy demand from economic growth in the literature, mainly in developed countries (Kemp-Benedict 2018) (decoupling here refers to either a much slower increase in demand or even a decrease). In the scenario literature, this is reflected by scenarios with very low demand for final energy based on increased energy efficiency and less energy-intensive lifestyles (e.g., SSP1 and the LED scenario) (Grubler et al. 2018; van Vuuren et al. 2018). While these studies show the feasibility of such

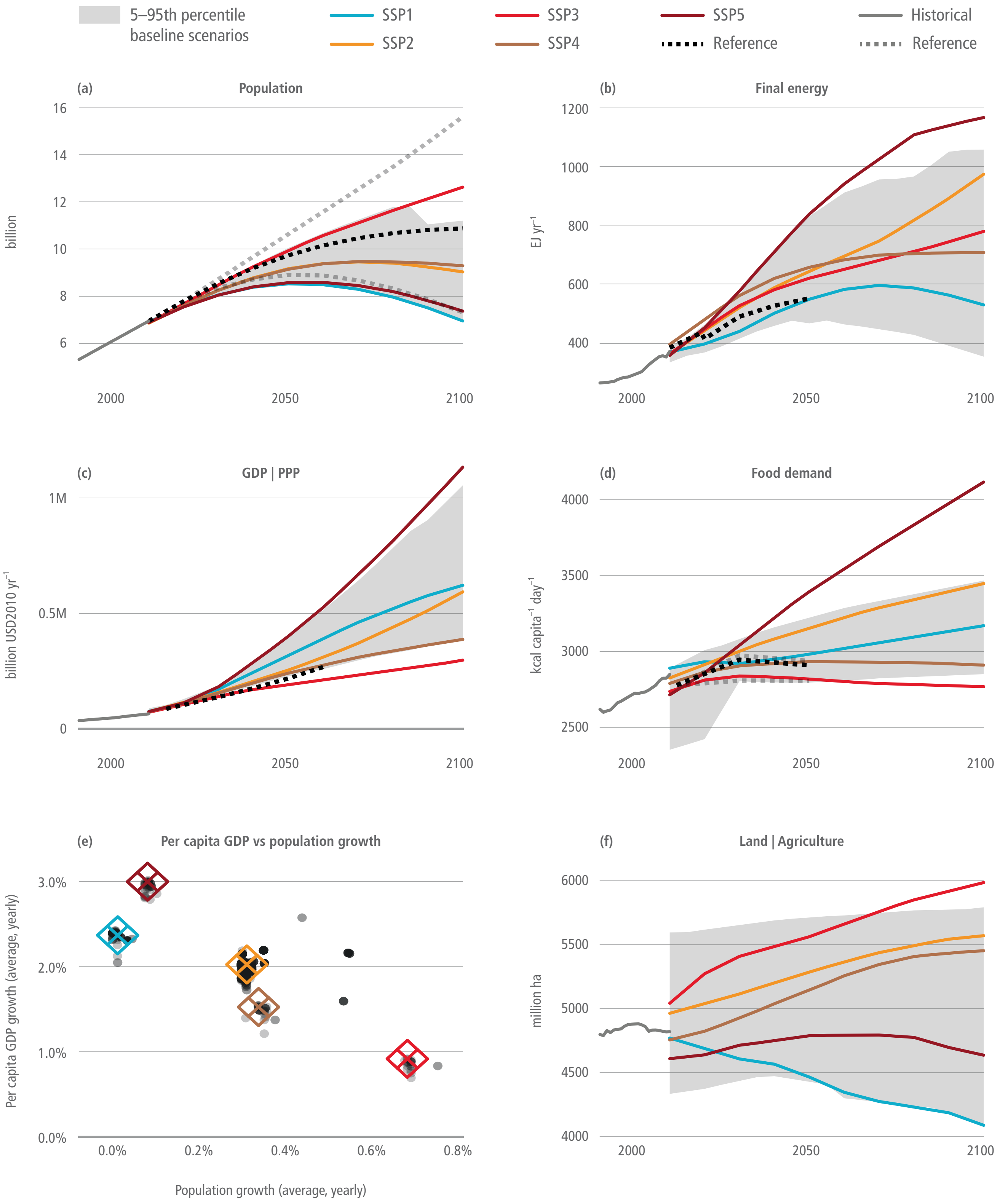


Figure 3.9 | Trends in key scenario characteristics and driving forces as included in the SSP scenarios (showing 5–95th percentiles of the reference scenarios as included in the database in grey shading). Reference (dotted lines) refers to the UN low-, medium- and high-population scenarios (UN 2019), the OECD long-term economic growth scenario (OECD 2021), the scenarios from the IEA's World Energy Outlook (IEA 2019), and the scenarios in the FAO assessment (FAO 2018).

pathways, their energy efficiency improvement rates are considerably above the historic range of around 2% (Gütschow et al. 2018; Jeffery et al. 2018; Vrontisi et al. 2018; Haberl et al. 2020; Roelfsema et al. 2020; Giarola et al. 2021; Höhne et al. 2021; IEA 2021a; Höhne et al. 2021; Sognnaes et al. 2021). These scenarios also show clear differences in food consumption and the amount of land used for agriculture. Food demand in terms of per-capita caloric intake is projected to increase in most scenarios (Figure 3.9d). However, it should be noted that there are large differences in dietary composition across the scenarios (from more meat-intensive in scenarios such as SSP5 to a decrease in meat consumptions in other scenarios such as SSP1). Land-use projections also depend on assumed changes in yield and the population scenarios (Figure 3.9f). Typically, changes in land use are less drastic than some other parameters (in fact, the 5–95th percentile database range is almost stable). Agriculture land is projected to increase in SSP3, SSP2, and SSP4 – it is more-or-less stable in SSP5 and is projected to decline in SSP1.

3.3.2 Emission Pathways and Temperature Outcomes

3.3.2.1 Overall Mitigation Profiles and Temperature Consequences

Figure 3.10 shows the GHG and CO_2 emission trajectories for different temperature categories as defined in Section 3.2 (the temperature levels are calculated using simple climate models, consistent with the outcomes of the recent WGI assessment, Cross-Chapter Box 7.1). It should be noted that most scenarios currently in the literature do not account for the impact of COVID-19 (Box 3.2).

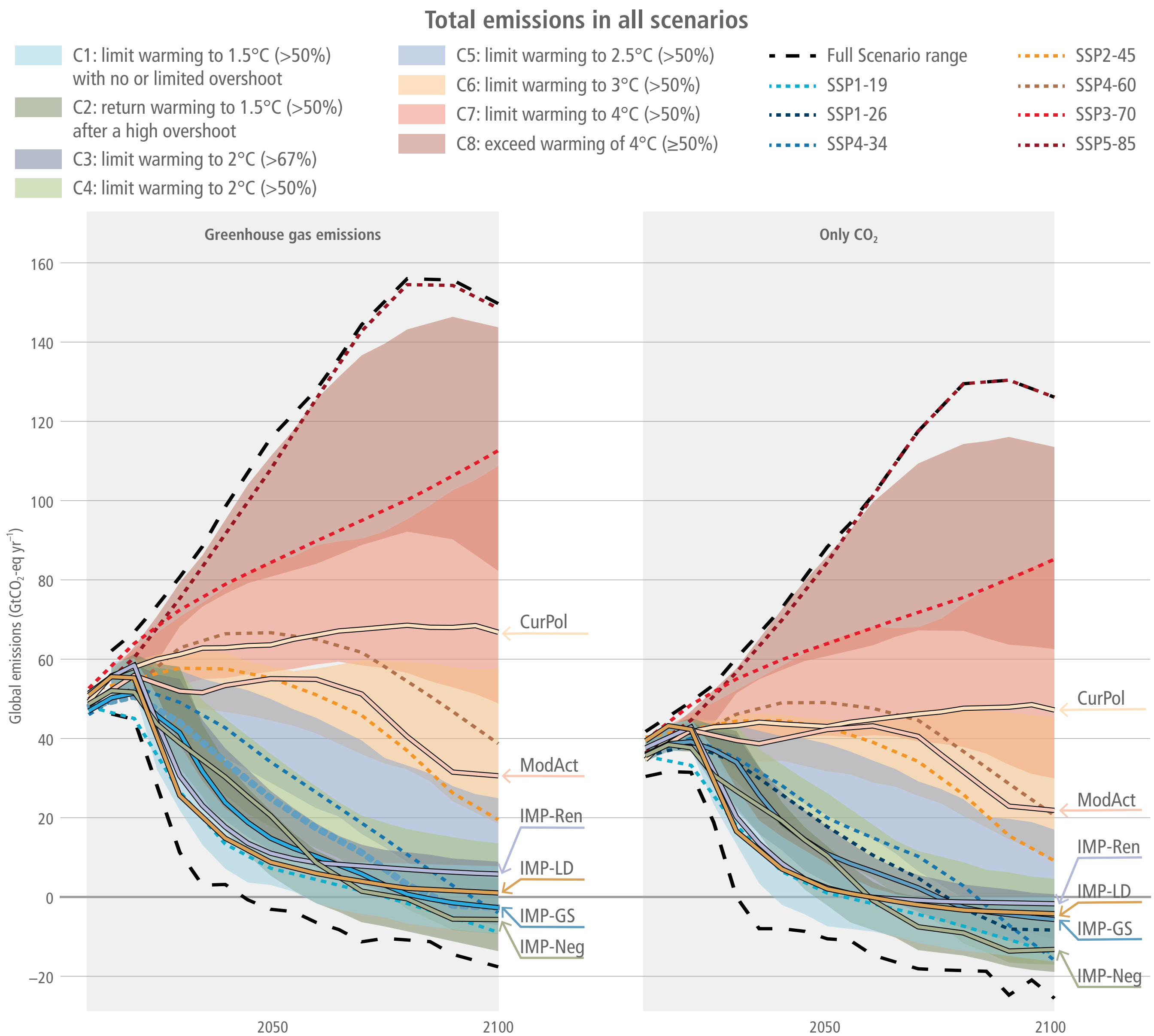


Figure 3.10 | Total emissions profiles in the scenarios based on climate category for GHGs (AR6 GWP-100) and CO_2. The Illustrative mitigation pathways (IMPs) are also indicated.

Box 3.2 | Impact of COVID-19 on Long-term Emissions

The reduction in CO_2 emissions of the COVID-19 pandemic in 2020 was estimated to be about 6% (Section 4.2.2.4 and Table 4.SM.2) lower than 2019 levels (Forster et al. 2020; Friedlingstein et al. 2020; Liu et al. 2020c; BP 2021; Crippa et al. 2021; IEA 2021; Le Quéré et al. 2021). Near-real-time monitoring estimates show a rebound in emissions levels, meaning 2021 emissions levels are expected to be higher than 2020 (Le Quéré et al. 2021). The longer-term effects are uncertain but so far do not indicate a clear structural change for climate policy related to the pandemic. The increase in renewable shares in 2020 could stimulate a further transition, but slow economic growth can also slow down (renewable) energy investments. Also, lifestyle changes during the crisis can still develop in different directions (working from home, but maybe also living further away from work). Without a major intervention, most long-term scenarios project that emissions will start to follow a similar pathway as earlier projections (although at a reduced level) (IEA 2020b; Kikstra et al. 2021a; Rochedo et al. 2021). If emissions reductions are limited to only a short time, the adjustment of pathways will lead to negligible outcomes in the order of 0.01K (Forster et al. 2020; Jones et al. 2021). At the same time, however, the large amount of investments pledged in the recovery packages could provide a unique opportunity to determine the long-term development of infrastructure, energy systems and land use (Andrijevic et al. 2020b; Hepburn et al. 2020; Pianta et al. 2021). Near-term alternative recovery pathways have been shown to have the potential to influence carbon-price pathways, and energy investments and electrification requirements under stringent mitigation targets (Bertram et al. 2021; Kikstra et al. 2021a; Pollitt et al. 2021; Rochedo et al. 2021; Shan et al. 202). Most studies suggest a noticeable reduction in 2030 emissions. However, much further reductions would be needed to reach the emission levels consistent with mitigation scenarios that limit warming to 2°C (>67%) or lower (see Chapter 4). At the moment, the share of investments in greenhouse gas reduction is relatively small in most recovery packages, and no structural shifts for climate policies are observed linked to the pandemic. Finally, most of the scenarios analysed in this Chapter do not include the 2020 emissions reduction related to the COVID-19 pandemic. The effect of the pandemic on the pathways will likely be very small. The assessment of climate mitigation pathways in this chapter should be interpreted as being almost exclusively based on the assumption of a fast recovery with limited persistent effects on emissions or structural changes.

The higher categories (C6 and C7) mostly included scenarios with no or modest climate policy. Because of the progression of climate policy, it is becoming more common that reference scenarios incorporate implemented climate policies. Modelling studies typically implement current or pledged policies up until 2030 (Vrontisi et al. 2018; Roelfsema et al. 2020; Sognnaes et al. 2021) with some studies focusing also on the policy development in the long term (Höhne et al. 2021; IEA 2021a; Jeffery et al. 2018; Gütschow et al. 2018). Based on the assessment in Chapter 4, reference pathways consistent with the implementation and trend from implemented policies until the end of 2020 are associated with increased GHG emissions from 59 (53–65) $GtCO_2$-eq yr^{-1} in 2019 to 54–60 $GtCO_2$-eq yr^{-1} by 2030 and to 47–67 $GtCO_2$-eq yr^{-1} by 2050 (Figure 3.6). Pathways with these near-term emissions characteristics lead to a median global warming of 2.2°C to 3.5°C by 2100 (see also further in this section). These pathways consider policies at the time that they were developed. A recent model comparison that harmonised socio-economic, technological, and policy assumptions (Giarola et al. 2021) found a 2.2°C–2.9°C median temperature rise in 2100 for current and stated policies, with the results sensitive to the model used and the method of implementing policies (Sognnaes et al. 2021). Scenario inference and construction methods using similar policy assumptions lead to a median range of 2.9°C–3.2°C in 2100 for current policies and 2.4°C–2.9°C in 2100 for 2030 pledges (Höhne et al. 2021). The median spread of 1°C across these studies (2.2°C–3.2°C) indicates the deep uncertainties involved with modelling temperature outcomes of 2030 policies through to 2100 (Höhne et al. 2021).

The lower categories include increasingly stringent assumed climate policies. For all scenario categories, except the highest category, emissions peak in the 21st century. For the lowest categories, the emissions peak is mostly before 2030. In fact, for scenarios in the category that avoids temperature overshoot for the 1.5°C scenario (C1 category), GHG emissions are reduced already to almost zero around the middle of the century. Typically, CO_2 emissions reach net zero about 10 to 40 years before total GHG emissions reach net zero. The main reason is that scenarios reduce non-CO_2 greenhouse gas emissions less than CO_2 due to a limited mitigation potential (Section 3.3.2.2). Figure 3.10 also shows that many scenarios in the literature with a temperature outcome below 2°C show net negative emissions. There are, however, also exceptions in which more immediate emission reductions limits the need for CDR. The IMPs illustrate alternative pathways to reach the C1–C3 temperature levels.

Figure 3.11 shows the possible consequences of the different scenario categories for global mean temperature calculated using a reduced complexity model (RCM) calibrated to the IPCC AR6 WGI assessment (see Annex III.II.2.5 of this report and Cross-Chapter Box 7.1 in AR6 WGI report). For the C5–C7 categories (containing most of the reference and current policy scenarios), the global mean temperature is expected to increase throughout the century (and further increase will happen after 2100 for C6 and C7). While warming would *more likely than not* be in the range from 2.2°C to 3.5°C, warming up to 5°C cannot be excluded. The highest emissions scenarios in the literature combine assumptions about rapid long-term economic growth and pervasive climate policy failures, leading to a reversal of some recent trends (Box 3.3). For the categories C1–C4, a peak in global mean temperature is reached mid-century for most scenarios in the database, followed by a small (C3/C4) or more considerable decline (C1/C2). There is a clear distinction between the scenarios with no or

Box 3.3 | The Likelihood of High-end Emissions Scenarios

At the time the Representative Concentration Pathways (RCPs) were published, they included three scenarios that could represent emission developments in the absence of climate policy: RCP4.5, RCP6 and RCP8.5, described as, respectively, low, medium and high-end scenarios in the absence of strong climate policy (van Vuuren et al. 2011). RCP8.5 was described as representative of the top 5% scenarios in the literature. The SSPs-based set of scenarios covered the RCP forcing levels, adding a new low scenario (at 1.9 W m^{-2}). Hausfather and Peters (2020) pointed out that since 2011, the rapid development of renewable energy technologies and emerging climate policy have made it considerably less likely that emissions could end up as high as RCP8.5. Still, emission trends in developing countries track RCP8.5 Pedersen et al. (2020), and high land-use emissions could imply that emissions would continue to do so in the future, even at the global scale (Schwalm et al. 2020). Other factors resulting in high emissions include higher population or economic growth as included in the SSPs (Section 3.3.1) or rapid development of new energy services. Climate projections of RCP8.5 can also result from strong feedbacks of climate change on (natural) emission sources and high climate sensitivity (AR6 WGI Chapter 7), and therefore their median climate impacts might also materialise while following a lower emission path (e.g., Hausfather and Betts 2020). The discussion also relates to a more fundamental discussion on assigning likelihoods to scenarios, which is extremely difficult given the deep uncertainty and direct relationship with human choice. However, it would help to appreciate certain projections (e.g., Ho et al. 2019). All in all, this means that high-end scenarios have become considerably less likely since AR5 but cannot be ruled out. It is important to realise that RCP8.5 and SSP5-8.5 do not represent a typical 'business-as-usual' projection but are only useful as high-end, high-risk scenarios. Reference emission scenarios (without additional climate policy) typically end up in the C5–C7 categories included in this assessment.

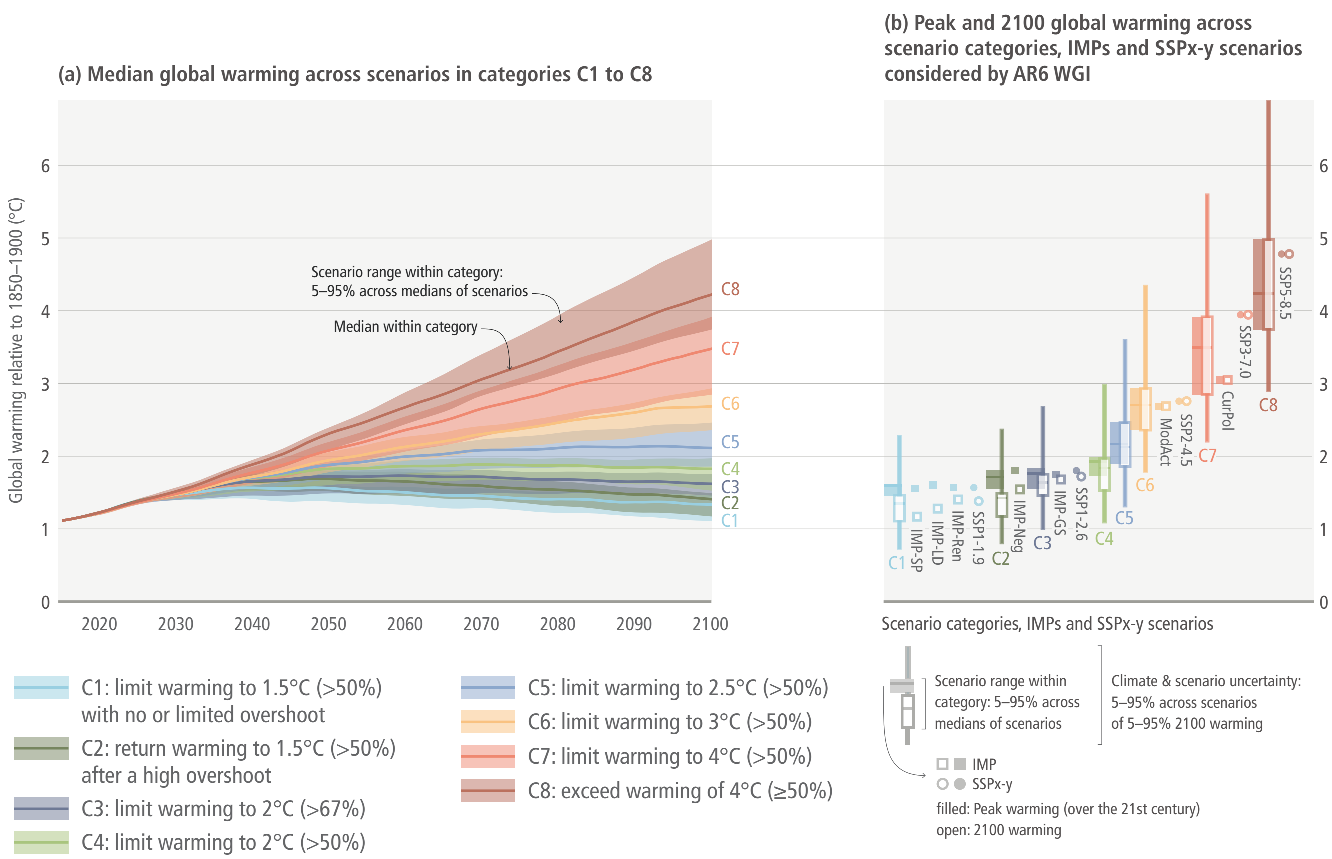


Figure 3.11 | Global mean temperature outcome of the ensemble of scenarios included in the climate categories C1–C8 (based on a reduced complexity model – RCM – calibrated to the WGI assessment, both in terms of future and historic warming). The left panel shows the ranges of scenario uncertainty (shaded area) with the P50 RCM probability (line). The right panel shows the P5 to P95 range of combined RCM climate uncertainty (C1–C8 is explained in Table 3.1) and scenario uncertainty, and the P50 (line).

limited overshoot (typically <0.1°C, C1) compared to those with high overshoot (C2): in emissions, the C1 category is characterised by steep early reductions and a relatively small contribution of net negative emissions (like *IMP-LD* and *IMP-Ren*) (Figure 3.10). In addition to the temperature caused by the range of scenarios in each category (main panel), climate uncertainties also contribute to a range of temperature outcomes (including uncertainties regarding the carbon cycle, climate sensitivity, and the rate of change, see AR6 WGI). The bars on the right of Figure 3.11 show the uncertainty range for each category (combining scenario and climate uncertainty). While the C1 category *more likely than not* limits warming to 1.5°C (>50%) by the end of the century, even with such a scenario, warming above 2°C cannot be excluded (95th percentile). The uncertainty range for the highest emission categories (C7) implies that these scenarios could lead to a warming above 6°C.

3.3.2.2 The Role of Carbon Dioxide and Other Greenhouse Gases

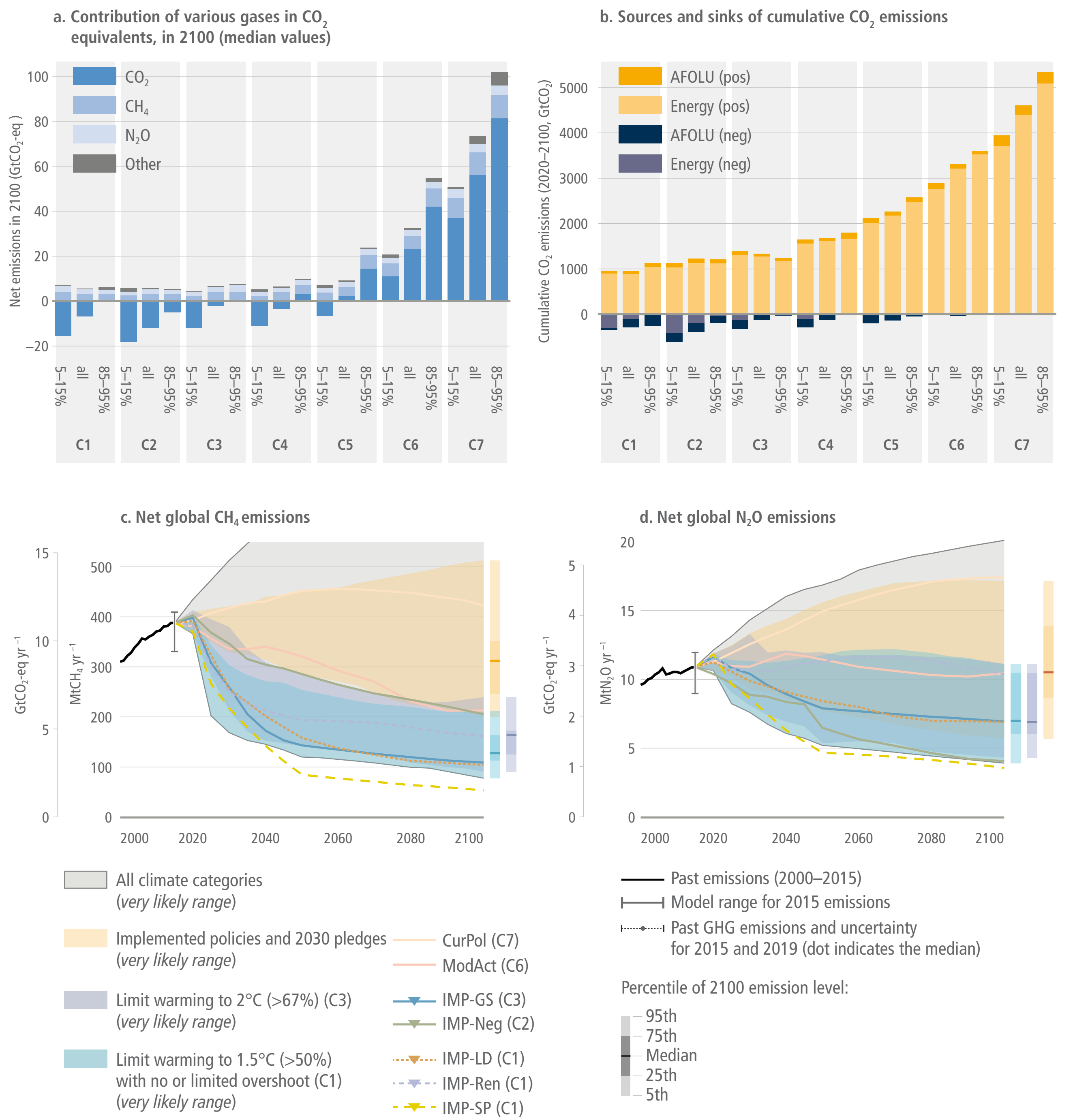


Figure 3.12 | (a) The role of CO_2 and other greenhouse gases. Emission in CO_2-eq in 2100 (using AR6 GWP-100) (other = halogenated gases) and **(b)** cumulative CO_2 emissions in the 2020–2100 period. Panels **(c)** and **(d)** show the development of CH_4 and N_2O emissions over time. Energy emissions include the contribution of BECCS. For both energy and AFOLU sectors, the positive and negative values represent the cumulated annual balances. In both panels, the three bars per scenario category represent the lowest 5–15th percentile, the average value and the highest 5–15th percentile. These illustrate the range of scenarios in each category. The definition of C1–C7 can be found in Table 3.1.

The trajectory of future CO_2 emissions plays a critical role in mitigation, given CO_2 long-term impact and dominance in total greenhouse gas forcing. As shown in Figure 3.12, CO_2 dominates total greenhouse gas emissions in the high-emissions scenarios but is also reduced most, going from scenarios in the highest to lower categories. In C4 and below, most scenarios exhibit net negative CO_2 emissions in the second half of the century compensating for some of the residual emissions of non-CO_2 gases as well as reducing overall warming from an intermediate peak. Still, early emission reductions and further reductions in non-CO_2 emissions can also lead to scenarios without net negative emissions in 2100, even in C1 and C3 (shown for the 85–95th percentile). In C1, avoidance of significant overshoot implies that immediate gross reductions are more relevant than long-term net negative emissions (explaining the lower number than in C2) but carbon dioxide removal (CDR) is still playing a role in compensating for remaining positive emissions in hard-to-abate sectors.

CH_4 and N_2O emissions are also reduced from C7 to C1, but this mostly occurs between C7 and C5. The main reason is the characteristics of abatement potential: technical measures can significantly reduce CH_4 and N_2O emissions at relatively low costs to about 50% of the current levels (e.g., by reducing CH_4 leaks from fossil fuel production and transport, reducing landfill emissions gazing, land management and introducing measures related to manure management, see also Chapter 7 and 11). However, technical potential estimates become exhausted even if the stringency of mitigation is increased (Harmsen et al. 2019a,b; Höglund-Isaksson et al. 2020). Therefore, further reduction may come from changes in activity levels, such as switching to a less meat-intensive diet, therefore reducing livestock (Stehfest et al. 2009; Willett et al. 2019; Ivanova et al. 2020) (Chapter 7). Other non-CO_2 GHG emissions (halogenated gases) are reduced to low levels for scenarios below 2.5°C.

Short-lived climate forcers (SLCFs) also play an important role in climate change, certainly for short-term changes (AR6 WGI, Figure SPM.2) (Shindell et al. 2012). These forcers consist of (i) substances contributing to warming, such as methane, black carbon and tropospheric ozone, and (ii) substances contributing to cooling (other aerosols, such as related to sulphur emissions). Most SLCFs are also air pollutants, and reducing their emissions provides additional co-benefits (Shindell et al. 2017a,b; Hanaoka and Masui 2020). In the case of the first group, emission reduction thus leads to both air pollution and climate benefits. For the second, group there is a possible trade-off (Shindell and Smith 2019; Lund et al. 2020). As aerosol emissions are mostly associated with fossil fuel combustion, the benefits of reducing CO_2 could, in the short term, be reduced as a result of lower aerosol cooling. There has been an active discussion on the exact climate contribution of SLCF-focused policies in the literature. This discussion partly emerged from different assumptions on possible reductions in the absence of ambitious climate policy and the uncertain global climate benefit from aerosol (black carbon) (Rogelj et al. 2014). The latter is now assessed to be smaller than originally thought (Takemura and Suzuki 2019; Smith et al. 2020b) (see also AR6 WGI Section 6.4). Reducing SLCF emissions is critical to meet long-term climate goals and might help reduce the rate of climate change in the short term. Deep SLCF emission reductions also increase the remaining carbon budget for a specific temperature goal (Rogelj et al. 2015a; Reisinger et al. 2021) (Box 3.4). A more detailed discussion can be found in AR6 WGI Chapters 5 and 6.

For accounting of emissions and the substitution of different gases as part of a mitigation strategy, typically, emission metrics are used to compare the climate impact of different gases. Most policies currently use Global Warming Potentials (GWPs) with a 100-year time horizon as this is also mandated for emissions reporting in the Paris Rulebook (for a wider discussion of GHG metrics, see Box 2.1 in Chapter 2 of this report, and AR6 WGI, Chapter 7, Section 7.6). Alternative metrics have also been proposed, such as those using a shorter or longer time horizon, or those that focus directly on the consequences of reaching a certain temperature target (Global Temperature Change Potential – GTP), allowing a more direct comparison with cumulative CO_2 emissions (Allen et al. 2016; Lynch et al. 2020) or focusing on damages (Global Damage Potential) (an overview is given in Chapter 2, and Cross-Chapter Box 3 in Chapter 3). Depending on the metric, the value attributed to reducing short-lived forcers such as methane can be lower in the near term (e.g., in the case of GTP) or higher (GWP with a short reference period). For most metrics, however, the impact on mitigation strategies is relatively small, among others, due to the marginal abatement cost curve of methane (low costs for low-to-medium mitigation levels; expensive for high levels). The timing of reductions across different gases impacts warming and the co-benefits (Harmsen et al. 2016; Cain et al. 2019). Nearly all scenarios in the literature use GWP-100 in cost-optimisation, reflecting the existing policy approach; the use of GWP-100 deviates from cost-optimal mitigation pathways by at most a few percent for temperature goals that limit warming to 2°C (>67%) or lower (Box 2.1).

Cumulative CO_2 emissions and temperature goals

The dominating role of CO_2 and its long lifetime in the atmosphere and some critical characteristics of the Earth System implies that there is a strong relationship between cumulative CO_2 emissions and temperature outcomes (Allen et al. 2009; Matthews et al. 2009; Meinshausen et al. 2009; MacDougall and Friedlingstein 2015). This is illustrated in Figure 3.13, which plots the cumulative CO_2 emissions against the projected outcome for global mean temperature, both until peak temperature and through to end of century (or 2100). The deviations from a linear relationship in Figure 3.13 are mostly caused by different non-CO_2 emission and forcing levels (see also Rogelj et al. 2015b). This means that reducing non-CO_2 emissions can play an important role in limiting peak warming: the smaller the residual non-CO_2 warming, the larger the carbon budget. This impact on carbon budgets can be substantial for stringent warming limits. For 1.5°C pathways, variations in non-CO_2 warming across different emission scenarios have been found to vary the remaining carbon budget by approximately 220 $GtCO_2$ (AR6 WGI Chapter 5, Section 5.5.2.2). In addition to reaching net zero CO_2 emissions, a strong reduction in methane emissions is the most critical component in non-CO_2 mitigation to keep the Paris climate goals in reach (Collins et al. 2018; van Vuuren et al. 2018) (see also AR6 WGI, Chapters 5, 6 and 7). It should be noted that the temperature categories (C1–C7) generally aligned with the horizontal axis, except for the end-of-century values for C1 and C2 that coincide.

3

Box 3.4 | Consistency of Remaining Carbon Budgets in the WGI Assessment and Cumulative CO_2 Emissions in WGIII Mitigation Pathways

Introduction

The WGI assessment has shown that the increase in global mean temperature has a near-linear relationship with cumulative CO_2 emissions (Chapter 5, Section 5.5, Box 5.3 of AR6 WGI report). Consistently, WGI has confirmed that net zero CO_2 emissions are required to halt CO_2-induced warming. This permits the estimation of carbon budgets consistent with specific temperature goals. In Chapter 3, we present the temperature outcomes and cumulative CO_2 emissions associated with different warming levels for around 1200 scenarios published in the literature and which were classified according to different warming levels (Section 3.2 and Annex III.II.3.2). In this box, we discuss the consistency of the assessments presented here and in IPCC AR6 WGI. The box summarises how the remaining carbon budgets assessed by AR6 WGI relate to the remaining cumulative CO_2 emissions until the time of net zero CO_2 emissions in mitigation pathways (Tables 3.2 and SPM.1) assessed by AR6 WGIII.

In its assessment, AR6 WGI uses a framework in which the various components of the remaining carbon budget are informed by various lines of evidence and assessed climate system characteristics. The AR6 WGIII, instead, uses around 1200 emission scenarios with estimated warming levels that cover the scenario range presented in AR6 WGI but also contain many more intermediate projections with varying emission profiles and a combination of CO_2 emissions and other greenhouse gases. In order to assess their climate outcomes, climate model emulators are used. The emulators are reduced complexity climate models that are provided by AR6 WGI, and which are calibrated to the AR6 WGI assessment of future warming for various purposes (a detailed description of the use of climate model emulators in the AR6 WGI and WGIII assessments can be found in Cross-Chapter Box 7.1 in the AR6 WGI report, with the connection of WGI and WGIII discussed in Annex III.2.5.1).

3

Remaining carbon budgets estimated by AR6 WGI

The AR6 WGI estimated the remaining carbon budgets from their assessment of (i) the transient climate response to cumulative emissions of carbon dioxide (TCRE), and estimates of (ii) the historical human-induced warming, (iii) the temperature change after reaching net zero CO_2 emissions, (iv) the contribution of future non-CO_2 warming (derived from the emissions scenarios assessed in the Special Report on 1.5°C Warming using WGI-calibrated emulators), and (v) the Earth System feedbacks (AR6 WGI Chapter 5.5, Box 5.2). For a given warming level, AR6 WGI assessed the remaining carbon budget from the beginning of 2020 onwards. These are 650/500/400 $GtCO_2$ for limiting warming to 1.5°C with 33%/50%/ 67% chance and 1350/1150 $GtCO_2$ for limiting warming to 2°C with 50%/67% chance. The estimates are subject to considerable uncertainty related to historical warming, future non-CO_2 forcing, and poorly quantified climate feedbacks. For instance, variation in non-CO_2 emissions across scenarios are estimated to either increase or decrease the remaining carbon budget estimates by 220 $GtCO_2$. The estimates of the remaining carbon budget assume that non-CO_2 emissions are reduced consistently with the tight temperature targets for which the budgets are estimated.

Cumulative CO_2 emissions until net zero estimated by AR6 WGIII

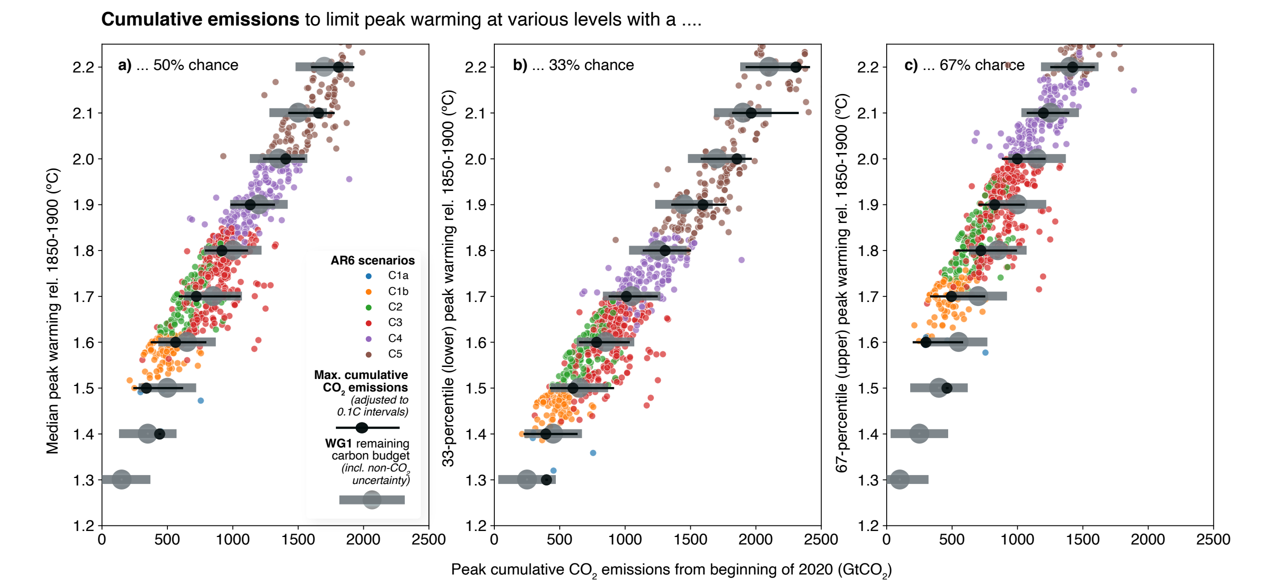
The AR6 WGIII provides estimates of cumulative net CO_2 emissions (from 2020 inclusive) until the time of reaching net zero CO_2 emissions (henceforth called 'peak cumulative CO_2 emissions') and until the end of the century for eight temperature classes that span a range of warming levels. The numbers can be found in Table 3.2 (330–710 $GtCO_2$ for C1; 530–930 for C2; and 640–1160 for C3).

Comparing the AR6 WGI remaining carbon budgets and remaining cumulative CO_2 emissions of the AR6 WGIII scenarios

A comparison between AR6 WGI and WGIII findings requires recognising that, unlike in WGI, cumulative emissions in WGIII are not provided for a specific peak-warming threshold or level but are instead provided for a set of scenarios in a category, representing a specific range of peak-temperature outcomes (for instance the C4 category contains scenarios with a median peak warming anywhere between approximately 1.8°C and up to 2°C). When accounting for this difference, the AR6 WGI and WGIII findings are very consistent for temperature levels below 2°C. Figure 1 compares the peak temperatures and associated cumulative CO_2 emissions (i.e., peak cumulative CO_2 emissions) for the WGIII scenarios to the remaining carbon budgets assessed by WGI. This shows only minor differences between the WGI and WGIII approaches.

After correcting for the categorisation, some (small) differences between the AR6 WGI and WGIII numbers arise from remaining differences between the outcomes of the climate emulators and their set-up (IPCC AR6 WGI Cross-Chapter Box 7.1) and the differences in the underlying scenarios. Moreover, the WGI assessment estimated the non-CO_2 warming at the time of net zero CO_2 emissions based on a relationship derived from the SR1.5 scenario database with historical emission estimates as in Meinshausen et al. (2020) (AR6 WGI Chapter 5). The WGIII assessment uses the same climate emulator with improved historical emissions estimates (Nicholls et al. 2021) (AR6 WGI Cross-Chapter Box 7.1). Annex III.II.2.5.1 further explores the effects of these factors on the relationship between non-CO_2 warming at peak cumulative CO_2 and peak surface temperature.

Box 3.4 (continued)



Box 3.4, Figure 1 | Cumulative CO_2 emissions from AR6 scenario categories (coloured dots), adjusted for distinct 0.1°C warming levels (black bars) in comparison to the WGI remaining carbon budgets (grey bars). The cumulative carbon emissions for the AR6 scenarios are shown for the median peak warming **(a)**, the 33rd-percentile peak warming **(b)** and the upper 67th-percentile peak warming **(c)** calculated with the WGI-calibrated emulator MAGICC7 (IPCC AR6 WGI, Cross-Chapter Box 7.1). The adjustment to the nearest 0.1°C intervals is made using AR6 WGI TCRE (at the relevant percentile, e.g., the 67th-percentile TCRE is used to adjust the 67th-percentile peak warming), with the 5–95% range of adjusted scenarios provided by the black bar. The AR6 WGI remaining carbon budget is shown, including the WGI estimate of at least a ±220 $GtCO_2$ uncertainty due to non-CO_2 emissions variations across scenarios (grey bars). For median peak warming (panel a) projections below 2°C relative to 1850–1900, the AR6 WGIII assessment of cumulative carbon emissions tends to be slightly smaller than the remaining carbon budgets provided by WGI but well within the uncertainties. Note that only a few scenarios in WGIII limit warming to below 1.5°C with a 50% chance, thus statistics for that specific threshold have low confidence.

Estimates of the remaining carbon budgets thus vary with the assumed level of non-CO_2 emissions, which are a function of policies and technology development. The linear relationship used in the AR6 WGI assessment between peak temperature and the warming as a result of non-CO_2 emissions (based on the SR1.5 data) is shown in the right panel of Figure 2 (dashed line). In the AR6 WGIII approach, the non-CO_2 warming for each single scenario is based on the individual scenario characteristics. This is shown in the same figure by plotting the outcomes of scenario outcomes of a range of models (dots). The lines show the fitted data for individual models, emphasising the clear differences across models and the relationship with peak warming (policy level). In some scenarios, stringent non-CO_2 emission reductions provide an option to reach more stringent climate goals with the same carbon budget. This is especially the case for scenarios with a very low non-CO_2 warming, for instance, as a result of methane reductions through diet change. The left panel shows how these differences impact estimates of the remaining carbon budget. While the AR6 scenarios database includes a broad range of non-CO_2 emission projections the overall range is still very consistent with the WGI relationship and the estimated uncertainty with a ±220 $GtCO_2$ range (see also Figure 5 in Annex III.II.2.5.1).

Overall, the slight differences between the cumulative emissions in AR6 WGIII and the carbon budget in AR6 WGI are because the non-CO_2 warming in the WGIII scenarios is slightly lower than in the SR1.5 scenarios that are used for the budget estimates in WGI (Annex III.2.5.1). In addition, improved consistency with Cross-Chapter Box 7.1 in Chapter 7, AR6 WGI results in a non-CO_2-induced temperature difference of about about 0.05K between the assessments. Recalculating the remaining carbon budget using the WGI methodology combined with the full AR6 WGIII scenario database results in a reduction of the estimated remaining 1.5°C carbon budget by about 100 $GtCO_2$ (–20%), and a reduction of about 40 $GtCO_2$ (–3%) for 2°C. Accounting also for the categorisation effect, the difference between the WGI and WGIII estimates is found to be small and well within the uncertainty range (Figure 1). This means that the cumulative CO_2 emissions presented in WGIII and the WGI carbon budgets are highly consistent.

A detailed comparison of the impact of different assessment steps (i.e., the new emulators, scenarios, and harmonisation methods), has been made and is presented in Figure 6 in Annex III.II.3.2 .

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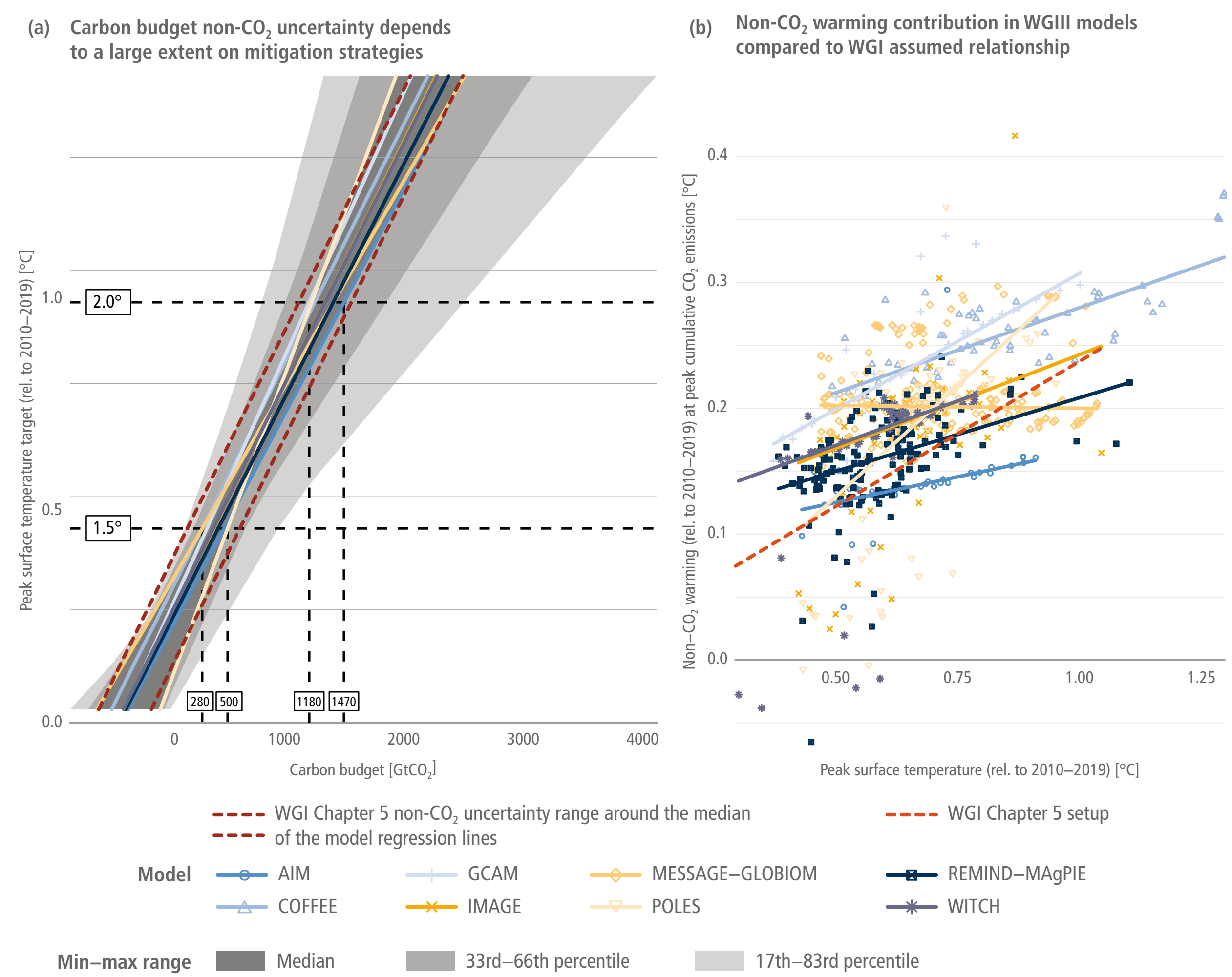
Box 3.4 (continued)



Box 3.4, Figure 2 | (a) Differences in regressions of the relationship between peak surface temperature and associated cumulative CO_2 emissions from 2020 derived from scenarios of eight integrated assessment model frameworks. The coloured lines show the regression at median for scenarios of the eight modelling frameworks, each with more than 20 scenarios in the database and a detailed land-use representation. The red dotted lines indicate the non-CO_2 uncertainty range of AR6 WGI Chapter 5 (±220 $GtCO_2$), here visualised around the median of the eight model framework lines. Carbon budgets from 2020 until 1.5°C (0.43K above 2010–2019 levels) and 2.0°C (0.93K above 2010–2019 levels) are shown for minimum and maximum model estimates at the median, rounded to the nearest 10 $GtCO_2$. Panel **(b)** shows the relationship between the estimated non-CO_2 warming in mitigation scenarios that reach net zero and the associated peak surface temperature outcomes. The coloured lines show the regression at median for scenarios of the eight modelling frameworks with more than 20 scenarios in the database and a detailed land-use representation. The black dashed line indicates the non-CO_2 relationship based on the scenarios and climate emulator setup as was assessed in AR6 WGI Chapter 5.

Policy implications

The concept of a finite carbon budget means that the world needs to get to net zero CO_2, no matter whether global warming is limited to 1.5°C or well below 2°C (or any other level). Moreover, exceeding the remaining carbon budget will have consequences by overshooting temperature levels. Still, the relationship between the timing of net zero and temperature targets is a flexible one, as discussed further in Cross-Chapter Box 3 in this chapter. It should be noted that the national-level inventory as used by UNFCCC for the land use, land-use change and forestry sector is different from the overall concept of anthropogenic emissions employed by IPCC AR6 WGI. For emissions estimates based on these inventories, the remaining carbon budgets must be correspondingly reduced by approximately 15%, depending on the scenarios (Grassi et al., 2021) (Chapter 7).

One of the uncertainties of the remaining carbon budget is the level of non-CO_2 emissions which is a function of policies and technology development. This represents a point of leverage for policies rather than an inherent geophysical uncertainty. Stringent non-CO_2 emission reductions hence can provide – to some degree – an option to reach more stringent climate goals with the same carbon budget.

The near-linear relationship implies that cumulative CO_2 emissions are critically important for climate outcomes (Collins et al. 2013). The maximum temperature increase is a direct function of the cumulative emissions until net zero CO_2 emissions is reached (the emission budget) (Figure 3.13, left side). The end-of-century temperature correlates well with cumulative emissions across the century (right panel). For long-term climate goals, positive emissions in the first half of the century can be offset by net removal of CO_2 from the atmosphere (net negative emissions) at the cost of a temporary overshoot of the target (Tokarska et al. 2019). The bottom panels of Figure 3.13 show the contribution of net negative CO_2 emissions.

Focusing on cumulative emissions, the right-hand panel of Figure 3.12b shows that for high-end scenarios (C6–C7), most emissions originate from fossil fuels, with a smaller contribution from net deforestation. For C5 and lower, there is also a negative contribution to emissions from both AFOLU emissions and energy systems. For the energy systems, these negative emissions originate from bioenergy with carbon capture and storage (BECCS), while for AFOLU, they originate from reforestation and afforestation. For C3–C5, reforestation has a larger CDR contribution than BECCS, mostly due to considerably lower costs (Rochedo et al. 2018). For C1 and C2, the tight carbon budgets imply in many scenarios more CDR use (Riahi et al. 2021). Please note that net negative emissions are not so relevant for peak-temperature targets, and thus the C1 category, but CDR can still be used to offset the remaining positive emissions (Riahi et al. 2021). While positive CO_2 emissions from fossil fuels are significantly reduced, inertia and hard-to-abate sectors imply that in many C1–C3 scenarios, around 800–1000 $GtCO_2$ of net positive cumulative CO_2 emissions remain. This is consistent with literature estimates that current infrastructure is associated with 650 $GtCO_2$ (best estimate) if operated until the end of its lifetime (Tong et al. 2019). These numbers are considerably above the estimated carbon budgets for 1.5°C estimated in AR6 WGI, hence explaining CDR reliance (either to offset emissions immediately or later in time).

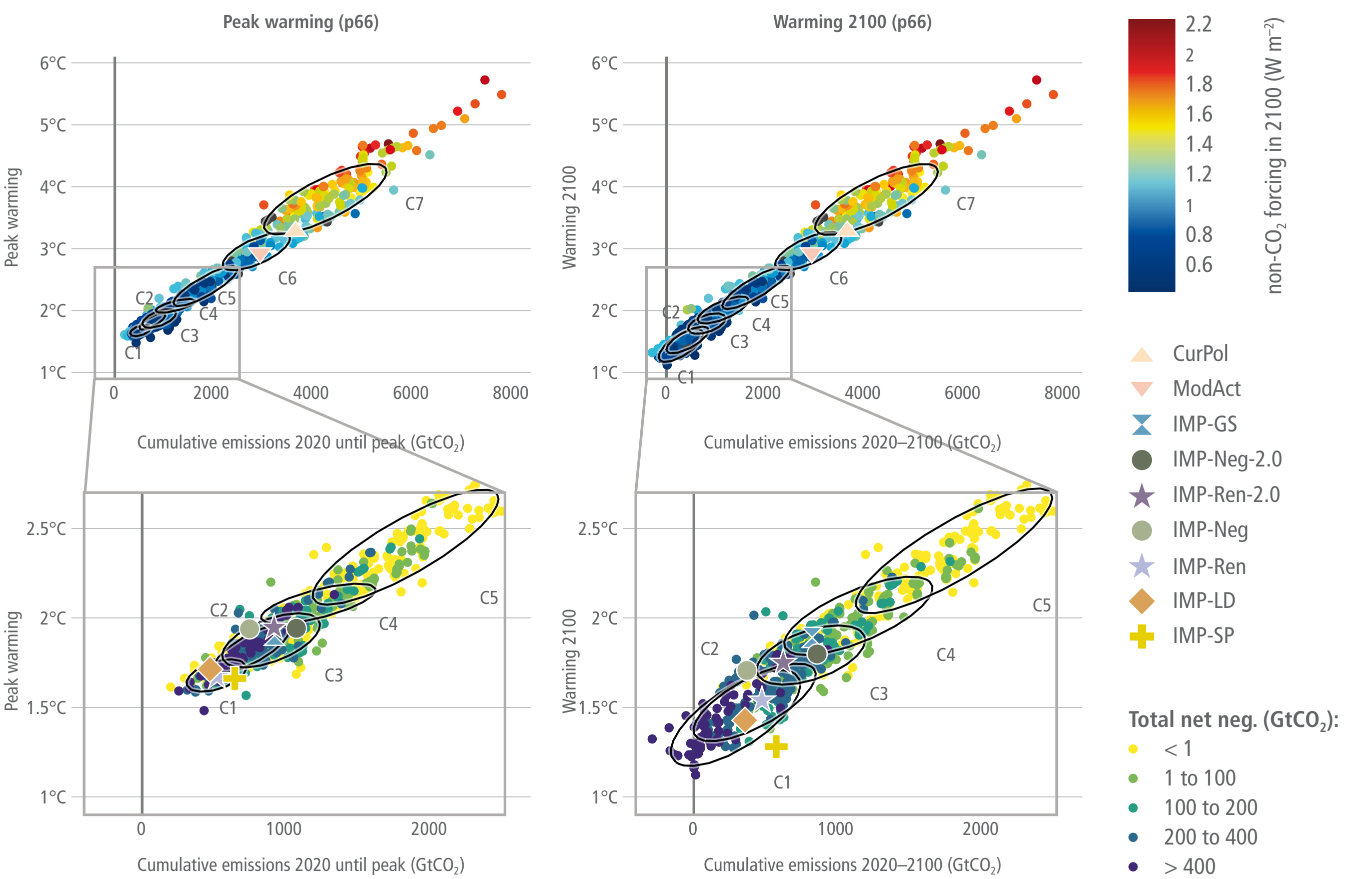


Figure 3.13 | The near-linear relationship between cumulative CO_2 emissions and temperature. The left panel shows cumulative emissions until net zero emission is reached. The right panel shows cumulative emissions until the end of the century, plotted against peak and end-of-century temperature, respectively. Both are shown as a function of non-CO_2 forcing and cumulative net negative CO_2 emissions. Position temperature categories (circles) and IPs are also indicated, including two 2°C sensitivity cases for *Neg* (Neg-2.0) and *Ren* (Ren-2.0).

Creating net negative emissions can thus be an important part of a mitigation strategy to offset remaining emissions or compensate for emissions earlier in time. As indicated above, there are different ways to potentially achieve this, including reforestation and afforestation and BECCS (as often covered in IAMs) but also soil carbon enhancement, direct air carbon capture and storage (DACCS) and ocean alkalinisation (Chapter 12). Except for reforestation, these options have not been tested at large scale and often require more R&D. Moreover, the reliance on CDR in scenarios has been discussed given possible consequences of land use related to biodiversity loss and food security (BECCS and afforestation), the reliance on uncertain storage potentials (BECCS and DACCS), water use (BECCS), energy use (DACCS), the risks of possible temperature overshoot and the consequences for meeting Sustainable Development Goals (SDGs) (Anderson and Peters 2016; Smith et al. 2016; Venton 2016; Peters and Geden 2017; van Vuuren et al. 2017; Honegger et al. 2021). In the case of BECCS, it should be noted that bioenergy typically is associated with early-on positive CO_2 emissions and net negative effects are only achieved in time (carbon debt), and its potential is limited (Cherubini et al. 2013; Hanssen et al. 2020); most IAMs have only a very limited representation of these time dynamics. Several scenarios have therefore explored how reliance on net negative CO_2 emissions can be reduced or even avoided by alternative emission strategies (Grubler et al. 2018; van Vuuren et al. 2018) or early reductions by more stringent emission reduction in the short term (Rogelj et al. 2019b; Riahi et al. 2021). A more in-depth discussion of land-based mitigation options can be found in Chapter 7. It needs to be emphasised that even in strategies with net negative CO_2 emissions, the emission reduction via more conventional mitigation measures (efficiency improvement, decarbonisation of energy supply) is much larger than the CDR contribution (Tsutsui et al. 2020).

3.3.2.3 The Timing of Net Zero Emissions

In addition to the constraints on change in global mean temperature, the Paris Agreement also calls for reaching a balance of sources and sinks of GHG emissions (Art. 4). Different interpretations of the concept related to balance have been published (Rogelj et al. 2015c; Fuglestvedt et al. 2018). Key concepts include that of net zero CO_2 emissions (anthropogenic CO_2 sources and sinks equal zero) and net zero greenhouse gas emissions (see Annex I: Glossary, and Box 3.3). The same notion can be used for all GHG emissions, but here ranges also depend on the use of equivalence metrics (Box 2.1). Moreover, it should be noted that while reaching net zero CO_2 emissions typically coincides with the peak in temperature increase; net zero GHG emissions (based on GWP-100) imply a decrease in global temperature (Riahi et al. 2021) and net zero GHG emissions typically require negative CO_2 emissions to compensate for the remaining emissions from other GHGs. Many countries have started to formulate climate policy in the year that net zero emissions (either CO_2 or all greenhouse gases) are reached – although, at the moment, formulations are often still vague (Rogelj et al. 2021). There has been increased attention on the timing of net zero emissions in the scientific literature and ways to achieve it.

Figure 3.14 shows that there is a relationship between the temperature target, the cumulative CO_2 emissions budget, and the net zero year for CO_2 emissions (panel a) and the sum of greenhouse gases (panel b) for the scenarios published in the literature. In other words, the temperature targets from the Paris Agreement can, to some degree, be translated into a net-zero emission year (Tanaka and O'Neill 2018). There is, however, a considerable spread. In addition to the factors influencing the emission budget (AR6 WGI and Section 3.3.2.2), this is influenced by the emission trajectory until net zero is reached, decisions related to temperature overshoot and non-CO_2 emissions (especially for the moment CO_2 reaches net zero emissions). Scenarios with limited or no net negative emissions and rapid near-term emission reductions can allow small positive emissions (e.g., in hard-to-abate-sectors). They may therefore have a later year that net zero CO_2 emissions are achieved. High emissions in the short term, in contrast, require an early net zero year.

For the scenarios in the C1 category (limit warming to 1.5°C (>50% with no or limited overshoot, the net zero year for CO_2 emissions is typically around 2035–2070. For scenarios in C3 (limiting warming to 2°C (>67%)), CO_2 emissions reach net zero around after 2050. Similarly, also the years for net zero GHG emissions can be calculated (see Fig 3.14b. The GHG net zero emissions year is typically around 10–40 years later than the carbon neutrality. Residual non-CO_2 emissions at the time of reaching net zero CO_2 range between 5–11 $GtCO_2$-eq in pathways that limit warming to 2°C (>67%) or lower. In pathways limiting warming to 2°C (>67%), methane is reduced by around 19% (3–46%) in 2030 and 46% (29–64%) in 2050, and in pathways limiting warming to 1.5°C (>50%) with no or limited overshoot by around 34% (21–57%) in 2030 and a similar 51% (35–70%) in 2050. Emissions-reduction potentials assumed in the pathways become largely exhausted when limiting warming to 2°C (>50%). N_2O emissions are reduced too, but similar to CH_4, emission reductions saturate for stringent climate goals. In the mitigation pathways, the emissions of cooling aerosols are reduced due to reduced use of fossil fuels. The overall impact on non-CO_2-related warming combines these factors.

In cost-optimal scenarios, regions will mostly achieve net zero emissions as a function of options for emission reduction, CDR, and expected baseline emission growth (van Soest et al. 2021b). This typically implies relatively early net zero emission years in scenarios for the Latin America region and relatively late net zero years for Asia and Africa (and average values for OECD countries). However, an allocation based on equity principles (such as responsibility, capability and equality) might result in different net zero years, based on the principles applied – with often earlier net zero years for the OECD (Fyson et al. 2020; van Soest et al. 2021b). Therefore, the emission trajectory until net zero emissions is a critical determinant of future warming (Section 3.5). The more CO_2 is emitted until 2030, the less CO_2 can be emitted after that to stay below a warming limit (Riahi et al. 2015). As discussed before, also non-CO_2 forcing plays a key role in the short term.

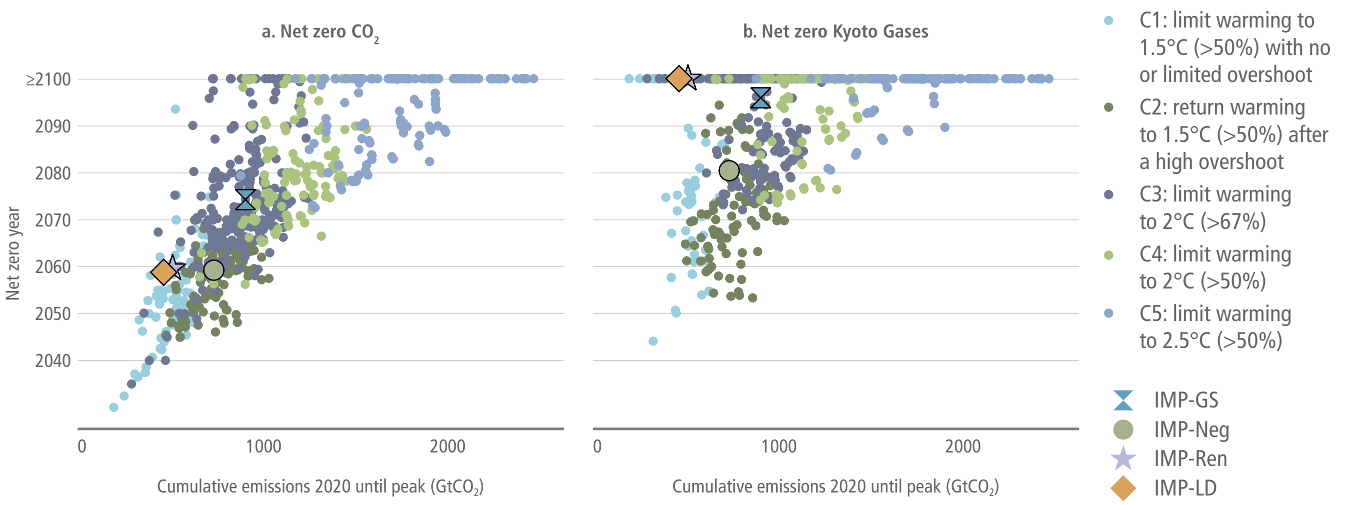


Figure 3.14 | Net zero year for CO_2 and all GHGs (based on AR6 GWP100) as a function of remaining carbon budget and temperature outcomes (note that scenarios that stabilise (near) zero are also included in determining the net zero year).

Cross-Chapter Box 3 | Understanding Net Zero CO_2 and Net Zero GHG Emissions

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This Cross-Chapter Box surveys scientific, technical and policy aspects of net zero carbon dioxide (CO_2) and net zero greenhouse gas (GHG) emissions, with a focus on timing, the relationship with warming levels, and sectoral and regional characteristics of net zero emissions. Assessment of net zero GHG emissions additionally requires consideration of non-CO_2 gases and choice of GHG emission metrics used to aggregate emissions and removals of different GHGs (Cross-Chapter Box 2 in Chapter 2 and Cross-Chapter Box 7 in Chapter 10). The following considers net zero CO_2 and GHG emissions globally, followed by regional and sectoral dimensions.

Net zero CO_2 emissions

Reaching net zero CO_2 emissions globally is necessary for limiting global warming to any level. At the point of net zero CO_2, the amount of CO_2 human activity is putting into the atmosphere equals the amount of CO_2 human activity is removing from the atmosphere (see Annex I: Glossary). Reaching and sustaining net zero CO_2 emissions globally stabilizes CO_2-induced warming. Reaching net zero CO_2 emissions and then moving to net negative CO_2 emissions globally leads to a peak and decline in CO_2-induced warming (AR6 WGI Sections 5.5 and 5.6).

Limiting warming to 1.5°C (>50%) or to 2°C (>67%) requires deep, rapid, and sustained reductions of other greenhouse gases including methane alongside rapid reductions of CO_2 emissions to net zero. This ensures that the warming contributions from non-CO_2 forcing agents as well as from CO_2 emissions are both limited at low levels. The AR6 WGI estimated remaining carbon budgets until the time of reaching net zero CO_2 emissions for a range of warming limits, taking into account historical CO_2 emissions and projections of the warming from non-CO_2 forcing agents (Box 3.4 in Section 3.3, AR6 WGI Section 5.5).

The earlier global net zero CO_2 emissions are reached, the lower the cumulative net amount of CO_2 emissions and human-induced global warming, all else being equal (Figure 1a in this Cross-Chapter Box). For a given net zero date, a variation in the shape of the CO_2 emissions profile can lead to a variation in the cumulative net amount of CO_2 emissions until the time of net zero CO_2 and as a result to different peak-warming levels. For example, cumulative net CO_2 emissions until the time of reaching net zero CO_2 will be smaller, and peak warming lower, if emissions are reduced steeply and then more slowly compared to reducing emissions slowly and then more steeply (Figure 1b in this Cross-Chapter Box).

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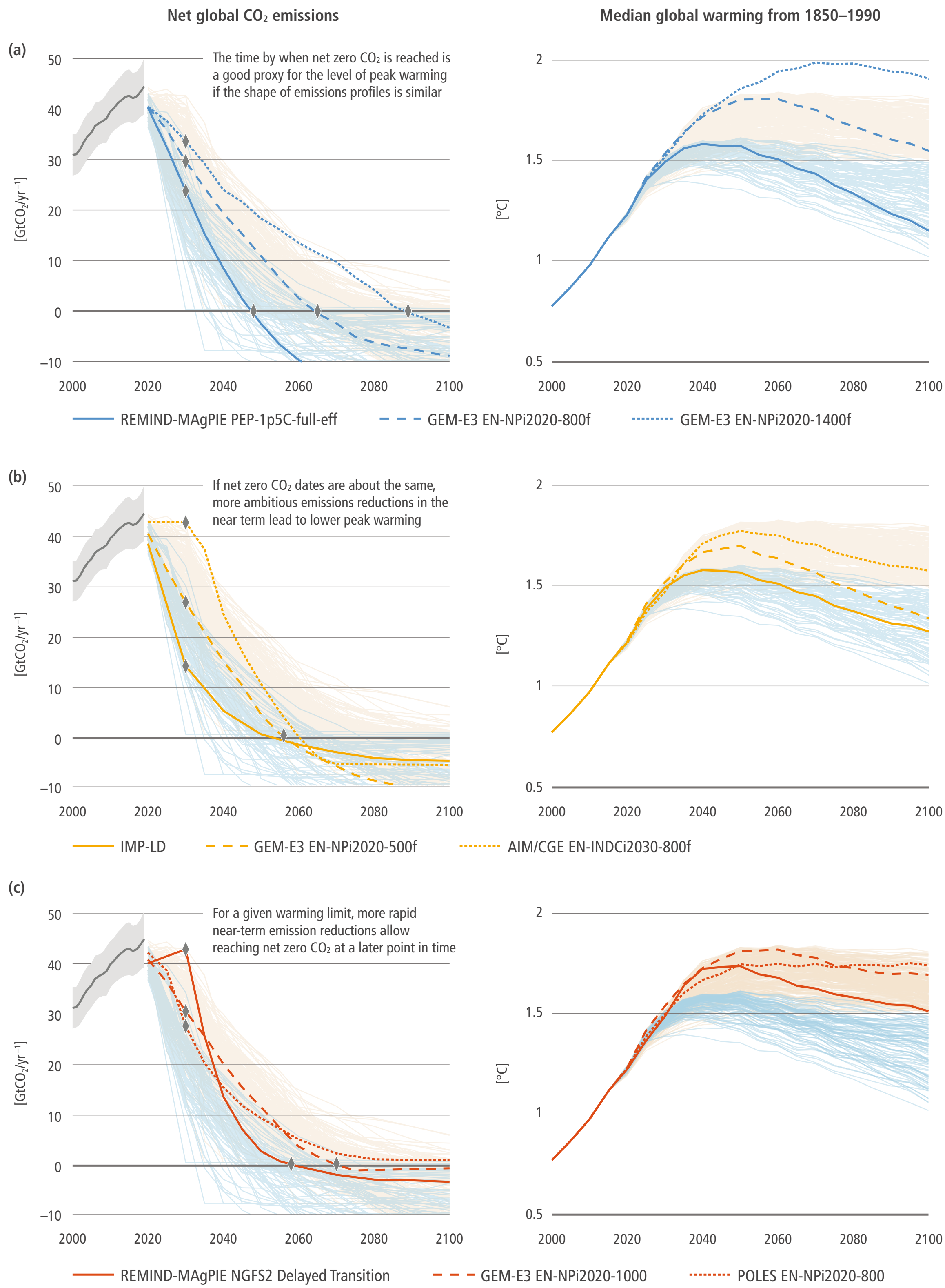
Cross-Chapter Box 3 (continued)



Cross-Chapter Box 3, Figure 1 | Selected global CO_2 emissions trajectories with similar shape and different net zero CO_2 date (a), different shape and similar net zero CO_2 date (b), and similar peak warming, but varying shapes and net zero CO_2 dates (c). Funnels show pathways limiting warming to 1.5°C (>50%) with no or limited overshoot (light blue) and limiting warming to 2°C (>67%) (beige). Historic CO_2 emissions from Section 2.2 (EDGAR v6).

Cross-Chapter Box 3 (continued)

Net zero CO_2 emissions are reached between 2050–2055 (2035–2070) in global emissions pathways limiting warming to 1.5°C (>50%) with no or limited overshoot, and between 2070–2075 (2055–…) in pathways limiting warming to 2°C (>67%) as reported in the AR6 scenarios database (median five-year interval and 5–95th percentile ranges).[5] The variation of non-CO_2 emissions in 1.5°C–2°C pathways varies the available remaining carbon budget which can move the time of reaching net zero CO_2 in these pathways forward or backward.[6] The shape of the CO_2 emissions reduction profile also affects the time of reaching net zero CO_2 (Figure 1c in this Cross-Chapter Box). Global emission pathways that more than halve CO_2 emissions from 2020 to 2030 can follow this rapid reduction by a more gradual decline towards net zero CO_2 and still limit warming to 1.5°C with no or limited overshoot, reaching the point of net zero after 2050. The literature since SR1.5 included a larger fraction of such pathways than were available at the time of SR1.5. This is the primary reason for the small backward shift in the median estimate of reaching global net zero CO_2 emissions in 1.5°C pathways collected in the AR6 scenario database compared to SR1.5. This does not mean that the world is assessed to have more time to rapidly reduce current emissions levels compared to SR1.5. The assessment of emissions reductions by 2030 and 2040 in pathways limiting warming to 1.5°C (>50%) with no or limited overshoot has not changed substantially. It only means that the exact timing of reaching net zero CO_2 after a steep decline of CO_2 emissions until 2030 and 2040 can show some variation, and the SR1.5 median value of 2050 is still close to the middle of the current range (Figure 1c in this Cross-Chapter Box).

Pathways following emissions levels projected from the implementation of Nationally Determined Contributions (NDCs) announced prior to COP26 until 2030 would result in substantially (>0.1°C) exceeding 1.5°C. They would have to reach net zero CO_2 around 5–10 years later[7] than in pathways with no or limited overshoot in order to reach the net negative emissions that would then be required to return warming to 1.5°C (>50%) after a high overshoot by 2100. Those high overshoot pathways have higher transient warming and higher reliance on net negative CO_2 emissions towards the end of the 21st century. As they need to reach net zero CO_2 emissions in only limited amount of time but from much higher 2030 emissions levels, their post-2030 CO_2 emissions reduction rates are substantially higher (by around 30%) than in pathways limiting warming to 1.5°C with no or limited overshoot. (Section 3.5).

Pathways following emissions levels projected from the implementation of NDCs announced prior to COP26 until 2030 would have to reach net zero CO_2 around 5 years earlier[8] than cost-effective pathways that limit warming to 2°C (>67%). While cost-effective pathways take around 50–55 years to reach net zero CO_2 emissions, those pathways would only have 35–40 years left for transitioning to net zero CO_2 from 2030 onwards, close to the transition times that 1.5°C pathways are faced with today. Current CO_2 emissions and 2030 emission levels projected under the NDCs announced prior to COP26 are in a similar range (Sections 3.5 and 4.2).

Net zero greenhouse gas (GHG) emissions

The amount of CO_2-equivalent emissions and the point when net zero GHG emissions are reached in multi-GHG emissions pathways depends on the choice of GHG emissions metric. Various GHG emission metrics are available for this purpose.[9] GWP-100 is the most commonly used metric for reporting CO_2-equivalent emissions and is required for emissions reporting under the Rulebook of the Paris Agreement. (Cross-Chapter Box 2 in Chapter 2, Annex I and Annex II.9)

5 A small fraction of pathways in the AR6 scenarios database that limit warming to 2°C (7% for C3 and 14% for C4) do not reach net zero CO_2 emissions during the 21st century. This is not inconsistent with the fundamental scientific requirement to reach net zero CO_2 emissions for a stable climate, but reflects that in some pathways, concurrent reductions in non-CO_2 emissions temporarily compensate for ongoing warming from CO_2 emissions. These would have to reach net zero CO_2 emissions eventually after 2100 to maintain these warming limits. For the two classes of pathways, the 95th percentile cannot be deduced from the scenario database as more than 5% of them do not reach net zero CO_2 by 2100.

6 The AR6 WGI Section 5.5 estimates a variation of the remaining carbon budget by ±220 $GtCO_2$ due to variations of the non-CO_2 warming contribution in 1.5°C–2°C pathways. This translates to a shift of the timing of net zero CO_2 by about ±10 years, assuming global CO_2 emissions decrease linearly from current levels of around 40 $GtCO_2$ to net zero.

7 Pathways following emissions levels of NDCs announced prior to COP26 to 2030 and then returning warming to 1.5°C (>50%) after high overshoot by 2100 reach net zero during 2055–2060 (2045–2070) (median five-year interval and 5–95th percentile range).

8 Pathways that follow emission levels projected from the implementation of NDCs announced prior to COP26 until 2030 and that still limit warming to 2°C (>67%) reach net zero CO_2 emissions during 2065–2070 (2055–2090) compared with 2070–2075 (2055–…) in cost-effective pathways acting immediately to *likely* limit warming to 2°C (median five-year interval and 5–95th percentile range). See Footnote 5 for the lack of 95th percentile (Section 3.3 and Table 3.2).

9 Defining net zero GHG emissions for a basket of greenhouse gases (GHGs) relies on a metric to convert GHG emissions including methane (CH_4), nitrous oxide (N_2O), fluorinated gases (F-gases), and potentially other gases, to CO_2-equivalent emissions. The choice of metric ranges from global warming potentials (GWPs) and global temperature change potentials (GTP) to economically oriented metrics. All metrics have advantages and disadvantages depending on the context in which they are used (Cross-Chapter Box 2 in Chapter 2).

Cross-Chapter Box 3 (continued)

For most choices of GHG emissions metric, reaching net zero GHG emissions requires net negative CO_2 emissions in order to balance residual CH_4, N_2O and F-gas emissions. Under foreseen technology developments, some CH_4, N_2O and F-gas emissions from, for example, agriculture and industry, will remain over the course of this century. Net negative CO_2 emissions will therefore be needed to balance these remaining non-CO_2 GHG emissions to obtain net zero GHG emissions at a point in time after net zero CO_2 has been reached in emissions pathways. Both the amount of net negative CO_2 emissions and the time lag to reaching net zero GHG depend on the choice of GHG emission metric.

Reaching net zero GHG emissions globally in terms of GWP-100 leads to a reduction in global warming from an earlier peak. This is due to net negative CO_2 emissions balancing the GWP-100-equivalent emissions of short-lived GHG emissions, which by themselves do not contribute to further warming if sufficiently declining (Fuglestvedt et al. 2018; Rogelj et al. 2021). Hence, 1.5°C–2°C emissions pathways in the AR6 scenario database that reach global net zero GHG emissions in the second half of the century show warming being halted at some peak value followed by a gradual decline towards the end of the century (AR6 WGI Chapter 1, Box 1.4).

Global net zero GHG emissions measured in terms of GWP-100 are reached between 2095 and 2100 (2050–…)[10] in emission pathways limiting warming to 1.5°C (>50%) with no or limited overshoot (median and 5–95th percentile). Around 50% of pathways limiting warming to 1.5°C (>50%) with no or limited overshoot and 70% of pathways limiting warming to 2°C (>67%) do not reach net zero GHG emissions in terms of GWP-100 before 2100. These pathways tend to show less reduction in warming after the peak than pathways that reach net zero GHG emissions. For the subset of pathways that reach net zero GHG emissions before 2100, including around 90% of pathways that return warming to 1.5°C after a high overshoot (>0.1°C) by 2100, the time lag between reaching net zero CO_2 and net zero GHG is 12–14 (7–39) years and the amount of net negative CO_2 emissions deployed to balance non-CO_2 emissions at the time of net zero GHG is around -7 (–10 to –4) $GtCO_2$ (range of medians and lowest 5th to highest 95 percentile across the four scenario classes that limit median warming to 2°C or lower) (Section 3.3 and Table 3.2).

Sectoral and regional aspects of net zero

The timing of net zero CO_2 or GHG emissions may differ across regions and sectors. Achieving net zero emissions globally implies that some sectors and regions must reach net zero CO_2 or GHG ahead of the time of global net zero CO_2 or GHG if others reach it later. Similarly, some sectors and regions would need to achieve net negative CO_2 or GHG emissions to compensate for continued emissions by other sectors and regions after the global net zero year. Differences in the timing to reach net zero emissions between sectors and regions depend on multiple factors, including the potential of countries and sectors to reduce GHG emissions and undertake carbon dioxide removal (CDR), the associated costs, and the availability of policy mechanisms to balance emissions and removals between sectors and countries (Fyson et al. 2020; Strefler et al. 2021a; van Soest et al. 2021b). A lack of such mechanisms could lead to higher global costs to reach net zero emissions globally, but less interdependencies and institutional needs (Fajardy and Mac Dowell 2020). Sectors will reach net zero CO_2 and GHG emissions at different times if they are aiming for such targets with sector-specific policies or as part of an economy-wide net zero emissions strategy integrating emissions reductions and removals across sectors. In the latter case, sectors with large potential for achieving net negative emissions would go beyond net zero to balance residual emissions from sectors with low potential, which in turn would take more time compared to the case of sector-specific action. Global pathways project global AFOLU emissions to reach global net zero CO_2 the earliest, around 2030 to 2035 in pathways to limit warming to 2°C (>67%) or lower, by rapid reduction of deforestation and enhancing carbon sinks on land, although net zero GHG emissions from global AFOLU are typically reached 30 years later, if at all. The ability of global AFOLU CO_2 emissions to reach net zero as early as in the 2030s in modelled pathways hinges on optimistic assumptions about the ability to establish global cost-effective mechanisms to balance emissions reductions and removals across regions and sectors. These assumptions have been challenged in the literature and the *Special Report on Climate Change and Land* (IPCC SRCCL).

The adoption and implementation of net zero CO_2 or GHG emission targets by countries and regions also depends on equity and capacity criteria. The Paris Agreement recognises that peaking of emissions will occur later in developing countries (Art. 4.1). Just transitions to net zero CO_2 or GHG could be expected to follow multiple pathways, in different contexts. Regions may decide about net zero pathways based on their consideration of potential for rapid transition to low-carbon development pathways, the capacity to design and implement those changes, and perceptions of equity within and across countries. Cost-effective pathways from global models have been shown to distribute the mitigation effort unevenly and inequitably in the absence of financial support mechanisms and capacity building (Budolfson et al. 2021), and hence would require additional measures to become aligned with

10 The 95th percentile cannot be deduced from the scenario database as more than 5% of pathways do not reach net zero GHG by 2100 (Section 3.3 and Table 3.2.), hence denoted by -….

Cross-Chapter Box 3 (continued)

equity considerations (Fyson et al. 2020; van Soest et al. 2021b). Formulation of net zero pathways by countries will benefit from clarity on scope, roadmaps and fairness (Rogelj et al. 2021; Smith 2021). Achieving net zero emission targets relies on policies, institutions and milestones against which to track progress. Milestones can include emissions levels, as well as markers of technological diffusion.

The accounting of anthropogenic carbon dioxide removal on land matters for the evaluation of net zero CO_2 and net zero GHG strategies. Due to the use of different approaches between national inventories and global models, the current net CO_2 emissions are lower by 5.5 $GtCO_2$, and cumulative net CO_2 emissions in modelled 1.5°C–2°C pathways would be lower by 104–170 $GtCO_2$, if carbon dioxide removals on land are accounted based on national GHG inventories. National GHG inventories typically consider a much larger area of managed forest than global models, and on this area additionally consider the fluxes due to human-induced global environmental change (indirect effects) to be anthropogenic, while global models consider these fluxes to be natural. Both approaches capture the same land fluxes, only the accounting of anthropogenic vs natural emissions is different. Methods to convert estimates from global models to the accounting scheme of national GHG inventories will improve the use of emission pathways from global models as benchmarks against which collective progress is assessed. (Section 7.2.2.5).

Net zero CO_2 and carbon neutrality have different meanings in this assessment, as is the case for net zero GHG and GHG neutrality. They apply to different boundaries in the emissions and removals being considered. Net zero (GHG or CO_2) refers to emissions and removals under the direct control or territorial responsibility of the reporting entity. In contrast, (GHG or carbon) neutrality includes anthropogenic emissions and anthropogenic removals within and also those beyond the direct control or territorial responsibility of the reporting entity. At the global scale, net zero CO_2 and carbon neutrality are equivalent, as is the case for net zero GHG and GHG neutrality. The term 'climate neutrality' is not used in this assessment because the concept of climate neutrality is diffuse, used differently by different communities, and not readily quantified.

Table 3.2 summarises the key characteristics for all temperature categories in terms of cumulative CO_2 emissions, near-term emission reductions, and the years of peak emission and net zero CO_2 and GHG emissions. The table shows again that many pathways in the literature limit global warming to 2°C (>67%) or limit warming to 1.5°C (>50%) with no or limited overshoot compared to pre-industrial levels. Cumulative net CO_2 emissions from the year 2020 until the time of net zero CO_2 in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot are 510 (330–710) $GtCO_2$ and in pathways that limit warming to 2°C (>67%), 890 (640–1160) $GtCO_2$ (see also Cross-Chapter Box 3 in this chapter). Mitigation pathways that limit warming to 2°C (>67%) compared to pre-industrial levels are associated with net global GHG emissions of 44 (32–55) $GtCO_2$-eq yr^{-1} by 2030 and 20 (13–26) $GtCO_2$-eq yr^{-1} in 2050. These correspond to GHG emissions reductions of 21% (1–42%) by 2030, and 64% (53–77%) by 2050 relative to 2019 emission levels. Pathways that limit global warming to 1.5°C (>50%) with no or limited overshoot require a further acceleration in the pace of the transformation, with GHG emissions reductions of 43% (34–60%) by 2030 and 84% (73–98%) in 2050 relative to modelled 2019 emission levels. The likelihood of limiting warming to below 1.5°C (>50%) with no or limited overshoot of the most stringent mitigation pathways in the literature (C1) has declined since SR1.5. This is because emissions have risen since 2010 by about 9 $GtCO_2$ yr^{-1}, resulting in relatively higher near-term emissions of the AR6 pathways by 2030 and slightly later dates for reaching net zero CO_2 emissions compared to SR1.5.

Given the larger contribution of scenarios in the literature that aim to reduce net negative emissions, emission reductions are somewhat larger in the short term compared to similar categories in the IPCC SR1.5. At the same time, the year of net zero emissions is somewhat later (but only if these rapid, short-term emission reductions are achieved). The scenarios in the literature in C1–C3 show a peak in global emissions before 2025. Not achieving this requires a more rapid reduction after 2025 to still meet the Paris goals (Section 3.5).

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

p50 [p5–p95][a]			GHG emissions Gt CO_2-eq/yr [g]			GHG emissions reductions from 2019 % [h]			Emissions milestones [i,j]				Cumulative CO_2 emissions Gt CO_2 [m]		Cumulative net-negative CO_2 emissions Gt CO_2	Global mean temperature changes 50% probability [n] °C		Likelihood of peak global warming staying below (%) [o]			Time when specific global warming levels are reached (with a 50% probability)		
Category [b, c, d] [# pathways]	Category/ subset label	WG I SSP & WG III IPs/IMPs alignment [e, f]	2030	2040	2050	2030	2040	2050	Peak CO_2 emissions (% peak before 2100)	Peak GHG emissions (% peak before 2100)	Net-zero CO_2 (% net-zero pathways)	Net-zero GHGs [k, l] (% net-zero pathways)	2020 to net-zero CO_2	2020–2100	Year of net-zero CO_2 to 2100	at peak warming	2100	<1.5°C	<2°C	<3°C	1.5°C	2°C	3°C
Modelled global emissions pathways categorised by projected global warming levels (GWL). Detailed likelihood definitions are provided in SPM Box1. The five illustrative scenarios (SSPx-yy) considered by AR6 WGI and the Illustrative (Mitigation) Pathways assessed in WGIII are aligned with the temperature categories and are indicated in a separate column. Global emission pathways contain regionally differentiated information. This assessment focuses on their global characteristics.			Projected median annual GHG emissions in the year across the scenarios, with the 5th–95th percentile in brackets. Modelled GHG emissions in 2019: 55 [53–58] Gt CO_2-eq.			Projected median GHG emissions reductions of pathways in the year across the scenarios compared to modelled 2019, with the 5th–95th percentile in brackets. Negative numbers indicate increase in emissions compared to 2019.			Median 5-year intervals at which projected CO_2 & GHG emissions peak, with the 5th–95th percentile interval in square brackets. Percentage of peaking pathways is denoted in round brackets. Three dots (…) denotes emissions peak in 2100 or beyond for that percentile.		Median 5-year intervals at which projected CO_2 & GHG emissions of pathways in this category reach net-zero, with the 5th–95th percentile interval in square brackets. Percentage of net zero pathways is denoted in round brackets. Three dots (…) denotes net zero not reached for that percentile.		Median cumulative net CO_2 emissions across the projected scenarios in this category until reaching net-zero or until 2100, with the 5th–95th percentile interval in square brackets.		Median cumulative net-negative CO_2 emissions between the year of net-zero CO_2 and 2100. More net-negative results in greater temperature declines after peak.	Projected temperature change of pathways in this category (50% probability across the range of climate uncertainties), relative to 1850–1900, at peak warming and in 2100, for the median value across the scenarios and the 5th–95th percentile interval in square brackets.		Median likelihood that the projected pathways in this category stay below a given global warming level, with the 5th–95th percentile interval in square brackets.			Median 5-year intervals at which specific global warming levels are reached (50% probability), with the 5th–95th percentile interval in square brackets. Percentage of pathways is denoted in round brackets. Three dots (…) denotes temperature does not exceed the GWL by 2100 for that percentile.		
C1 [97]	**limit warming to 1.5°C (>50%) with no or limited overshoot**		31 [21–36]	17 [6–23]	9 [1–15]	43 [34–60]	69 [58–90]	84 [73–98]	2020–2025 (100%) [2020–2025]		2050–2055 (100%) [2035–2070]	2095–2100 (52%) [2050–…]	510 [330–710]	320 [–210–570]	–220 [–660–20]	1.6 [1.4–1.6]	1.3 [1.1–1.5]	38 [33–58]	90 [86–97]	100 [99–100]	2030–2035 (91%) [2030–…]	…–… (0%) […–…]	…–… (0%) […–…]
C1a [50]	**… with net-zero GHGs**	SSP1-1.9, IMP-SP IMP-LD	33 [22–37]	18 [6–24]	8 [0–15]	41 [31–59]	66 [58–89]	85 [72–100]				2070–2075 (100%) [2050–2090]	550 [340–760]	160 [–220–620]	–360 [–680–140]	1.6 [1.4–1.6]	1.2 [1.1–1.4]	38 [34–60]	90 [85–98]	100 [99–100]	2030–2035 (90%) [2030–…]	…–… (0%) […–…]	…–… (0%) […–…]
C1b [47]	**… without net-zero GHGs**	IMP-Ren	29 [21–36]	16 [7–21]	9 [4–13]	48 [35–61]	70 [62–87]	84 [76–93]				…–… (0%) […–…]	460 [320–590]	360 [10–540]	–60 [–440–0]	1.6 [1.5–1.6]	1.4 [1.3–1.5]	37 [33–56]	89 [87–96]	100 [99–100]	2030–2035 (91%) [2030–…]	…–… (0%) […–…]	…–… (0%) […–…]
C2 [133]	**return warming to 1.5°C (>50%) after a high overshoot**	IMP-Neg	42 [31–55]	25 [17–34]	14 [5–21]	23 [0–44]	55 [40–71]	75 [62–91]	2020–2025 (100%) [2020–2030]	[2020–2025]	2055–2060 (100%) [2045–2070]	2070–2075 (87%) [2055–…]	720 [530–930]	400 [–90–620]	–360 [–680–60]	1.7 [1.5–1.8]	1.4 [1.2–1.5]	24 [15–42]	82 [71–93]	100 [99–100]	2030–2035 (100%) […–…]	…–… (0%) […–…]	…–… (0%) […–…]
C3 [311]	*limit warming to 2°C (>67%)*		44 [32–55]	29 [20–36]	20 [13–26]	21 [1–42]	46 [34–63]	64 [53–77]	2020–2025 (100%) [2020–2030]	[2020–2025]	2070–2075 (93%) [2055–…]	…–… (30%) [2075–…]	890 [640–1160]	800 [510–1140]	–40 [–290–0]	1.7 [1.6–1.8]	1.6 [1.5–1.8]	20 [13–41]	76 [68–91]	99 [98–100]	2030–2035 (100%) […–…]	…–… (0%) […–…]	…–… (0%) […–…]
C3a [204]	**… with action starting in 2020**	SSP1-2.6	40 [30–49]	29 [21–36]	20 [14–27]	27 [13–45]	47 [35–63]	63 [52–76]	2020–2025 (100%) [2020–2025]		2070–2075 (91%) [2055–…]	…–… (24%) [2080–…]	860 [640–1180]	790 [480–1150]	–30 [–280–0]	1.7 [1.6–1.8]	1.6 [1.5–1.8]	21 [14–42]	78 [69–91]	100 [98–100]	2030–2035 (100%) [2030–2040]	…–… (0%) […–…]	…–… (0%) […–…]

Table 3.2 (continued):

p50 [p5–p95][a]			GHG emissions Gt CO_2-eq/yr [g]			GHG emissions reductions from 2019 % [h]			Emissions milestones [i,j]				Cumulative CO_2 emissions Gt CO_2 [m]		Cumulative net-negative CO_2 emissions Gt CO_2	Global mean temperature changes 50% probability [n] °C		Likelihood of peak global warming staying below (%) [o]			Time when specific global warming levels are reached (with a 50% probability)		
Category [b, c, d] [# pathways]	Category/ subset label	WG I SSP & WG III IPs/IMPs alignment [e, f]	2030	2040	2050	2030	2040	2050	Peak CO_2 emissions (% peak before 2100)	Peak GHG emissions (% peak before 2100)	Net-zero CO_2 (% net-zero pathways)	Net-zero GHGs [k, l] (% net-zero pathways)	2020 to net-zero CO_2	2020–2100	Year of net-zero CO_2 to 2100	at peak warming	2100	<1.5°C	<2°C	<3°C	1.5°C	2°C	3°C
Modelled global emissions pathways categorised by projected global warming levels (GWL). Detailed likelihood definitions are provided in SPM Box1. The five illustrative scenarios (SSPx-yy) considered by AR6 WGI and the Illustrative (Mitigation) Pathways assessed in WGIII are aligned with the temperature categories and are indicated in a separate column. Global emission pathways contain regionally differentiated information. This assessment focuses on their global characteristics.			Projected median annual GHG emissions in the year across the scenarios, with the 5th–95th percentile in brackets. Modelled GHG emissions in 2019: 55 [53–58] Gt CO_2-eq.			Projected median GHG emissions reductions of pathways in the year across the scenarios compared to modelled 2019, with the 5th–95th percentile in brackets. Negative numbers indicate increase in emissions compared to 2019.			Median 5-year intervals at which projected CO_2 & GHG emissions peak, with the 5th–95th percentile interval in square brackets. Percentage of peaking pathways is denoted in round brackets. Three dots (…) denotes emissions peak in 2100 or beyond for that percentile.		Median 5-year intervals at which projected CO_2 & GHG emissions of pathways in this category reach net-zero, with the 5th–95th percentile interval in square brackets. Percentage of net zero pathways is denoted in round brackets. Three dots (…) denotes net zero not reached for that percentile.		Median cumulative net CO_2 emissions across the projected scenarios in this category until reaching net-zero or until 2100, with the 5th–95th percentile interval in square brackets.		Median cumulative net-negative CO_2 emissions between the year of net-zero CO_2 and 2100. More net-negative results in greater temperature declines after peak.	Projected temperature change of pathways in this category (50% probability across the range of climate uncertainties), relative to 1850–1900, at peak warming and in 2100, for the median value across the scenarios and the 5th–95th percentile interval in square brackets.		Median likelihood that the projected pathways in this category stay below a given global warming level, with the 5th–95th percentile interval in square brackets.			Median 5-year intervals at which specific global warming levels are reached (50% probability), with the 5th–95th percentile interval in square brackets. Percentage of pathways is denoted in round brackets. Three dots (…) denotes temperature does not exceed the GWL by 2100 for that percentile.		
C3b [97]	… NDCs until 2030	IMP-GS	52 [47–56]	29 [20–36]	18 [10–25]	5 [0–14]	46 [34–63]	68 [56–82]			2065–2070 (97%) [2055–2090]	…–… (41%) [2075–…]	910 [720–1150]	800 [560–1050]	–60 [–300–0]	1.8 [1.6–1.8]	1.6 [1.5–1.7]	17 [12–35]	73 [67–87]	99 [98–99]	2030–2035 (100%) [2030–2035]	…–… (0%) […–…]	…–… (0%) […–…]
C4 [159]	limit warming to 2°C (>50%)		50 [41–56]	38 [28–44]	28 [19–35]	10 [0–27]	31 [20–50]	49 [35–65]	2020–2025 (100%) [2020–2030]		2080–2085 (86%) [2065–…]	…–… (31%) [2075–…]	1210 [970–1490]	1160 [700–1490]	–30 [–390–0]	1.9 [1.7–2.0]	1.8 [1.5–2.0]	11 [7–22]	59 [50–77]	98 [95–99]	2030–2035 (100%) [2030–2035]	…–… (0%) […–…]	…–… (0%) […–…]
C5 [212]	limit warming to 2.5°C (>50%)		52 [46–56]	45 [37–53]	39 [30–49]	6 [–1–18]	18 [4–33]	29 [11–48]			…–… (41%) [2080–…]	…–… (12%) [2090–…]	1780 [1400–2360]	1780 [1260–2360]	0 [–160–0]	2.2 [1.9–2.5]	2.1 [1.9–2.5]	4 [0–10]	37 [18–59]	91 [83–98]	2030–2035 (100%) [2030–2035]	2060–2065 (99%) [2050–2095]	…–… (0%) […–…]
C6 [97]	limit warming to 3°C (>50%)	SSP2-4.5 Mod-Act	54 [50–62]	53 [48–61]	52 [45–57]	2 [–10–11]	3 [–14–14]	5 [–2–18]	2030–2035 (96%) [2020–2090]	2020–2025 (97%)				2790 [2440–3520]			2.7 [2.4–2.9]	0 [0–0]	8 [2–18]	71 [53–88]	2030–2035 (100%) [2030–2035]	2050–2055 (100%) [2045–2060]	…–… (0%) […–…]
C7 [164]	limit warming to 4°C (>50%)	SSP3-7.0 Cur-Pol	62 [53–69]	67 [56–76]	70 [58–83]	–11 [–18–3]	–19 [–31–1]	–24 [–41–2]	2085–2090 (57%) [2040–…]	2090–2095 (56%)	no net-zero		no net-zero	4220 [3160–5000]	no net-zero	temperature does not peak by 2100	3.5 [2.8–3.9]	0 [0–0]	0 [0–2]	22 [7–60]	2030–2035 (100%) [2030–2035]	2045–2050 (100%) [2040–2055]	2080–2085 (100%) [2070–2100]
C8 [29]	exceed warming of 4°C (≥50%)	SSP5-8.5	71 [69–81]	80 [78–96]	88 [82–112]	–20 [–34–17]	–35 [–65–29]	–46 [–92–36]	2080–2085 (90%) [2070–…]					5600 [4910–7450]			4.2 [3.7–5.0]	0 [0–0]	0 [0–0]	4 [0–11]	2030–2035 (100%) [2030–2035]	2040–2045 (100%) [2040–2050]	2065–2070 (100%) [2060–2075]

Table 3.2 (continued):

[a] Values in the table refer to the 50th and [5th–95th] percentile values across the pathways falling within a given category as defined in Box SPM.1. For emissions-related columns these values relate to the distribution of all the pathways in that category. Harmonised emissions values are given for consistency with projected global warming outcomes using climate emulators. Based on the assessment of climate emulators in AR6 WGI (WG1 Chapter 7, Box 7.1), two climate emulators are used for the probabilistic assessment of the resulting warming of the pathways. For the 'Temperature change' and 'Likelihood' columns, the single upper-row values represent the 50th percentile across the pathways in that category and the median [50th percentile] across the warming estimates of the probabilistic MAGICC climate model emulator. For the bracketed ranges, the median warming for every pathway in that category is calculated for each of the two climate model emulators (MAGICC and FaIR). Subsequently, the 5th and 95th percentile values across all pathways for each emulator are calculated. The coolest and warmest outcomes (i.e., the lowest p5 of two emulators, and the highest p95, respectively) are shown in square brackets. These ranges therefore cover both the uncertainty of the emissions pathways as well as the climate emulators' uncertainty.

[b] For a description of pathways categories see Box SPM.1 and Table 3.1.

[c] All global warming levels are relative to 1850–1900. (See footnote n below and Box SPM.1[45] for more details.)

[d] C3 pathways are sub-categorised according to the timing of policy action to match the emissions pathways in Figure SPM.4. Two pathways derived from a cost-benefit analysis have been added to C3a, whilst 10 pathways with specifically designed near-term action until 2030, whose emissions fall below those implied by NDCs announced prior to COP26, are not included in either of the two subsets.

[e] Alignment with the categories of the illustrative SSP scenarios considered in AR6 WGI, and the Illustrative (Mitigation) Pathways (IPs/IMPs) of WGIII. The IMPs have common features such as deep and rapid emissions reductions, but also different combinations of sectoral mitigation strategies. See Box SPM.1 for an introduction of the IPs and IMPs, and Chapter 3 for full descriptions. {3.2, 3.3, Annex III.II.2.4}

[f] The Illustrative Mitigation Pathway 'Neg' has extensive use of carbon dioxide removal (CDR) in the AFOLU, energy and the industry sectors to achieve net negative emissions. Warming peaks around 2060 and declines to below 1.5°C (50% likelihood) shortly after 2100. Whilst technically classified as C3, it strongly exhibits the characteristics of C2 high-overshoot pathways, hence it has been placed in the C2 category. See Box SPM.1 for an introduction of the IPs and IMPs.

[g] The 2019 range of harmonised GHG emissions across the pathways [53–58 $GtCO_2$-eq] is within the uncertainty ranges of 2019 emissions assessed in Chapter 2 [53–66 $GtCO_2$-eq].[49] (Figure SPM.1, Figure SPM.2, Box SPM.1)

[h] Rates of global emission reduction in mitigation pathways are reported on a pathway-by-pathway basis relative to harmonised modelled global emissions in 2019 rather than the global emissions reported in SPM Section B and Chapter 2; this ensures internal consistency in assumptions about emission sources and activities, as well as consistency with temperature projections based on the physical climate science assessment by WGI.[49] {Annex III.II.2.5}. Negative values (e.g., in C7, C8) represent an increase in emissions.

3

[i] Emissions milestones are provided for five-year intervals in order to be consistent with the underlying five-year time-step data of the modelled pathways. Peak emissions (CO_2 and GHGs) are assessed for five-year reporting intervals starting in 2020. The interval 2020–2025 signifies that projected emissions peak as soon as possible between 2020 and at latest before 2025. The upper five-year interval refers to the median interval within which the emissions peak or reach net zero. Ranges in square brackets underneath refer to the range across the pathways, comprising the lower bound of the 5th percentile five-year interval and the upper bound of the 95th percentile five-year interval. Numbers in round brackets signify the fraction of pathways that reach specific milestones.

[j] Percentiles reported across all pathways in that category include those that do not reach net zero before 2100 (fraction of pathways reaching net zero is given in round brackets). If the fraction of pathways that reach net zero before 2100 is lower than the fraction of pathways covered by a percentile (e.g., 0.95 for the 95th percentile), the percentile is not defined and denoted with '…'. The fraction of pathways reaching net zero includes all with reported non-harmonised, and/or harmonised emissions profiles that reach net zero. Pathways were counted when at least one of the two profiles fell below 100 $MtCO_2\ yr^{-1}$ until 2100.

[k] The timing of net zero is further discussed in SPM C2.4 and Cross-Chapter Box 3 in Chapter 3 on net zero CO_2 and net zero GHG emissions.

[l] For cases where models do not report all GHGs, missing GHG species are infilled and aggregated into a Kyoto basket of GHG emissions in CO_2-eq defined by the 100-year global warming potential. For each pathway, reporting of CO_2, CH_4, and N_2O emissions was the minimum required for the assessment of the climate response and the assignment to a climate category. Emissions pathways without climate assessment are not included in the ranges presented here. {See Annex III.II.2.5 }

[m] Cumulative emissions are calculated from the start of 2020 to the time of net zero and 2100, respectively. They are based on harmonised net CO_2 emissions, ensuring consistency with the WGI assessment of the remaining carbon budget.[50] {Box 3.4}

[n] Global mean temperature change for category (at peak, if peak temperature occurs before 2100, and in 2100) relative to 1850–1900, based on the median global warming for each pathway assessed using the probabilistic climate model emulators calibrated to the AR6 WGI assessment.[12] (See also Box SPM.1) {Annex III.II.2.5; WGI Cross-Chapter Box 7.1}

[o] Probability of staying below the temperature thresholds for the pathways in each category, taking into consideration the range of uncertainty from the climate model emulators consistent with the AR6 WGI assessment. The probabilities refer to the probability at peak temperature. Note that in the case of temperature overshoot (e.g., category C2 and some pathways in C1), the probabilities of staying below at the end of the century are higher than the probabilities at peak temperature.

3.3.2.4 Mitigation Strategies

Detailed sectoral implications are discussed in Section 3.4 and Chapters 5–11 (see also Table 3.3). The stringency of climate policy has clear implications for mitigation action (Figure 3.15). There are a number of important commonalities of pathways limiting warming to 2°C (>67%) or lower: for instance, they all rely on significant improvement of energy efficiency, rapid decarbonisation of supply and, many of them, CDR (in energy supply or AFOLU), either in terms of net negative emissions or to compensate residual emissions. Still, there are also important differences and the (IMPs) show how different choices can steer the system into alternative directions with different combinations of response options. For decarbonisation of energy supply many options exist, including CCS, nuclear power, and renewables (Chapter 6). In the majority of the scenarios reaching low GHG targets, a considerable amount of CCS is applied (Figure 3.15d). The share of renewables is around 30–70% in the scenarios that limit warming to 2°C (>67%) and clearly above 40% for scenarios that limit warming 1.5°C (>50%) (panel c). Scenarios have been published with 100% renewable energy systems even at a global scale, partly reflecting the rapid progress made for these technologies in the last decade (Creutzig et al. 2017; Jacobson et al. 2018; Breyer and Jefferson 2020). These scenarios do not show in the graph due to a lack of information from non-energy sources. There is a debate in the literature on whether it is possible to achieve a 100% renewable energy system by 2050 (Brook et al. 2018). This critically depends on assumptions made on future system integration, system flexibility, storage options, consequences for material demand and the ability to supply high-temperature functions and specific mobility functions with renewable energy. The range of studies published showing 100% renewable energy systems show that it is possible to design such systems in the context of energy system models (Hong et al.

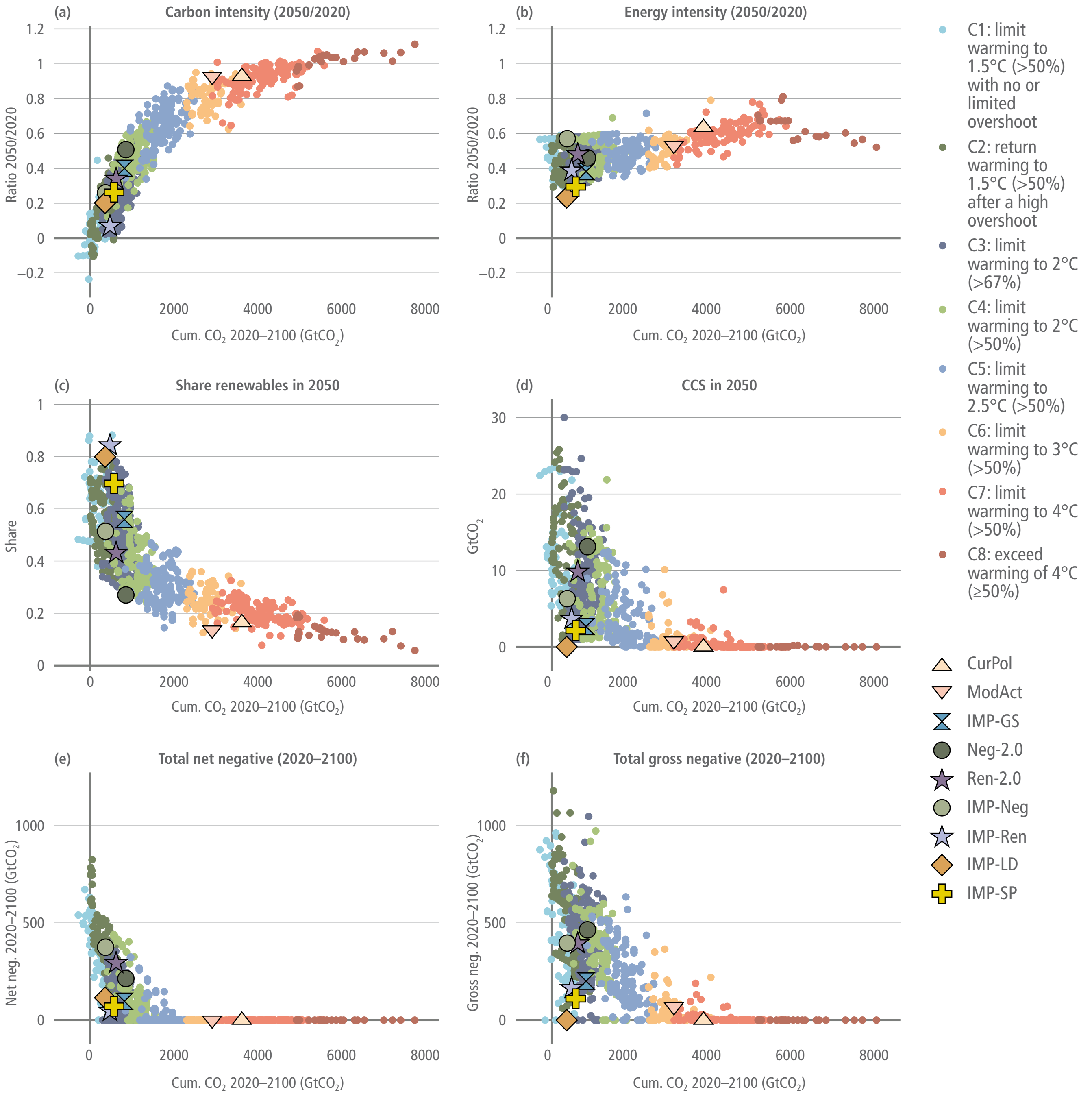


Figure 3.15 | Characteristics of scenarios as a function of the remaining carbon budget (mean decarbonisation rate is shown as the average reduction in the period 2010–2050 divided by 2010 emissions). The categories C1–C7 are explained in Table 3.1.

2014a,b; Lehtveer and Hedenus 2015a,b; Pfenninger and Keirstead 2015; Sepulveda et al. 2018; Zappa et al. 2019; IEA 2021b) (see also Box 6.6 on 100% renewables in net zero CO_2 systems). Panels e and f, finally, show the contribution of CDR – both in terms of net negative emissions and gross CDR. The contribution of total CDR obviously exceeds the net negative emissions. It should be noted that while a majority of scenarios rely on net negative emissions to reach stringent mitigation goals – this is not the case for all of them.

The spread shown in Figure 3.15 implies different mitigation strategies that could all lead to emissions levels consistent with the Paris Agreement (and reach zero emissions). The IMPs illustrate some options for different decarbonisation pathways with heavy reliance on renewables (*IMP-Ren*), strong emphasis on energy-demand reductions (*IMP-LD*), widespread deployment of CDR methods coupled with CCS (BECCS and DACCS) (*IMP-Neg*), mitigation in the context of sustainable development (*IMP-SP*) (Figure 3.16). For example, in some scenarios, a small part of the energy system is still based on fossil fuels in 2100 (*IMP-Neg*), while in others, fossil fuels are almost or completely phased out (*IMP-Ren*). Nevertheless, in all scenarios, fossil fuel use is greatly reduced and unabated coal use is completely phased out by 2050. Also, nuclear power can be part of a mitigation strategy (however, the literature only includes some scenarios with high-nuclear contributions, such as Berger et al. 2017).

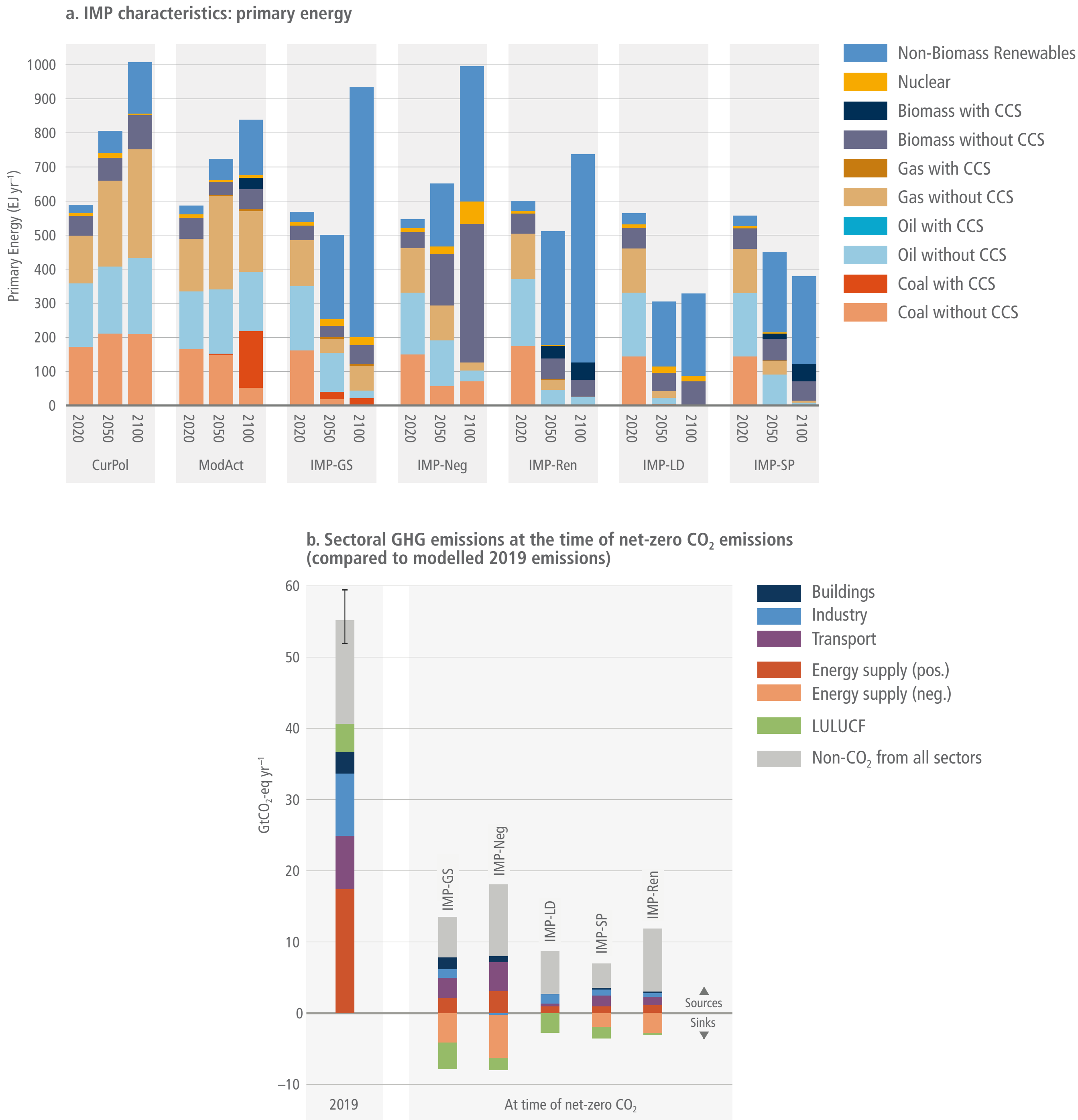


Figure 3.16 | Primary energy use and net emissions at net zero year for the different IMPS. Source: AR6 Scenarios Database.

This is explored further in Section 3.5. The different strategies are also clearly apparent in the way they scenarios reach net zero emissions. While *IMP-GS* and *IMP-Neg* rely significantly on BECCS and DACCS, their use is far more restricted in the other IMPs. Consistently, in these IMPs residual emissions are also significantly lower.

Mitigation pathways also have a regional dimension. In 2010, about 40% of emissions originated from the Developed Countries and Eastern Europe and West Central Asia regions. According to the projections shown in Figure 3.17, the share of the latter regions will further increase to about 70% by 2050. In the scenarios in the literature, emissions are typically almost equally reduced across the regions.

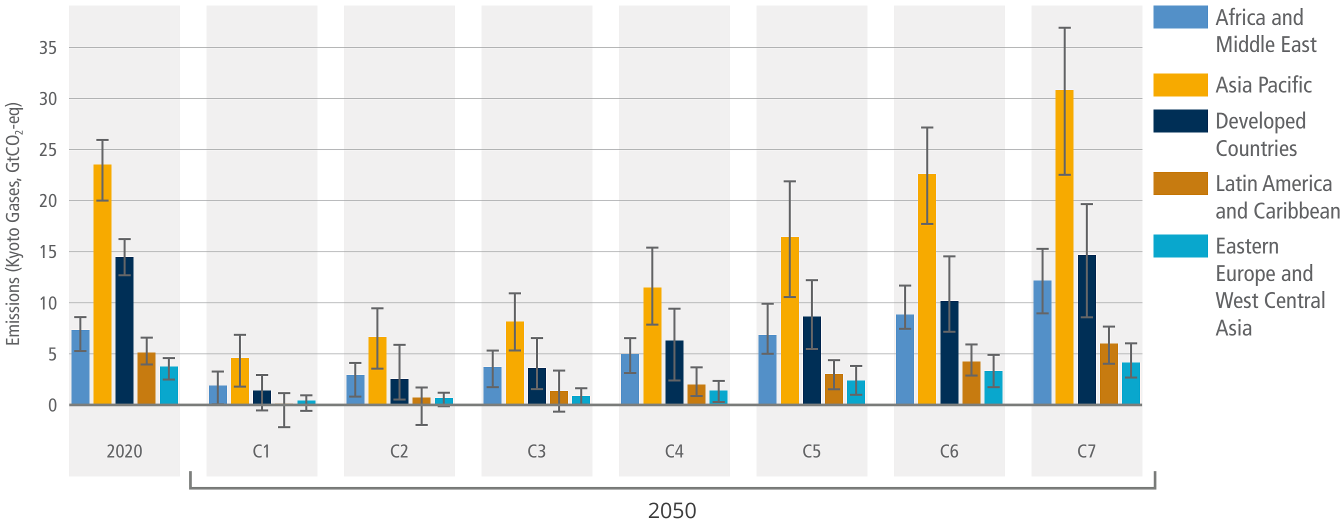


Figure 3.17[11] | Emissions by region (including 5–95th percentile range). Source: AR6 Scenarios Database.

3.3.3 Climate Impacts on Mitigation Potential

At the moment, climate change impact on mitigation potential is hardly considered in model-based scenarios. While a detailed overview of climate impacts is provided in IPCC AR6 WGII and Section 3.6 discusses the economic consequences, here we concentrate on the implications for mitigation potential. Climate change directly impacts the carbon budget via all kinds of feedbacks – which is included in the ranges provided for the carbon budget (e.g., 300–900 $GtCO_2$ for 17th–83rd percentile for not exceeding 1.5°C; see AR6 WGI Chapter 5, 2021). Climate change, however, alters the production and consumption of energy (Section 6.5). An overview of the literature is provided by Yalew et al. (2020). In terms of supply, impacts could influence the cooling capacity of thermal plants, the potential and predictability of renewable energy, and energy infrastructure (van Vliet et al. 2016; Turner et al. 2017; Cronin et al. 2018a; Lucena et al. 2018; Yalew et al. 2020; Gernaat et al. 2021). Although the outcomes of these studies differ, they seem to suggest that although impacts might be relatively small at the global scale, they could be substantial at the regional scale (increasing or decreasing potential). Climate change can also impact energy demand, with rising temperatures resulting in decreases in heating demand and increases in cooling demand (Isaac and van Vuuren 2009; Zhou et al. 2014; Labriet et al. 2015; McFarland et al. 2015; Auffhammer et al. 2017; Clarke et al. 2018; van Ruijven et al. 2019; Yalew et al. 2020). As expected, the increase in cooling demand dominates the impact in warm regions and decreases in heating demand in cold regions (Isaac and van Vuuren 2009; Zhou et al. 2014; Clarke et al. 2018). Globally, most studies show a net increase in energy demand at the end of the century due to climate impacts (Isaac and van Vuuren 2009; Clarke et al. 2018; van Ruijven et al. 2019); however, one study shows a net decrease (Labriet et al. 2015). Only a few studies quantify the combined impacts of climate change on energy supply and energy demand (McFarland et al. 2015; Mima and Criqui 2015; Emodi et al. 2019; Steinberg et al. 2020). These studies show increases in electricity generation in the USA (McFarland et al. 2015; Steinberg et al. 2020) and increases in CO_2 emissions in Australia (Emodi et al. 2019) or the USA (McFarland et al. 2015).

Climate change can impact the potential for AFOLU mitigation action by altering terrestrial carbon uptake, crop yields and bioenergy potential (Chapter 7). Carbon sequestration in forests may be positively or adversely affected by climate change and CO_2 fertilisation. On the one hand, elevated CO_2 levels and higher temperatures could enhance tree growth rates, carbon sequestration, and timber and biomass production (Beach et al. 2015; Kim et al. 2017; Anderegg et al. 2020). On the other hand, climate change could lead to greater frequency and intensity of disturbance events in forests, such as fires, prolonged droughts, storms, pests and diseases (Kim et al. 2017; Anderegg et al. 2020). The impact of climate change on crop yields could also indirectly impact the availability of land for mitigation and AFOLU emissions (Calvin et al. 2013; Bajželj and Richards 2014; Kyle et al. 2014; Beach et al. 2015; Meijl et al. 2018). The impact is, however, uncertain, as discussed in AR6 WGII Chapter 5. A few studies estimate the effect of climate impacts on AFOLU on mitigation, finding increases in carbon prices or mitigation costs by 1–6% in most scenarios (Calvin et al. 2013; Kyle et al. 2014).

In summary, a limited number of studies quantify the impact of climate on emissions pathways. The most important impact in energy systems might be through the impact on demand, although climate change could also impact renewable mitigation potential – certainly at the local and regional scale. Climate change might be more important for land-use related mitigation measures, including afforestation, bioenergy and nature-based solutions. The net effect of changes in climate and CO_2 fertilisation are uncertain but could be substantial (Chapter 7).

[11] The countries and areas classification in this figure deviate from the standard classification scheme adopted by AR6 WGIII as set out in Annex II.I.1.

3.4 Integrating Sectoral Analysis Into Systems Transformations

This section describes the role of sectors in long-term emissions pathways (Table 3.3). We discuss both sectoral aspects of IAM pathways and some insights from sectoral studies. Sectoral studies typically include more detail and additional mitigation options compared to IAMs. However, sectoral studies miss potential feedbacks and cross-sectoral linkages that are captured by IAMs. Additionally, since IAMs include all emissions sources, these models can be used to identify pathways to particular climate goals. In such pathways, emissions are balanced across sectors typically based on relative marginal abatement costs; as a result, some sectors are sources and some are sinks at the time of net zero CO_2 emissions. For these reasons, the mitigation observed in each sector in an IAM may differ from the potential in sectoral studies. Given the strengths and limitations of each type of model, IAMs and sectoral models are complementary, providing different perspectives.

Table 3.3 | Section 3.4 structure, definitions, and relevant chapters.

Section	Sector	What is included	Relevant chapter(s)
3.4.1	Cross-sector	Supply and demand, bioenergy, timing of net zero CO_2, other interactions among sectors	Chapters 5, 12
3.4.2	Energy supply	Energy resources, transformation (e.g., electricity generation, refineries, etc.)	Chapter 6
3.4.3	Buildings[a]	Residential and commercial buildings, other non-specified[b]	Chapter 9
3.4.4	Transportation[a]	Road, rail, aviation, and shipping	Chapter 10
3.4.5	Industry[a]	Industrial energy use and industrial processes	Chapter 11
3.4.6	AFOLU	Agriculture, forestry, and other land use	Chapter 7
3.4.7	Other CDR	CDR options not included in individual sectors (e.g., direct air carbon capture and sequestration, enhanced weathering)	Chapter 12

[a] Direct energy use and direct emissions only; emissions do not include those associated with energy production.

[b] Other non-specified fuel use, including military. Some models report this category in the buildings sector, while others report it in the 'Other' sector.

3.4.1 Cross-sector Linkages

3.4.1.1 Demand and Supply Strategies

Most IAM pathways rely heavily on supply-side mitigation strategies, including fuel switching, decarbonisation of fuels, and CDR (Creutzig et al. 2016; Bertram et al. 2018; Rogelj et al. 2018b; Mundaca et al. 2019). For demand-side mitigation, IAMs incorporate changes in energy efficiency, but many other demand-side options (e.g., behaviour and lifestyle changes) are often excluded from models (van Sluisveld et al. 2015; Creutzig et al. 2016; van den Berg et al. 2019; Wilson et al. 2019). In addition, this mitigation is typically price-driven and limited in magnitude (Yeh et al. 2017; Luderer et al. 2018; Wachsmuth and Duscha 2019; Sharmina et al. 2020). In contrast, bottom-up modelling studies show considerable potential for demand-side mitigation (Creutzig et al. 2016; Yeh et al. 2017; Mundaca et al. 2019; Wachsmuth and Duscha 2019) (Chapter 5), which can slow emissions growth and/or reduce emissions (Creutzig et al. 2016; Samadi et al. 2017).

A small number of mitigation pathways include stringent demand-side mitigation, including changes in thermostat set points (van Sluisveld et al. 2016; van Vuuren et al. 2018), more efficient or smarter appliances (van Sluisveld et al. 2016; Grubler et al. 2018; Napp et al. 2019), increased recycling or reduced industrial goods (Liu et al. 2018; van Sluisveld et al. 2016; Grubler et al. 2018; van de Ven et al. 2018; Napp et al. 2019), telework and travel avoidance (Grubler et al. 2018; van de Ven et al. 2018), shifts to public transit (van Sluisveld et al. 2016; Grubler et al. 2018; van Vuuren et al. 2018), reductions in food waste (van de Ven et al. 2018) and less meat-intensive diets (Liu et al. 2018; van de Ven et al. 2018; van Vuuren et al. 2018). These pathways show reduced dependence on CDR and reduced pressure on land (Grubler et al. 2018; Rogelj et al. 2018a; van de Ven et al. 2018; van Vuuren et al. 2018) (Section 5.3.3). However, the representation of these demand-side mitigation options in IAMs is limited, with most models excluding the costs of such changes (van Sluisveld et al. 2016), using stylised assumptions to represent them (van den Berg et al. 2019), and excluding rebound effects (Krey et al. 2019; Brockway et al. 2021). Furthermore, there are questions about the achievability of such pathways, including whether the behavioural changes included are feasible (Azevedo et al. 2021) and the extent to which development and demand can be decoupled (Steckel et al. 2013; Brockway et al. 2021; Keyßer and Lenzen 2021; Semieniuk et al. 2021).

Figure 3.18 shows indicators of supply- and demand-side mitigation in the IMPs, as well as the range across the database. Two of these IMPs (*IMP-SP*, *IMP-LD*) show strong reductions in energy demand, resulting in less reliance on bioenergy and limited CDR from energy supply. In contrast, *IMP-Neg* has higher energy demand, depending more on bioenergy and net negative CO_2 emissions from energy supply.

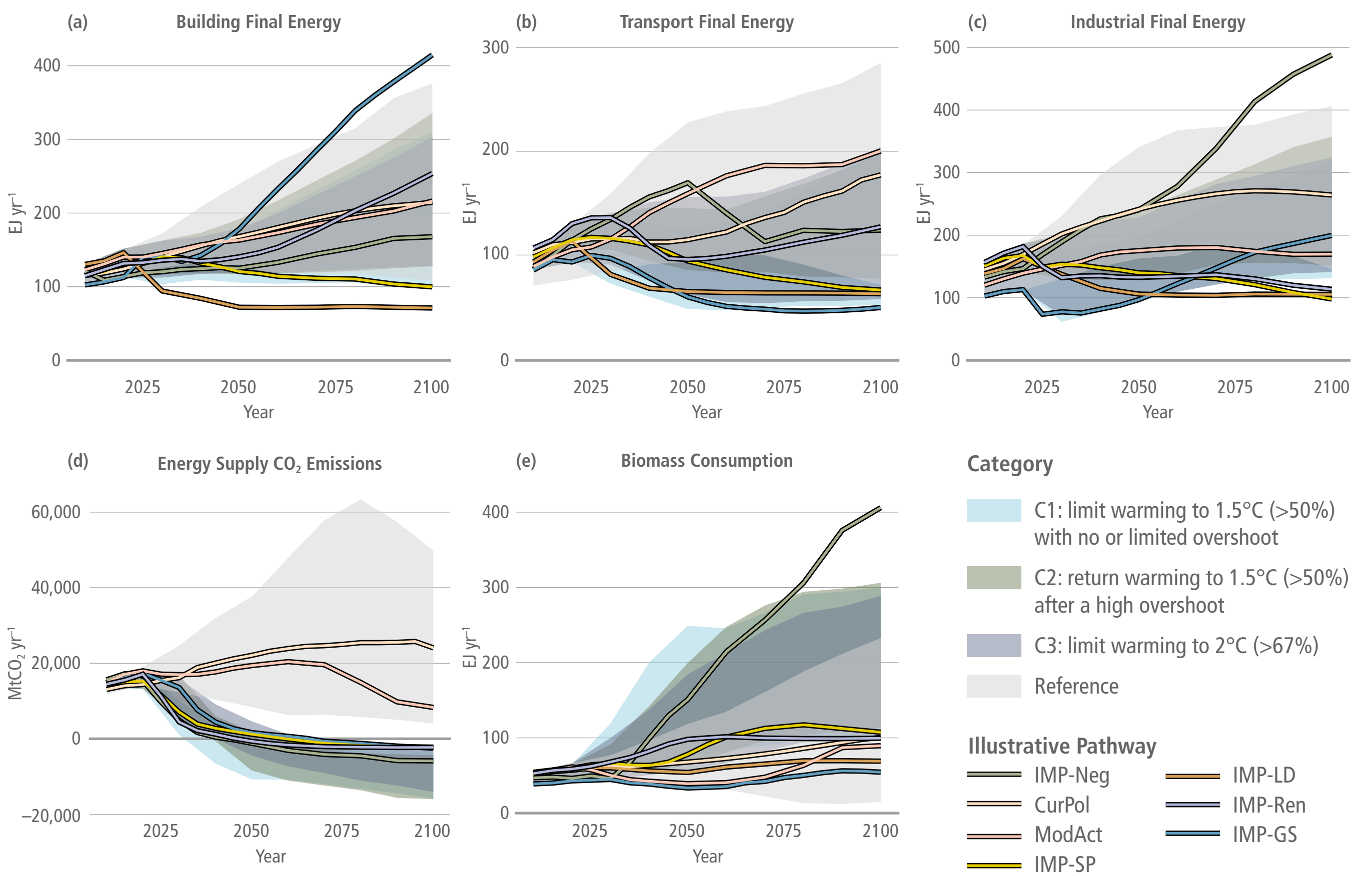


Figure 3.18 | Indicators of demand and supply-side mitigation in the Illustrative Pathways (lines) and the 5–95% range of Reference, 1.5°C and 2°C scenarios (shaded areas).

3.4.1.2 Sectoral Emissions Strategies and the Timing of Net Zero

Mitigation pathways show differences in the timing of decarbonisation (Figure 3.20) and the timing of net zero (Figure 3.19) across sectors and regions (*high confidence*); the timing in a given sector depends on the cost of abatement in it, the availability of CDR options, the scenario design, near-term emissions levels, and the amount of non-CO_2 abatement (Yeh et al. 2017; Emmerling et al. 2019; Rogelj et al. 2019a,b; Johansson et al. 2020; Azevedo et al. 2021; Ou et al. 2021; van Soest et al. 2021b) (Cross-Chapter Box 3 in this chapter). However, delaying emissions reductions, or more limited emissions reductions in one sector or region, involves compensating reductions in other sectors or regions if warming is to be limited (*high confidence*) (Price and Keppo 2017; Grubler et al. 2018; Rochedo et al. 2018; van Soest et al. 2021b).

At the time of net zero global CO_2 emissions, emissions in some sectors are positive and some negative. In cost-effective mitigation pathways, the energy supply sector typically reaches net zero CO_2 before the economy as a whole, while the demand sectors reach net zero CO_2 later, if at all (Pietzcker et al. 2014; Price and Keppo 2017; Luderer et al. 2018; Rogelj et al. 2018a,b; Méjean et al. 2019; Azevedo et al. 2021) (Section 6.7). CO_2 emissions from transport, industry, and buildings are positive, and non-CO_2 GHG emissions are also positive at the time of global net zero CO_2 emissions (Figure 3.20).

So, while pathways indicate some flexibility in emissions reductions across sectors, all pathways involve substantial CO_2 emissions reductions in all sectors and regions (*high confidence*) (Luderer et al. 2018; Rogelj et al. 2018a,b; Méjean et al. 2019; Azevedo et al. 2021). Projected CO_2 emissions reductions between 2019 and 2050 in 1.5°C (>50%) pathways with no or limited overshoot are around 77% for energy demand, with a 5–95% range of 31–96%,[12] 115% for energy supply (90–167%), and 148% for AFOLU (94–387%). In pathways that limit warming to 2°C (>67%), projected CO_2 emissions are reduced between 2019 and 2050 by around 49% for energy demand, 97% for energy supply, and 136% for AFOLU (Sections 3.4.2–3.4.6). Almost 75% of GHG reductions at the time of net zero GHG are from the energy system, 13% are from AFOLU CO_2, and 13% from non-CO_2 (Figure 3.21). These reductions are achieved through a variety of sectoral strategies, illustrated in Figure 3.21 (Figure 3.21b), and described in Sections 3.4.2 to 3.4.7; the primary strategies include declines in fossil energy, increases in low-carbon energy use, and CDR to address residual emissions.

12 Unless otherwise specified, the values in parentheses in Section 3.4 from this point forward indicate the 5–95th percentile range.

Table 3.4 | Energy and emissions characteristics of the pathways by climate category for 2030, 2050, 2100. Source: AR6 scenarios database.

p50 (p5–p95)[a]	Global Mean Surface Air Temperature change		Low-carbon share of Primary Energy [d, e] [%] 2020 = 16 (12–18)			Energy & Industrial Processes Index 2020 = 100			Final energy demand [EJ/yr] 2020 = 419 (367–458)			Final energy intensity of GDP Index 2020 = 100			Electricity share in final energy [%] 2020 = 20 (18–25)			CO2 intensity of electricity [Mt CO_2/TWh] 2020 = 469 (419–538)			Non-energy GHG emissions [Gt CO_2-eq] 2020 = 18 (15–21)			Fossil CCS (2100) [Gt CO_2] 2020 = 0 (0–0)			
Category [# pathways] [b, c]	Category/ subset	WG1 SSP & IPs alignment	2030	2050	2100	2030	2050	2100	2030	2050	2100	2030	2050	2100	2030	2050	2100	2030	2050	2100	2030	2050	2100	2030	2050	2100	2020–2100
C1 [97]	limit warming to 1.5°C (>50%) with no or limited overshoot	IMP-SD, IMP-LD, IMP-Ren, SSP1-1.9	32 (17–48)	68 (25–86)	75 (19–98)	65 (49–75)	8 (–8–24)	–3 (–20–8)	399 (293–447)	410 (325–540)	612 (321–818)	71 (59–81)	46 (34–60)	26 (14–45)	27 (23–35)	52 (40–64)	66 (50–78)	99 (4–215)	–5 (–66–11)	–4 (–104–1)	10 (5–13)	5 (1–9)	2 (–2–9)	1 (0–5)	2 (0–13)	3 (0–16)	196 (3–882)
C2 [133]	return warming to 1.5°C (>50%) after a high overshoot	IMP-Neg	24 (11–35)	57 (19–77)	86 (25–97)	79 (66–94)	18 (2–37)	–14 (–25–0)	458 (372–504)	442 (345–561)	675 (415–819)	76 (64–88)	44 (35–63)	23 (15–45)	25 (20–29)	45 (34–56)	61 (49–73)	218 (99–353)	0 (–75–16)	–1 (–118–3)	13 (10–19)	6 (2–9)	1 (–7–7)	0 (0–4)	3 (0–13)	1 (0–16)	280 (7–831)
C3 [311]	*limit warming to 2°C (>67%)*		24 (16–32)	51 (29–75)	73 (34–94)	84 (70–95)	31 (9–47)	–1 (–19–8)	446 (356–491)	448 (344–540)	625 (421–788)	77 (65–88)	50 (36–62)	26 (18–41)	24 (20–29)	42 (30–54)	60 (43–72)	248 (93–375)	5 (–72–51)	–8 (–105–5)	12 (6–18)	7 (3–12)	5 (–1–8)	0 (0–3)	3 (0–12)	5 (0–15)	266 (7–773)
C3a [204]	… with action starting in 2020	SSP2-2.6	21 (14–24)	39 (24–63)	71 (34–91)	92 (80–100)	45 (26–64)	–3 (–21–9)	459 (379–497)	489 (362–601)	641 (450–796)	76 (71–87)	45 (39–65)	22 (19–41)	23 (19–28)	35 (23–44)	56 (44–69)	322 (227–381)	24 (–48–112)	–14 (–117–7)	13 (8–19)	9 (3–12)	2 (–1–9)	0 (0–2)	2 (0–9)	6 (0–16)	279 (7–684)
C3b [97]	… NDCs until 2030	IMP-GS	21 (12–24)	31 (22–44)	67 (42–84)	92 (84–102)	66 (50–84)	9 (–13–32)	466 (389–499)	519 (435–585)	680 (383–812)	77 (74–88)	51 (45–66)	23 (18–40)	23 (19–28)	32 (19–41)	53 (40–65)	341 (257–418)	107 (14–208)	–3 (–73–34)	15 (10–19)	10 (5–15)	4 (–1–11)	0 (0–1)	1 (0–7)	5 (0–15)	200 (5–730)
C4 [159]	limit warming to 2°C (>50%)		20 (11–23)	25 (14–36)	47 (28–65)	94 (87–101)	82 (67–92)	47 (21–78)	467 (410–508)	551 (471–632)	701 (432–910)	79 (75–89)	55 (50–70)	26 (20–42)	23 (19–28)	29 (19–38)	48 (30–56)	354 (257–469)	216 (69–317)	28 (–20–166)	17 (11–20)	13 (9–17)	8 (2–12)	0 (0–0)	0 (0–4)	4 (0–16)	47 (0–536)
C5 [212]	limit warming to 2.5°C (>50%)		17 (11–21)	19 (8–29)	29 (8–51)	98 (91–101)	94 (80–101)	73 (56–106)	492 (434–540)	599 (513–701)	804 (557–983)	85 (76–91)	64 (54–76)	33 (27–48)	24 (20–28)	29 (23–35)	41 (29–50)	414 (311–538)	311 (130–499)	185 (12–461)	19 (13–24)	19 (14–25)	16 (9–26)	0 (0–0)	0 (0–2)	0 (0–8)	0 (0–221)
C6 [97]	limit warming to 3°C (>50%)	SSP2-4.5 Mod-Act	13 (11–17)	13 (9–20)	29 (14–45)	102 (99–103)	106 (104–109)	91 (87–95)	540 (413–574)	696 (504–856)	941 (692–1136)	89 (88–92)	73 (64–79)	47 (25–51)	26 (22–30)	31 (28–35)	43 (35–50)	463 (372–514)	425 (352–484)	189 (142–441)	20 (19–25)	21 (20–29)	20 (13–31)	0 (0–0)	0 (0–0)	0 (0–2)	0 (0–38)
C7 [164]	limit warming to 4°C (>50%)	SSP3-7.0 Cur-Pol	32 (17–48)	68 (25–86)	75 (19–98)	65 (49–75)	8 (–8–24)	–3 (–20–8)	399 (293–447)	410 (325–540)	612 (321–818)	71 (59–81)	46 (34–60)	26 (14–45)	27 (23–35)	52 (40–64)	66 (50–78)	99 (4–215)	–5 (–66–11)	–4 (–104–1)	10 (5–13)	5 (1–9)	2 (–2–9)	1 (0–5)	2 (0–13)	3 (0–16)	196 (3–882)
C8 [29]	exceed warming of 4°C (≥50%)	SSP5-8.5	24 (11–35)	57 (19–77)	86 (25–97)	79 (66–94)	18 (2–37)	–14 (–25–0)	458 (372–504)	442 (345–561)	675 (415–819)	76 (64–88)	44 (35–63)	23 (15–45)	25 (20–29)	45 (34–56)	61 (49–73)	218 (99–353)	0 (–75–16)	–1 (–118–3)	13 (10–19)	6 (2–9)	1 (–7–7)	0 (0–4)	3 (0–13)	1 (0–16)	280 (7–831)

[a] Values in the table refer to the 50th and (5–95th) percentile values.

[b] See category descriptions in Table 3.1.

[c] The warming profile of *IMP-Neg* peaks around 2060 and declines thereafter to below 1.5°C (50% likelihood) shortly after 2100. Whilst technically classified as a C3, it strongly exhibits the characteristics of C2 high-overshoot scenarios.

[d] Primary Energy as calculated in 'Direct Equivalent' terms according to IPCC reporting conventions.

[e] Low-carbon energy here defined to include: renewables (including biomass, solar, wind, hydro, geothermal, ocean); fossil fuels when used with CCS; and, nuclear power.

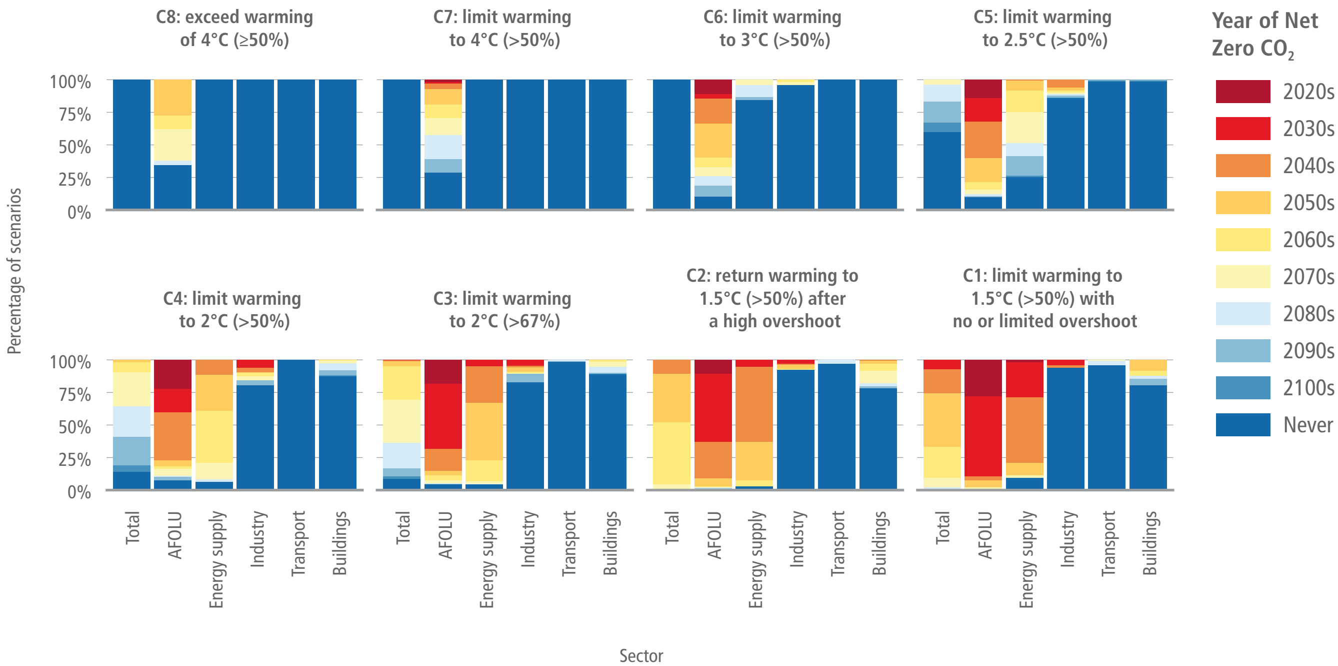


Figure 3.19 | Decade in which sectoral CO_2 emissions first reach net negative values. Each panel is a different temperature level. The colours indicate the decade in which CO_2 emissions go negative; the y-axis indicates the share of scenarios achieving net zero in that decade. Only scenarios that pass the vetting criteria are included (Section 3.2). Scenarios achieving net zero prior to 2020 are excluded.

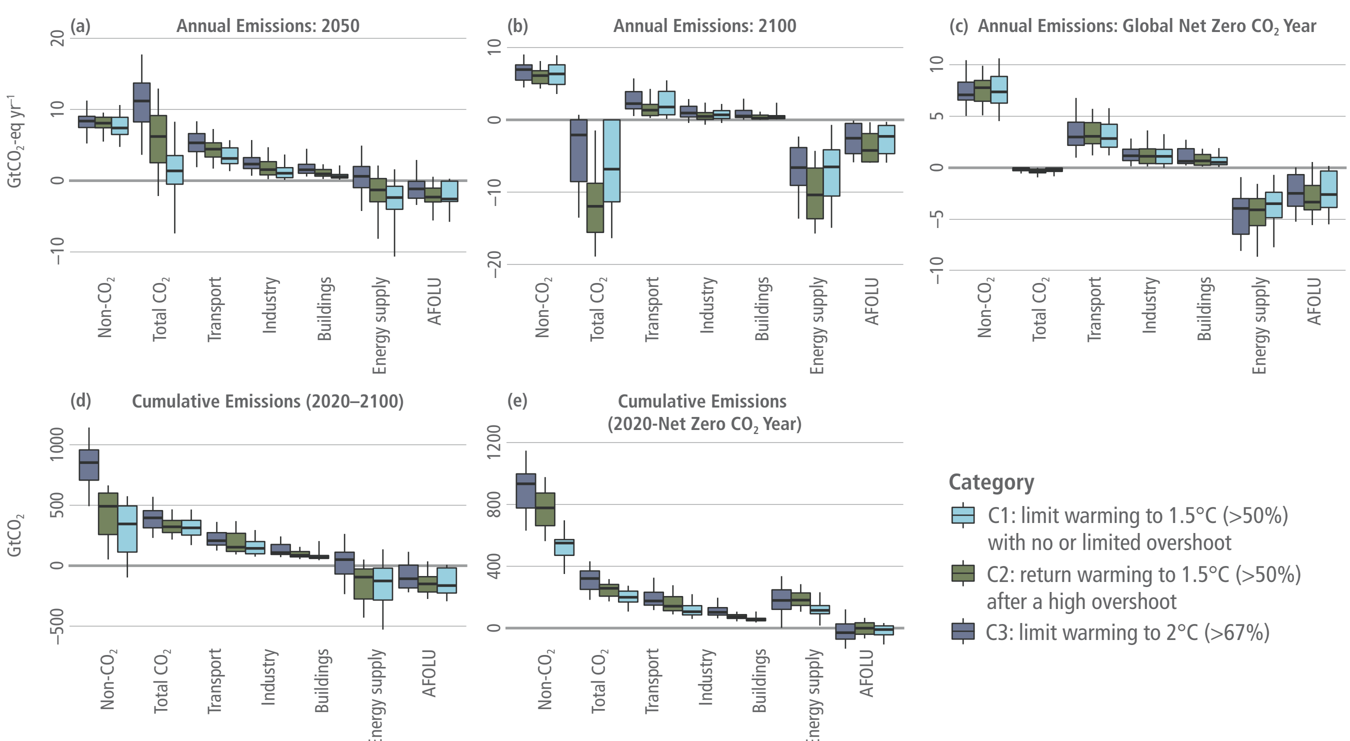


Figure 3.20 | Greenhouse gas (GHG) emissions, including CO_2 emissions by sector and total non-CO_2 GHGs in 2050 (top left), 2100 (top middle), year of global net zero CO_2 (top right), cumulative CO_2 emissions from 2020–2100 (bottom left), and cumulative CO_2 emissions from 2020 until the year of net zero CO_2 for scenarios that limit warming to below 2°C. Scenarios are grouped by their temperature category. 'Industry' includes CO_2 emissions associated with industrial energy use only; sectors shown in this figure do not necessarily sum to total CO_2. In this, and other figures in Section 3.4, unless stated otherwise, only scenarios that pass the vetting criteria are included (Section 3.2). Boxes indicate the interquartile range, the median is shown with a horizontal black line, while vertical lines show the 5–95% interval.

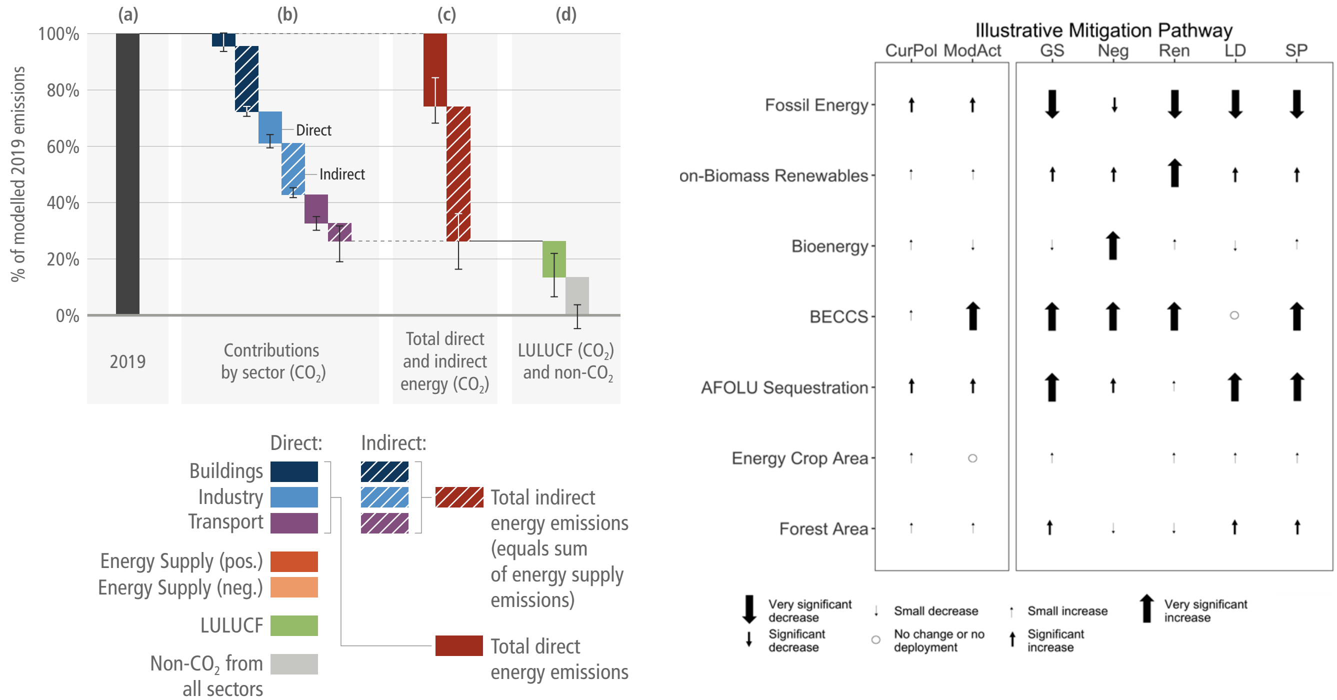


Figure 3.21 | Left panel: Greenhouse gas (GHG) emissions reductions from 2019 by sector at the year of net zero GHG for all scenarios that reach net zero GHG. Emissions reductions by sector for direct (demand) and indirect (upstream supply) are shown as the percent of total GHG reductions. **Right panel:** key indicators in 2050 for the IMPs. Definitions of significant and very significant are defined relative to 2019 and vary between indicators, as follows: fossil energy (significant >10%, very significant >50%), renewables (>150 EJ yr^{-1}, >200 EJ yr^{-1}), bioenergy (>100%, >200%), BECCS (>2.0 $GtCO_2$ yr^{-1}, >3.5 $GtCO_2$ yr^{-1}), AFOLU (>100% decline, >130% decline), energy crops (>150 million ha, >400 million ha), forest (>5% increase, >15% increase). Source: AR6 Scenarios Database.

In the context of mitigation pathways, only a few studies have examined solar radiation modification (SRM), typically focusing on Stratospheric Aerosol Injection (Arinoa et al. 2016; Emmerling and Tavoni 2018a,b; Heutel et al. 2018; Helwegen et al. 2019; Rickels et al. 2020; Belaia et al. 2021). These studies find that substantial mitigation is required to limit warming to a given level, even if SRM is available (Moreno-Cruz and Smulders 2017; Emmerling and Tavoni 2018b; Belaia et al. 2021). SRM may reduce some climate impacts, reduce peak temperatures, lower mitigation costs, and extend the time available to achieve mitigation; however, SRM does not address ocean acidification and may involve risks to crop yields, economies, human health, or ecosystems (AR6 WGII Chapter 16; AR6 WGI TS and Chapter 5; SR1.5 SPM; and Cross-Working Group Box 4 in Chapter 14 of this report). There are also significant uncertainties surrounding SRM, including uncertainties on the costs and risks, which can substantially alter the amount of SRM used in modelled pathways (Tavoni et al. 2017; Heutel et al. 2018; IPCC 2018; Helwegen et al. 2019; NASEM 2021). Furthermore, the degree of international cooperation can influence the amount of SRM deployed in scenarios, with uncoordinated action resulting in larger SRM deployment and consequently larger risks/impacts from SRM (Emmerling and Tavoni 2018a). Bridging research and governance involves consideration of the full range of societal choices and ramifications (Sugiyama et al. 2018). More information on SRM, including the caveats, risks, uncertainties, and governance issues is found in AR6 WGI Chapter 4; AR6 WGIII Chapter 14; and Cross-Working Group Box 4 in Chapter 14 of this report.

3.4.1.3 Linkages Among Sectors

Mitigation in one sector can be dependent upon mitigation in another sector, or may involve trade-offs between sectors. Mitigation in energy demand often includes electrification (Pietzcker et al. 2014; Luderer et al. 2018; Sharmina et al. 2020; DeAngelo et al. 2021), however such pathways only result in reduced emissions *if* the electricity sector is decarbonised (Zhang and Fujimori 2020) (Chapter 12). Relatedly, the mitigation potential of some sectors (e.g., transportation) depends on the decarbonisation of liquid fuels, for example, through biofuels (Pietzcker et al. 2014; Wise et al. 2017; Sharmina et al. 2020) (Chapter 12). In other cases, mitigation in one sector results in reduced emissions in another sector. For example, increased recycling can reduce primary resource extraction; planting trees or green roofs in urban areas can reduce the energy demand associated with space cooling (Chapter 12).

Mitigation in one sector can also result in additional emissions in another. One example is electrification of end use which can result in increased emissions from energy supply. However, one comparitively well-researched example of this linkage is bioenergy. An increase in demand for bioenergy within the energy system has the potential to influence emissions in the AFOLU sector through the intensification of land and forest management and/or via land-use change (Daioglou et al. 2019; Smith et al. 2019; Smith et al. 2020a; IPCC 2019a). The effect of bioenergy and BECCS on mitigation depends on a variety of factors in modelled pathways. In the energy system, the emissions mitigation depends on the scale of deployment, the conversion technology, and the fuel displaced (Calvin et al. 2021).

Limiting or excluding bioenergy and/or BECCS increases mitigation cost and may limit the ability of a model to reach a low warming level (Edmonds et al. 2013; Calvin et al. 2014b; Luderer et al. 2018; Muratori et al. 2020). In AFOLU, bioenergy can increase or decrease terrestrial carbon stocks and carbon sequestration, depending on the scale, biomass feedstock, land management practices, and prior land use (Calvin et al. 2014c; Wise et al. 2015; IPCC 2019a; Smith et al. 2019, 2020a; Calvin et al. 2021).

Pathways with very high biomass production for energy use typically include very high carbon prices in the energy system (Popp et al. 2017; Rogelj et al. 2018b), little or no land policy (Calvin et al. 2014b), a high discount rate (Emmerling et al. 2019), and limited non-BECCS CDR options (e.g., afforestation, DACCS) (Chen and Tavoni 2013; Calvin et al. 2014b; Marcucci et al. 2017; Realmonte et al. 2019; Fuhrman et al. 2020). Higher levels of bioenergy consumption are likely to involve trade-offs with mitigation in other sectors, notably in construction (i.e., wood for material and structural products) and AFOLU (carbon stocks and future carbon sequestration), as well as trade-offs with sustainability (Section 3.7) and feasibility concerns (Section 3.8). Not all of these trade-offs are fully represented in all IAMs. Based on sectoral studies, the technical potential for bioenergy, when constraints for food security and environmental considerations are included, are 5–50 EJ yr^{-1} and 50–250 EJ yr^{-1} in 2050 for residues and dedicated biomass production systems, respectively (Chapter 7). Bioenergy deployment in IAMs is within the range of these potentials, with between 75 and 248 EJ yr^{-1} in 2050 in pathways that limit warming to 1.5°C with no or limited overshoot. Finally, IAMs do not include all potential feedstock and management practices, and have limited representation of institutions, governance, and local context (Brown et al. 2019; Butnar et al. 2020; Calvin et al. 2021).

The inclusion of CDR options, like BECCS, can affect the timing of emissions mitigation in IAM scenarios, that is, delays in mitigations actions are compensated by net negative emissions in the second half of the century. However, studies with limited net negative emissions in the long term require very rapid declines in emissions in the near term (van Vuuren et al. 2017). Especially in forest-based systems, increased harvesting of forests can perturb the carbon balance of forestry systems, increasing emissions for some period; the duration of this period of increased emissions, preceding net emissions reductions, can be very variable (Mitchell et al. 2012; Lamers and Junginger 2013; Röder et al. 2019; Hanssen et al. 2020; Cowie et al. 2021). However, the factors contributing to differences in recovery time are known (Mitchell et al. 2012; Zanchi et al. 2012; Lamers and Junginger 2013; Laganière et al. 2017; Röder et al. 2019). Some studies that consider market-mediated effects find that an increased demand for biomass from forests can provide incentives to maintain existing forests and potentially to expand forest areas, providing additional carbon sequestration as well as additional biomass (Dwivedi et al. 2014; Kim et al. 2018; Baker et al. 2019; Favero et al. 2020). However, these responses are uncertain and likely to vary geographically.

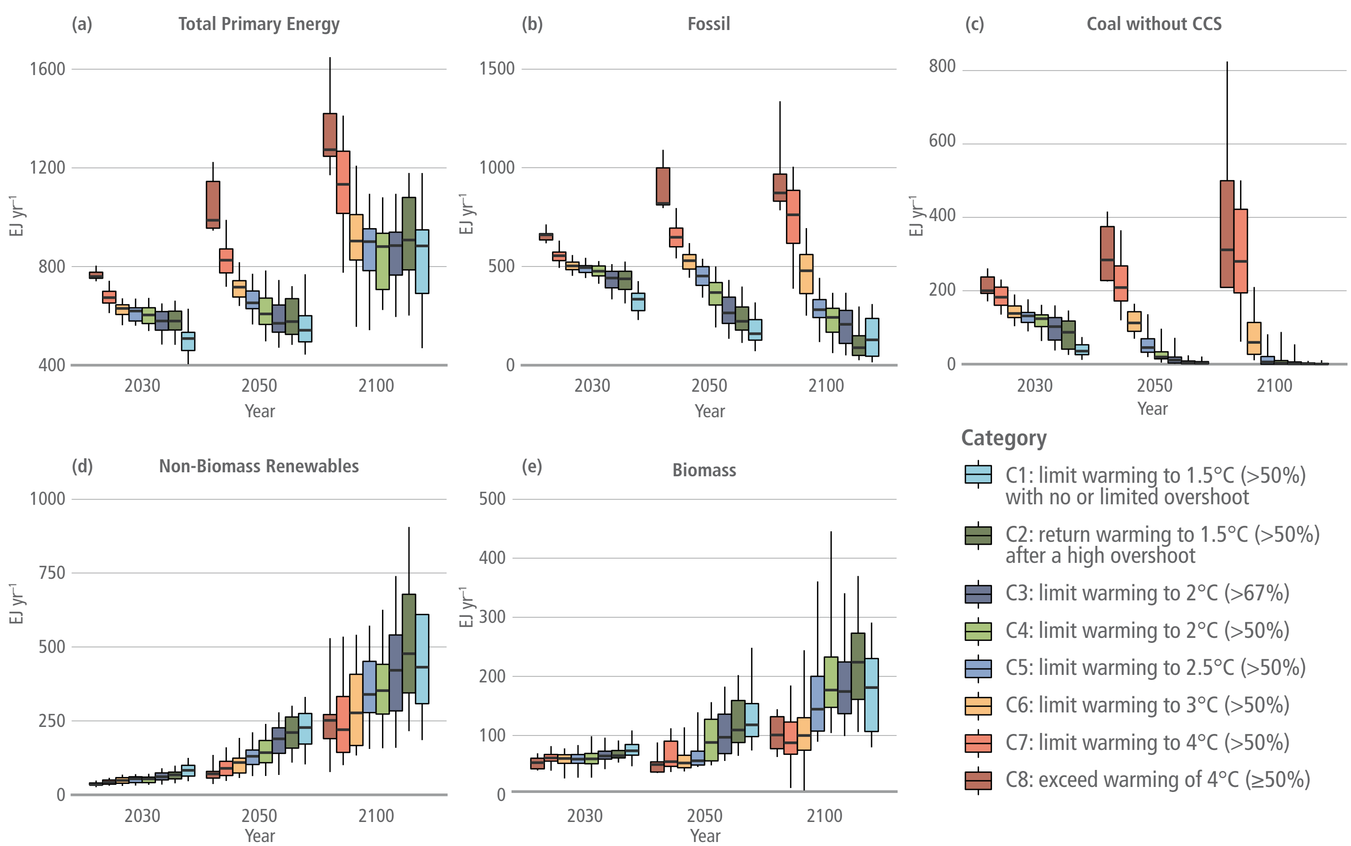


Figure 3.22 | Primary energy consumption across scenarios: total primary energy (a), fossil fuels (b), coal without CCS (c), non-biomass renewables (d), and biomass (e). Scenarios are grouped by their temperature category. Primary energy is reported in direct equivalent, where one unit of nuclear or non-biomass renewable energy output is reported as one unit of primary energy. Not all subcategories of primary energy are shown.

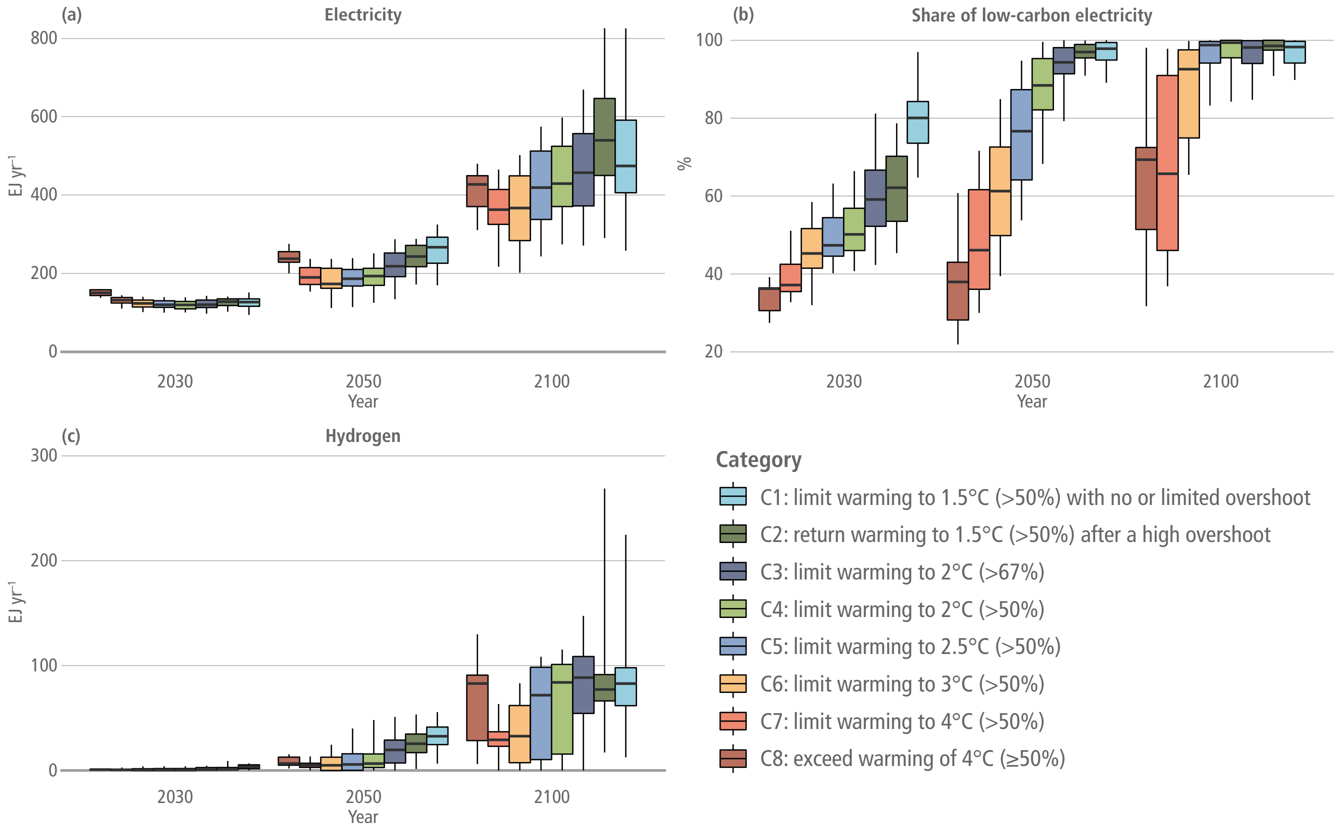


Figure 3.23 | Electricity (top left), share of low-carbon electricity (top right), and hydrogen (bottom left) production across all scenarios, grouped by the categories introduced in Section 3.2. Low carbon includes non-biomass renewables, biomass, nuclear, and CCS.

3.4.2 Energy Supply

Without mitigation, energy consumption and supply emissions continue to rise (*high confidence*) (Kriegler et al. 2016; Bauer et al. 2017; Riahi et al. 2017; Mcjeon et al. 2021) (Section 6.7). While the share of renewable energy continues to grow in reference scenarios, fossil fuel accounts for the largest share of primary energy (Bauer et al. 2017; Price and Keppo 2017; Riahi et al. 2017). In scenarios that limit warming to 2°C or lower, transition of the energy-supply sector to a low- or no-carbon system is rapid (Rogelj et al. 2016, 2018b; Grubler et al. 2018; Luderer et al. 2018; van Vuuren et al. 2018). CO_2 emissions from energy supply reach net zero around 2041 (2033–2057) in pathways limiting warming to 1.5°C (>50%) with no or limited overshoot and around 2053 (2040–2066) in pathways that limit warming to 2°C (>67%). Emissions reductions continue, with emissions reaching –7.1 $GtCO_2\ yr^{-1}$ (–15 to –2.3 $GtCO_2\ yr^{-1}$) in 2100 in all pathways that limit warming to 2°C (>67%) or lower.

All pathways that limit warming to 2°C (>67%) or lower show substantial reductions in fossil fuel consumption and a near elimination of the use of coal without CCS (*high confidence*) (Bauer et al. 2017; van Vuuren et al. 2018; Grubler et al. 2018; Luderer et al. 2018; Rogelj et al. 2018a,b; Azevedo et al. 2021; Mcjeon et al. 2021; Welsby et al. 2021) (Figure 3.22). In these pathways, the use of coal, gas and oil is reduced by 90%, 25%, and 41%, respectively, between 2019 and 2050 and 91%, 39%, and 78% between 2019 and 2100; coal without CCS is further reduced to 99% below its 2019 levels in 2100. These pathways show an increase in low-carbon energy, with 88% (69–97%) of primary energy from low-carbon sources in 2100, with different combinations of low-carbon fuels (e.g., non-biomass renewables, biomass, nuclear, and CCS) (Rogelj et al. 2018a,b; van Vuuren et al. 2018) (Sections 3.4.1 and 6.7). Across all pathways that limit warming to 2°C and below, non-biomass renewables account for 52% (24–77%) of primary energy in 2100 (Creutzig et al. 2017; Pietzcker et al. 2017; Rogelj et al. 2018b) (Chapter 6 and Figure 3.22). There are some studies analysing the potential for 100% renewable energy systems (Hansen et al. 2019); however, there are a range of issues around such systems (Box 6.6).

Stringent emissions reductions at the level required to limit warming to 2°C (>67%) or 1.5°C are achieved through increased electrification of end use, resulting in increased electricity generation in all pathways (*high confidence*) (Rogelj et al. 2018a; Azevedo et al. 2021) (Figure 3.23). Nearly all electricity in pathways *likely* to limit warming to 2°C and below is from low- or no-carbon fuels (Rogelj et al. 2018a; Azevedo et al. 2021), with different shares of nuclear, biomass, non-biomass renewables, and fossil CCS across pathways. Low-emissions scenarios also show increases in hydrogen use (Figure 3.23).

3.4.3 Buildings

Global final energy use in the building sector increases in all pathways as a result of population growth and increasing affluence

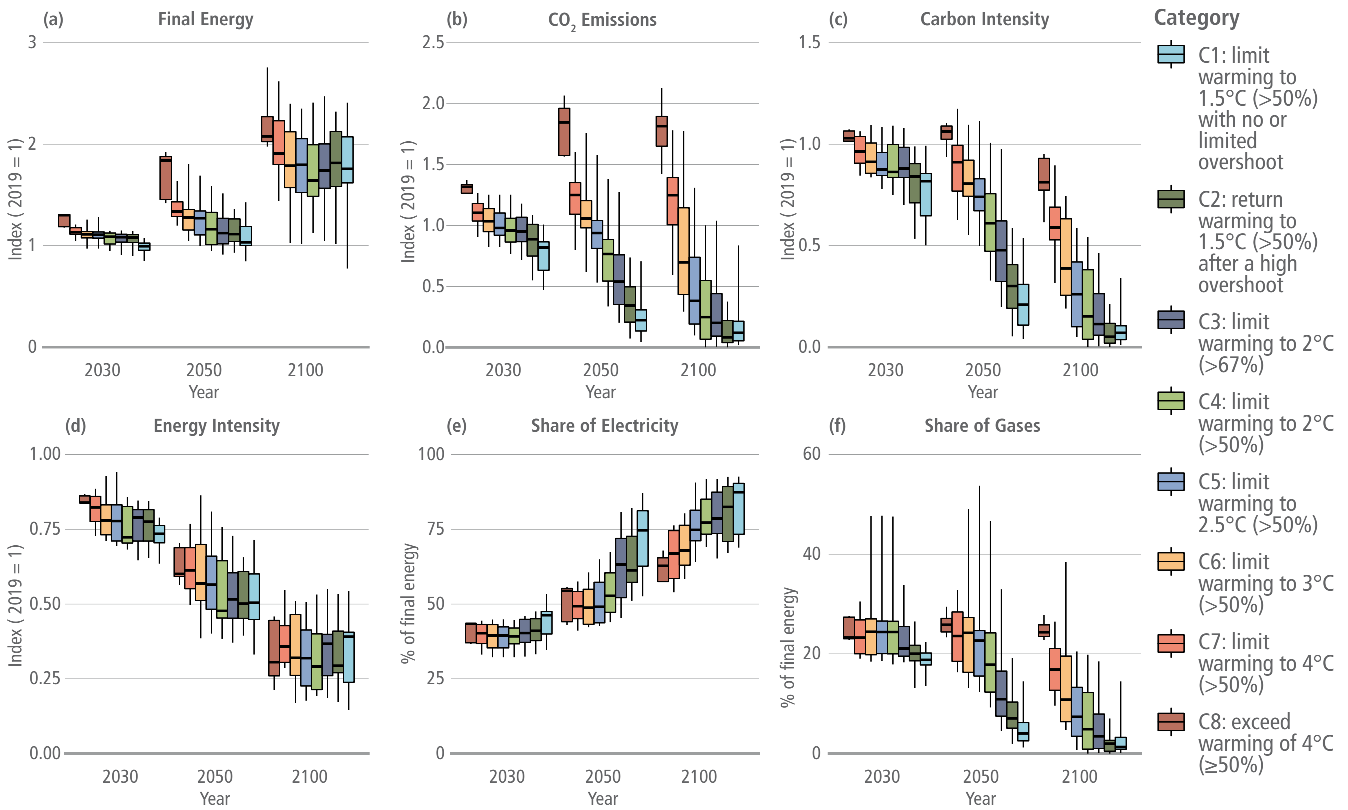


Figure 3.24 | Buildings final energy (a), CO_2 emissions (b), carbon intensity (c), energy intensity (d), share of final energy from electricity (e), and share of final energy from gases (f). Energy intensity is final energy per unit of GDP. Carbon intensity is CO_2 emissions per EJ of final energy. The first four indicators are indexed to 2019,[12] where values less than 1 indicate a reduction.

(Figure 3.24). There is very little difference in final energy intensity for the buildings sector across scenarios. Direct CO_2 emissions from the buildings sector vary more widely across temperature stabilisation levels than energy consumption. In 2100, scenarios above 3°C [C7–C8] still show an increase of CO_2 emissions from buildings around 29% above 2019, while all scenarios *likely* to limit warming to 2°C and below have emission reductions of around 85% (8–100%). Carbon intensity declines in all scenarios, but much more sharply as the warming level is reduced.

In all scenarios, the share of electricity in final energy use increases, a trend that is accelerated by 2050 for the scenarios *likely* to limit warming to 2°C and below (Figure 3.23). By 2100, the low-warming scenarios show large shares of electricity in final energy consumption for buildings. The opposite is observed for gases.

While several global IAM models have developed their buildings modules considerably over the past decade (Daioglou et al. 2012; Knobloch et al. 2017; Clarke et al. 2018; Edelenbosch et al. 2021; Mastrucci et al. 2021), the extremely limited availability of key sectoral variables in the AR6 scenarios database (such as floor space and energy use for individual services) prohibit a detailed analysis of sectoral dynamics. Individual studies in the literature often focus on single aspects of the buildings sector, though collectively providing a more comprehensive overview (Edelenbosch et al. 2020; Ürge-Vorsatz et al. 2020). For example, energy demand is driven by economic development that fulfills basic needs (Mastrucci et al. 2019; Rao et al. 2019a), but also drives up floor space in general (Daioglou et al. 2012; Levesque et al. 2018; Mastrucci et al. 2021) and ownership of energy-intensive appliances such as air conditioners (Isaac and van Vuuren 2009; Colelli and Cian 2020; Poblete-Cazenave et al. 2021). These dynamics are heterogeneous and lead to differences in energy demand and emission mitigation potential across urban/rural buildings and income levels (Krey et al. 2012; Poblete-Cazenave et al. 2021). Mitigation scenarios rely on fuel switching and technology (Knobloch et al. 2017; Dagnachew et al. 2020), efficiency improvement in building envelopes (Levesque et al. 2018; Edelenbosch et al. 2021) and behavioural changes (van Sluisveld et al. 2016; Niamir et al. 2018, 2020). The in-depth dynamics of mitigation in the building sector are explored in Chapter 9.

3.4.4 Transport

Reference scenarios show growth in transport demand, particularly in aviation and freight (Yeh et al. 2017; Sharmina et al. 2020; Müller-Casseres et al. 2021b). Energy consumption continues to be dominated by fossil fuels in reference scenarios, with some increases in electrification (Yeh et al. 2017; Edelenbosch et al. 2020; Yeh et al.

[13] 2019 values are from model results and interpolated from other years when not directly reported.

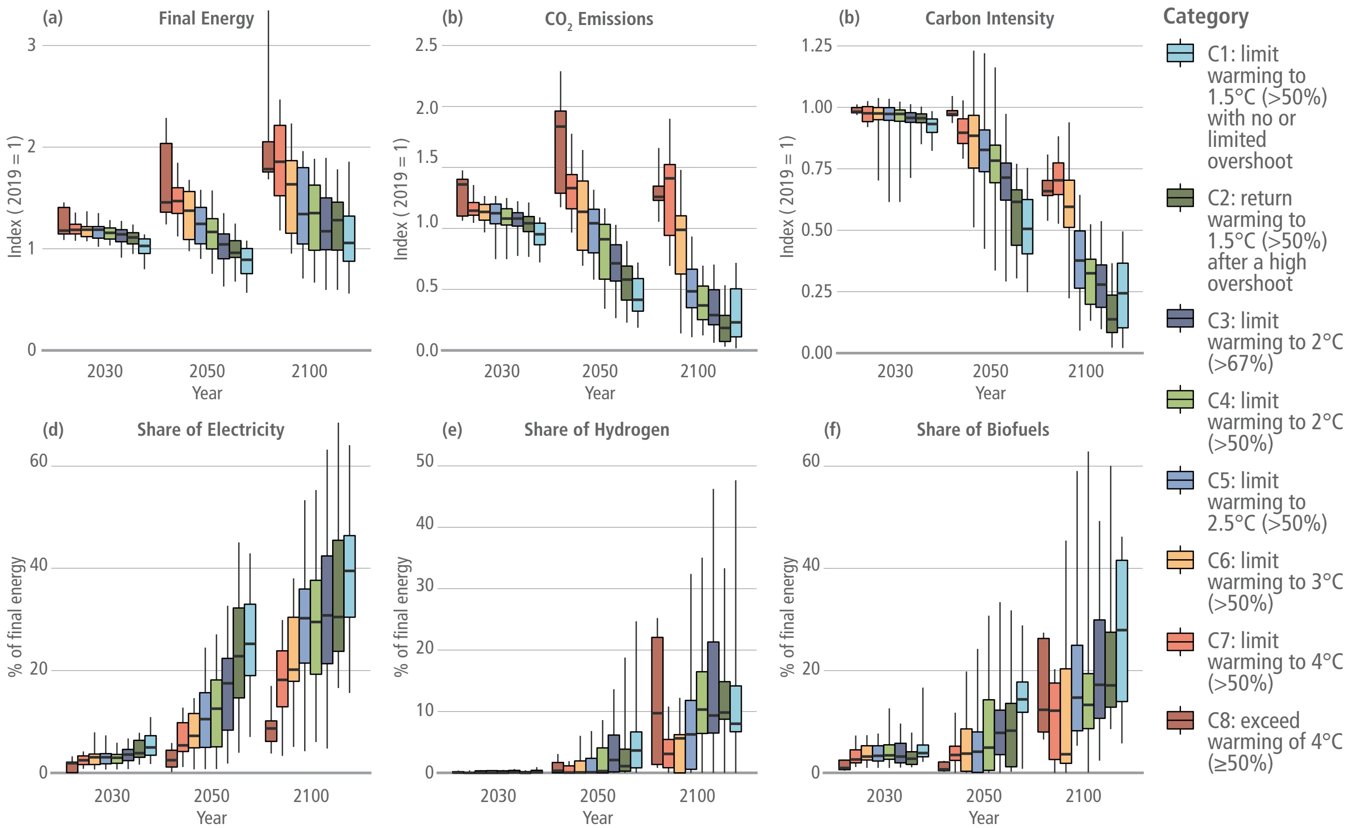


Figure 3.25 | Transport final energy (a), CO_2 emissions (b), carbon intensity (cand share of final energy from electricity (d), hydrogen (e), and biofuels (f). See Chapter 10 for a discussion of energy intensity. Carbon intensity is CO_2 emissions per EJ of final energy. The first three indicators are indexed to 2019,[13], where values less than 1 indicate a reduction.

2017). CO_2 emissions from transport increase for most models in reference scenarios (Yeh et al. 2017; Edelenbosch et al. 2020).

The relative contribution of demand-side reduction, energy- efficiency improvements, fuel switching, and decarbonisation of fuels, varyies by model, level of mitigation, mitigation options available, and underlying socio-economic pathway (Longden 2014; Wise et al. 2017; Yeh et al. 2017; Luderer et al. 2018; Yeh et al. 2017; Edelenbosch et al. 2020; Müller-Casseres et al. 2021a,b). IAMs typically rely on technology-focused measures like energy- efficiency improvements and fuel switching to reduce carbon emissions (Pietzcker et al. 2014; Edelenbosch et al. 2017a; Yeh et al. 2017; Zhang et al. 2018a,b; Rogelj et al. 2018b; Zhang et al. 2018a,b; Sharmina et al. 2020). Many mitigation pathways show electrification of the transport system (Luderer et al. 2018; Pietzcker et al. 2014; Longden 2014; Luderer et al. 2018; Zhang et al. 2018a); however, without decarboniszation of the electricity system, transport electrification can increase total energy system emissions (Zhang and Fujimori 2020). A small number of pathways include demand-side mitigation measures in the transport sector; these studies show reduced carbon prices and reduced dependence on CDR (Grubler et al. 2018; Méjean et al. 2019; van de Ven et al. 2018; Zhang et al. 2018c; Méjean et al. 2019) (Section 3.4.1).

Across all IAM scenarios assessed, final energy demand for transport continues to grow, including in many stringent mitigation pathways (Figure 3.25). The carbon intensity of energy declines substantially by 2100 in *likely* 2°C (>67%) and below scenarios, leading to substantial declines in transport sector CO_2 emissions with increased electrification of the transport system (Figure 3.23).

The transport sector has more detail than other sectors in many IAMs (Edelenbosch et al. 2020); however, there is considerable variation across models. Some models (e.g., GCAM, IMAGE, MESSAGE-GLOBIOM) represent different transport modes with endogenous shifts across modes as a function of income, price, and modal speed (Edelenbosch et al. 2020).[15] However, IAMs, including those with detailed transport, exclude several supply-side (e.g., synthetic fuels) and demand-side (e.g., behaviour change, reduced shipping, telework and automation) mitigation options (Pietzcker et al. 2014; Creutzig et al. 2016; Mittal et al. 2017; Davis et al. 2018; Köhler et al. 2020; Mittal et al. 2017; Gota et al. 2019; Wilson et al. 2019; Creutzig et al. 2016; Köhler et al. 2020; Sharmina et al. 2020; Pietzcker et al. 2014; Lefèvre et al. 2021; Müller-Casseres et al. 2021a,b).

14 2019 values are from model results and interpolated from other years when not directly reported.

15 Some of these models are treated as global transport energy sectoral models (GTEMs) in Chapter 10.

As a result of these missing options and differences in how mitigation is implemented, IAMs tend to show less mitigation than the potential from national transport/energy models (Wachsmuth and Duscha 2019; Gota et al. 2019; Yeh et al. 2017; Gota et al. 2019; Wachsmuth and Duscha 2019; Edelenbosch et al. 2020). For the transport sector as a whole, studies suggest a mitigation potential of 4–-5 $GtCO_2$ per year in 2030 (Edelenbosch et al. 2020) with complete decarbonization decarbonisation possible by 2050 (Gota et al. 2019; Wachsmuth and Duscha 2019). However, in the scenarios assessed in this chapter that limit warming to below 1.5°C (>50%) with no or limited overshoot, transport sector CO_2 emissions are reduced by only 59% (28–% to 81%) in 2050 compared to 2015. IAM pathways also show less electrification than the potential from other studies; pathways that limit warming to 1.5°C with no or limited overshoot show a median of 25% (7– to 43%) of final energy from electricity in 2050, while the IEA NZE scenario includes 45% (IEA 2021a).

3.4.5 Industry

Reference scenarios show declines in energy intensity, but increases in final energy use in the industrial sector (Edelenbosch et al. 2017b). These scenarios show increases in CO_2 emissions both for the total industrial sector (Edelenbosch et al. 2017b, 2020; Luderer et al. 2018) and individual subsectors such as cement and iron and steel (van Ruijven et al. 2016; van Sluisveld et al. 2021) or chemicals (Daioglou et al. 2014; van Sluisveld et al. 2021).

In mitigation pathways, CO_2 emissions reductions are achieved through a combination of energy savings (via energy-efficiency improvements and energy conservation), structural change, fuel switching, and decarbonisation of fuels (Edelenbosch et al. 2017b, 2020; Grubler et al. 2018; Luderer et al. 2018). Mitigation pathways show reductions in final energy for industry compared to the baseline (Edelenbosch et al. 2017b; Luderer et al. 2018; Edelenbosch et al. 2020) and reductions in the carbon intensity of the industrial sector through both fuel switching and the use of CCS (van Ruijven et al. 2016; Edelenbosch et al. 2017b, 2020; Luderer et al. 2018; Paltsev et al. 2021; van Sluisveld et al. 2021). The mitigation potential differs depending on the industrial subsector and the availability of CCS, with larger potential reductions in the steel sector (van Ruijven et al. 2016) and cement industry (Sanjuán et al. 2020) than in the

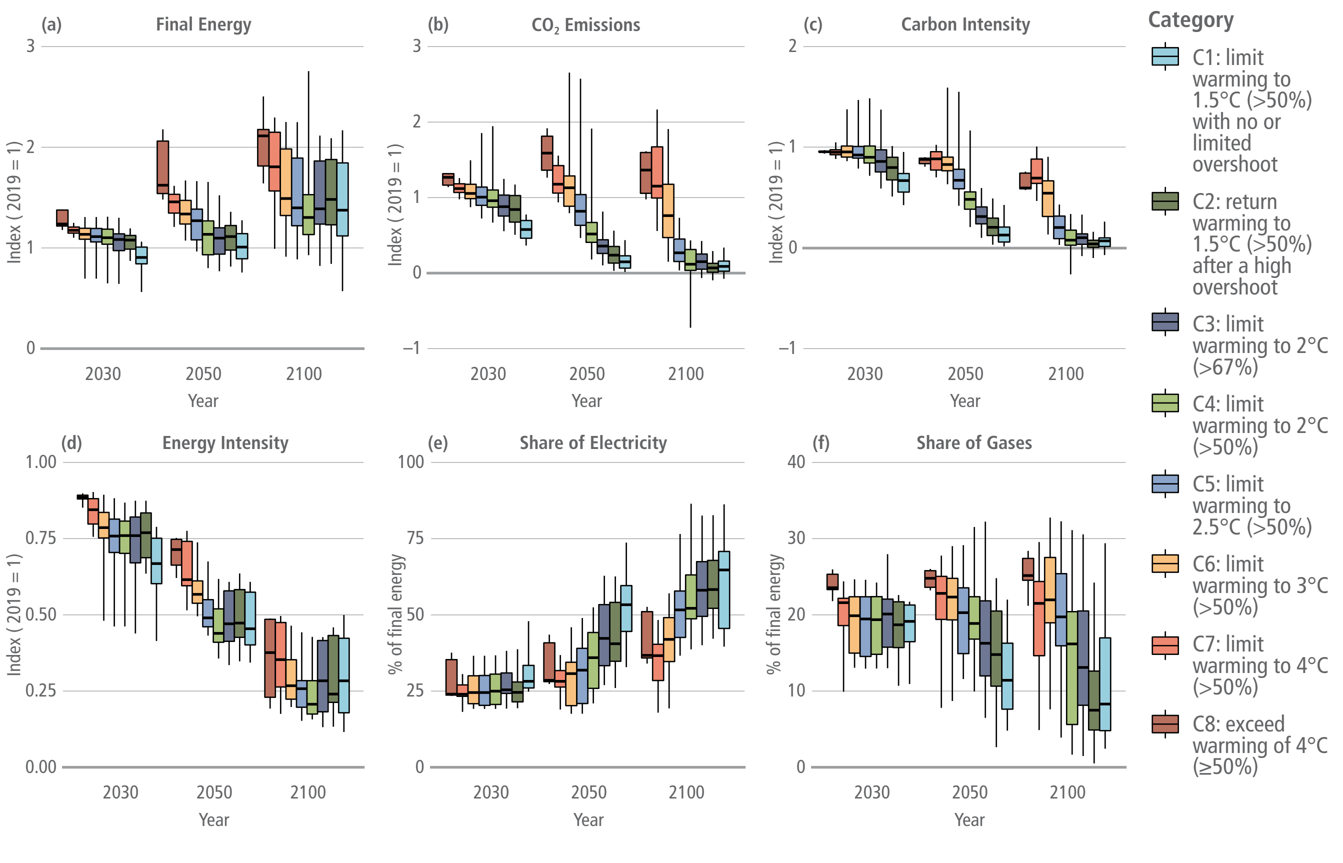


Figure 3.26 | Industrial final energy, including feedstocks (a), CO_2 emissions (b), carbon intensity (c), energy intensity (d), share of final energy from electricity (e), and share of final energy from gases (f). Energy intensity is final energy per unit of GDP. Carbon intensity is CO_2 emissions per EJ of final energy. The first four indicators are indexed to 2019,[15] where values less than 1 indicate a reduction. Industrial sector CO_2 emissions include fuel combustion emissions only.

16 2019 values are from model results and interpolated from other years when not directly reported.

chemicals sector (Daioglou et al. 2014). Many scenarios, including stringent mitigation scenarios, show continued growth in final energy; however, the carbon intensity of energy declines in all mitigation scenarios (Figure 3.26).

The representation of the industry sector is very aggregated in most IAMs, with only a small subset of models disaggregating key sectors such as cement, fertiliser, chemicals, and iron and steel (Daioglou et al. 2014; Edelenbosch et al. 2017b; Pauliuk et al. 2017; Napp et al. 2019; van Sluisveld et al. 2021). IAMs often account for both energy combustion and feedstocks (Edelenbosch et al. 2017b), but IAMs typically ignore material flows and miss linkages between sectors (Pauliuk et al. 2017; Kermeli et al. 2019). By excluding these processes, IAMs misrepresent the mitigation potential of the industry sector, for example by overlooking mitigation from material efficiency and circular economies (Sharmina et al. 2020), which can have substantial mitigation potential (Sections 5.3.4 and 11.3).

Sectoral studies indicate a large mitigation potential in the industrial sector by 2050, including the potential for net zero CO_2 emissions for steel, plastics, ammonia, and cement (Section 11.4.1). Detailed industry sector pathways show emissions reductions between 39% and 94% by mid-century compared to the present day[17] (Section 11.4.2) and a substantial increase in direct electrification (IEA 2021a). IAMs show comparable mitigation potential to sectoral studies with median reductions in CO_2 emissions between 2019 and 2050 of 70% in scenarios *likely* to limit warming to 2°C (>67%) and below and a maximum reduction of 96% (Figure 3.26). Some differences between IAMs and sectoral models can be attributed to differences in technology availability, with IAMs sometimes including more technologies (van Ruijven et al. 2016) and sometimes less (Sharmina et al. 2020).

3.4.6 Agriculture, Forestry and Other Land Use (AFOLU)

Mitigation pathways show substantial reductions in CO_2 emissions, but more modest reductions in AFOLU CH_4 and N_2O emissions (*high confidence*) (Popp et al. 2017; Roe et al. 2019; Reisinger et al. 2021) (Figure 3.27). Pathways limiting warming to *likely* 2°C or lower are projected to reach net zero CO_2 emissions in the AFOLU sector around 2033 (2024–2060); however, AFOLU CH_4 and N_2O emissions remain positive in all pathways (Figure 3.27). While IAMs include many land-based mitigation options, these models exclude several options with large mitigation potential, such as biochar, agroforestry, restoration/avoided conversion of coastal wetlands, and restoration/avoided conversion of peatland (IPCC 2019a; Smith et al. 2019) (Chapter 7 and Section 3.4). Sectoral studies show higher mitigation potential than IAM pathways, as

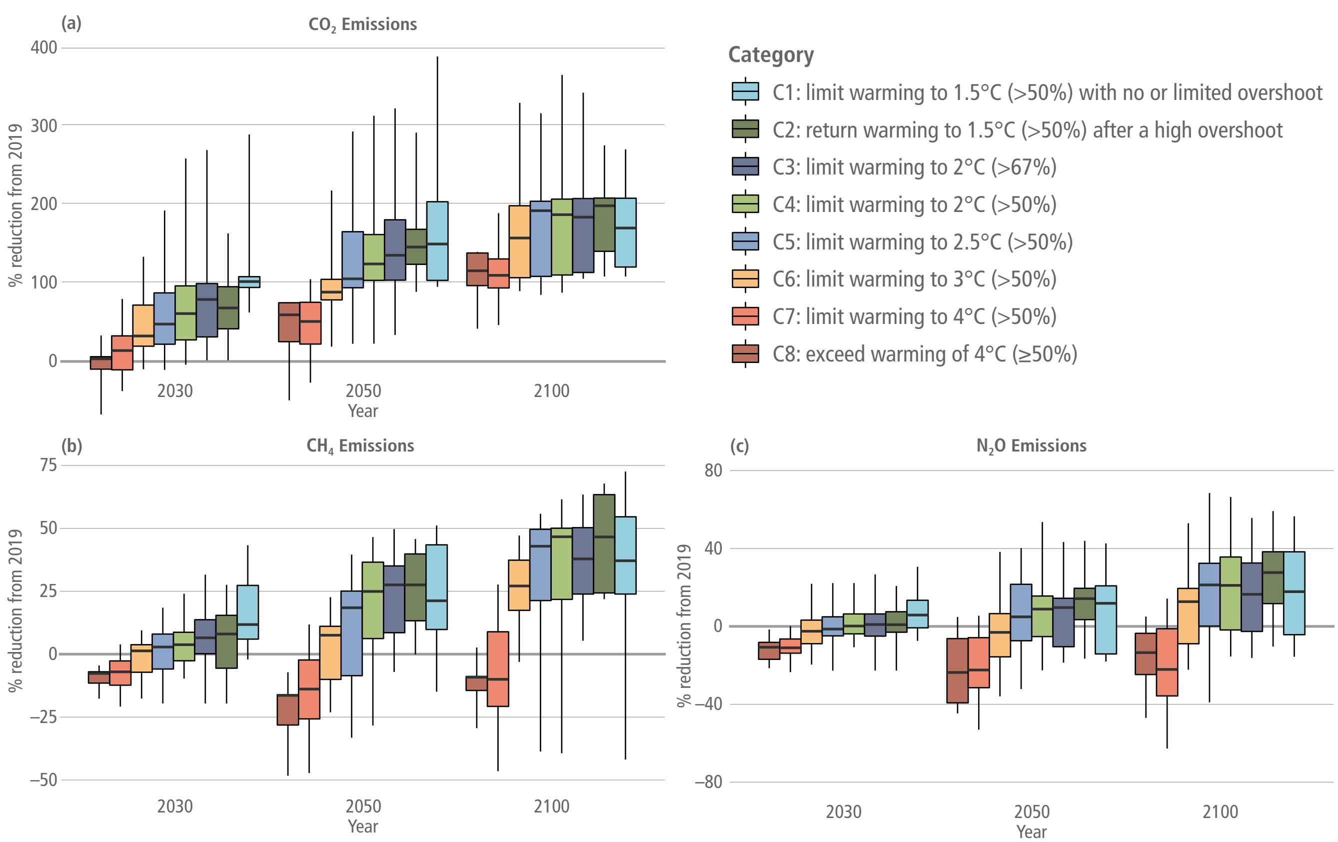


Figure 3.27 | Reduction in AFOLU GHG emissions from 2019. The AFOLU CO_2 estimates in this figure are not necessarily comparable with country GHG inventories (see Chapter 7).

[17] Some studies calculate emissions reductions in 2050 compared to 2014, while others note emissions reductions in 2060 relative to 2018.

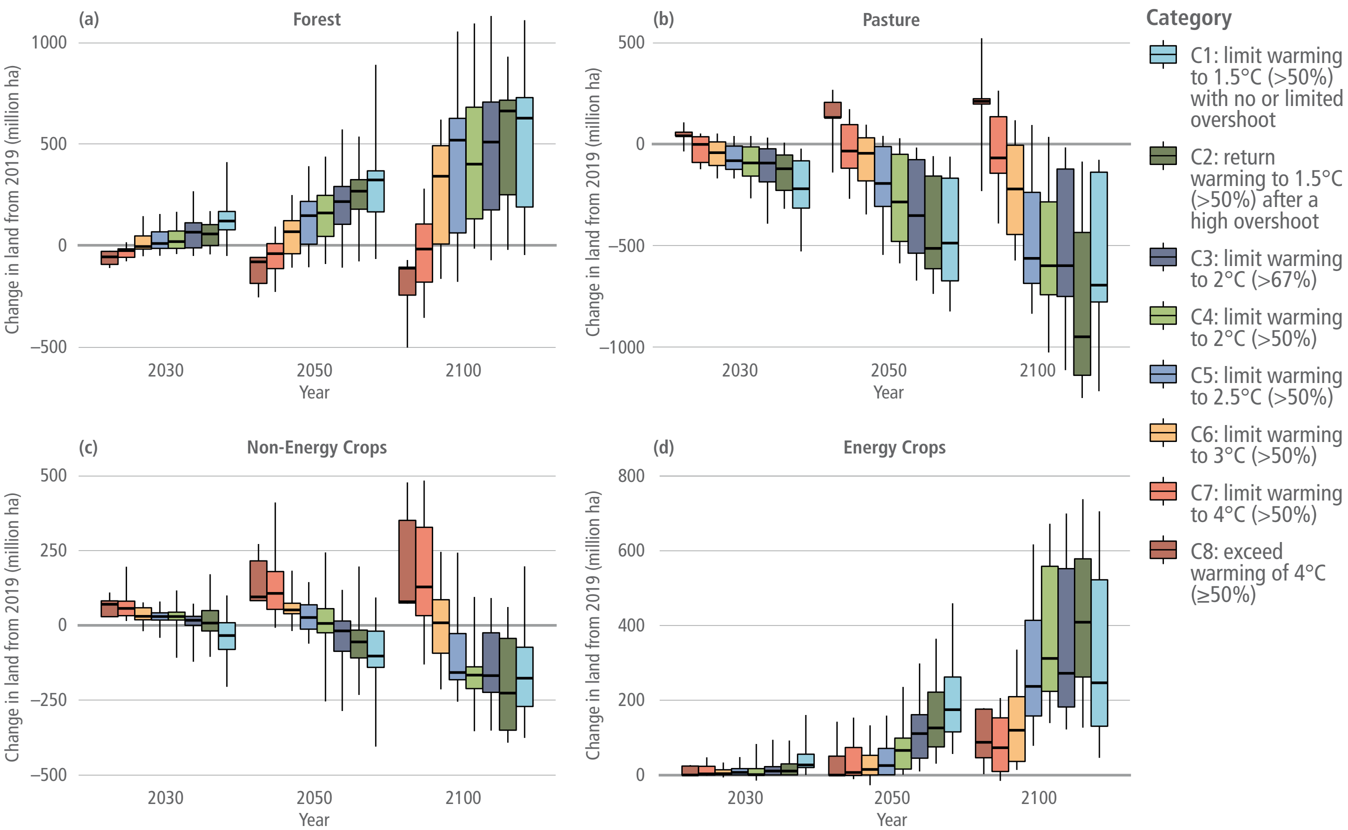


Figure 3.28 | Change in land cover from 2019 in million hectares. Positive values indicate an increase in area.

these studies include more mitigation options than IAMs (*medium confidence*) (Chapter 7).

Limiting warming to *likely* 2°C (>67%) or lower can result in large-scale transformation of the land surface (*high confidence*) (Popp et al. 2017; Rogelj et al. 2018a,b; Brown et al. 2019; Roe et al. 2019). The scale of land transformation depends, *inter alia*, on the temperature goal and the mitigation options included (Popp et al. 2017; Rogelj et al. 2018a; IPCC 2019a). Pathways with more demand-side mitigation options show less land transformation than those with more limited options (Grubler et al. 2018; van Vuuren et al. 2018; IPCC 2019a). Most of these pathways show increases in forest cover, with an increase of 322 million ha (–67 to 890 million ha) in 2050 in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, whereas bottom-up models portray an economic potential of 300–500 million ha of additional forest (Chapter 7). Many IAM pathways also include large amounts of energy cropland area, to supply biomass for bioenergy and BECCS, with 199 (56–482) million ha in 2050 in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. Large land transformations, such as afforestation/reforestation and widespread planting of energy crops, can have implications for biodiversity and sustainable development (Sections 3.7, 7.7.4 and 12.5).

Delayed mitigation has implications for land-use transitions (Hasegawa et al. 2021a). Delaying mitigation action can result in a temporary overshoot of temperature and large-scale deployment of CDR in the second half of the century to reduce temperatures from their peak to a given level (Smith et al. 2019; Hasegawa et al. 2021a). IAM pathways rely on afforestation and BECCS as CDR measures, so delayed mitigation action results in substantial land-use change in the second half of the century with implications for sustainable development (Hasegawa et al. 2021a) (Section 3.7). Shifting to earlier mitigation action reduces the amount of land required for this, though at the cost of larger land-use transitions earlier in the century (Hasegawa et al. 2021a). Earlier action could also reduce climate impacts on agriculture and land-based mitigation options (Smith et al. 2019).

Some AFOLU mitigation options can enhance vegetation and soil carbon stocks such as reforestation, restoration of degraded ecosystems, protection of ecosystems with high carbon stocks and changes to agricultural land management to increase soil carbon (*high confidence*) (Griscom et al. 2017; de Coninck et al. 2018; Fuss et al. 2018; Smith et al. 2019) (AR6 WGIII Chapter 7). The time scales associated with these options indicate that carbon sinks in terrestrial vegetation and soil systems can be maintained or enhanced so as to contribute towards long-term mitigation (*high confidence*); however, many AFOLU mitigation options do not continue to sequester carbon indefinitely (Fuss et al. 2018; de Coninck et al. 2018; IPCC 2019a) (AR6 WGIII Chapter 7). In the very long term (the latter part of the century and beyond), it will become more challenging to continue to enhance vegetation and soil carbon stocks, so that the associated carbon sinks could diminish or even become sources (*high confidence*) (de Coninck et al. 2018; IPCC 2019a) (AR6 WGI Chapter 5). Sustainable forest management, including harvest and forest regeneration, can help to remediate and slow any decline in the forest carbon sink, for example by restoring degraded forest areas, and so go some way towards addressing the issue of sink saturation (IPCC 2019) (AR6 WGI Chapter 5; and Chapter 7 in this report). The accumulated carbon resulting from mitigation options that enhance carbon sequestration (e.g., reforestation, soil carbon sequestration) is also at risk of future loss due to disturbances (e.g., fire, pests) (Boysen et al. 2017; de Coninck et al. 2018; Fuss et al. 2018; Smith et al. 2019; IPCC 2019a; Anderegg et al. 2020) (AR6 WGI Chapter 5). Maintaining the resultant high vegetation and soil carbon stocks could limit future land-use options, as maintaining these carbon stocks would require retaining the land use and land-cover configuration implemented to achieve the increased stocks.

Anthropogenic land CO_2 emissions and removals in IAM pathways cannot be directly compared with those reported in national GHG inventories (*high confidence*) (Grassi et al. 2018, 2021) (Section 7.2). Due to differences in definitions for the area of managed forests and which emissions and removals are considered anthropogenic, the reported anthropogenic land CO_2 emissions and removals differ by about 5.5 $GtCO_2$ yr^{-1} between IAMs, which rely on bookkeeping approaches (e.g., Houghton and Nassikas 2017), and national GHG inventories (Grassi et al. 2021). Such differences in definitions can alter the reported time at which anthropogenic net zero CO_2 emissions are reached for a given emission scenario. Using national inventories would lead to an earlier reported time of net zero (van Soest et al. 2021b) or to lower calculated cumulative emissions until the time of net zero (Grassi et al. 2021) as compared to IAM pathways. The numerical differences are purely due to differences in the conventions applied for reporting the anthropogenic emissions and do not have any implications for the underlying land-use changes or mitigation measures in the pathways. Grassi et al. (Grassi et al. 2021) offer a methodology for adjusting to reconcile these differences and enable a more accurate assessment of the collective progress achieved under the Paris Agreement (Chapter 7 and Cross-Chapter Box 6 in Chapter 7).

3.4.7 Other Carbon Dioxide Removal Options

This subsection includes other CDR options not discussed in the previous subsections, including direct air carbon capture and storage (DACCS), enhanced weathering (EW), and ocean-based approaches, focusing on the role of these options in long-term mitigation pathways, using both IAMs (Chen and Tavoni 2013; Marcucci et al. 2017; Rickels et al. 2018; Fuhrman et al. 2019, 2020, 2021; Realmonte et al. 2019; Akimoto et al. 2021; Strefler et al. 2021a) and non-IAMs (Fuss et al. 2013; González and Ilyina 2016; Bednar et al. 2021; Shayegh et al. 2021). There are other options discussed in the literature, such as methane capture (Jackson et al. 2019), however, the role of these options in long-term mitigation pathways has not been quantified and is thus excluded here. Chapter 12 includes a more detailed description of the individual technologies, including their costs, potentials, financing, risks, impacts, maturity and upscaling.

Very few studies and pathways include other CDR options (Table 3.5). Pathways with DACCS include potentially large removal from DACCS (up to 37 $GtCO_2$ yr^{-1} in 2100) in the second half of the century (Chen and Tavoni 2013; Marcucci et al. 2017; Realmonte et al. 2019; Fuhrman et al. 2020, 2021; Shayegh et al. 2021; Akimoto et al. 2021) and reduced cost of mitigation (Bistline and Blanford 2021; Strefler et al. 2021a). At large scales, the use of DACCS has substantial implications for energy use, emissions, land, and water; substituting DACCS for BECCS results in increased energy usage, but reduced land-use change and water withdrawals (Fuhrman et al., 2020, 2021) (Chapter 12.3.2; AR6 WGI Chapter 5). The level of deployment of DACCS is sensitive to the rate at which it can be scaled up, the climate goal or carbon budget, the underlying socio-economic scenario, the availability of other decarbonisation options, the cost of DACCS and other mitigation options, and the strength of carbon-cycle feedbacks (Chen and Tavoni 2013; Fuss et al. 2013; Honegger and Reiner 2018; Realmonte et al. 2019; Fuhrman et al. 2020; Bistline and Blanford 2021; Fuhrman et al. 2021; Strefler et al. 2021a) (AR6 WGI Chapter 5). Since DACCS consumes energy, its effectiveness depends on the type of energy used; the use of fossil fuels would reduce its sequestration efficiency (Creutzig et al. 2019; NASEM 2019; Babacan et al. 2020). Studies with additional CDR options in addition to DACCS (e.g., enhanced weathering, BECCS, afforestation, biochar, and soil carbon sequestration) find that CO_2 removal is spread across available options (Holz et al. 2018; Strefler et al. 2021a). Similar to DACCS, the deployment of deep-ocean storage depends on cost and the strength of carbon-cycle feedbacks (Rickels et al. 2018).

Table 3.5 | Carbon dioxide removal in assessed pathways. Scenarios are grouped by temperature categories, as defined in Section 3.2.4. Quantity indicates the median and 5–95th percentile range of cumulative sequestration from 2020 to 2100 in $GtCO_2$. Count indicates the number of scenarios with positive values for that option. Source: AR6 Scenarios Database.

CDR option	C1: Limit warming to 1.5°C (>50%) with no or limited overshoot		C2: Return warming to 1.5°C (>50%) after a high overshoot		C3: Limit warming to 2°C (>67%)	
	Quantity	Count	Quantity	Count	Quantity	Count
CO_2 removal on managed land including Afforestation/Reforestation[1]	262 (17–397)	64	330 (28–439)	82	209 (20–415)	196
BECCS	334 (32–780)	91	464 (226–842)	122	291 (174–653)	294
Enhanced weathering	0 (0–47)	2	0 (0–0)	1	0 (0–0)	1
DACCS	30 (0–308)	31	109 (0 – 539)	24	19 (0–253)	91

[1] Cumulative CDR from AFOLU cannot be quantified precisely because models use different reporting methodologies that in some cases combine gross emissions and removals, and use different baselines.

3.5 Interaction Between Near-, Medium- and Long-term Action in Mitigation Pathways

This section assesses the relationship between long-term climate goals and short- to medium-term emissions reduction strategies based on the mitigation pathway literature. After an overview of this relationship (Section 3.5.1), it provides an assessment of what currently planned near-term action implies for limiting warming to 1.5°C–2°C (Section 3.5.2), and to what extent pathways with accelerated action beyond current NDCs can improve the ability to keep long-term targets in reach (Section 3.5.3).

The assessment in this section shows that if mitigation ambitions in NDCs announced prior to COP26[2,18] are followed until 2030, leading to estimated emissions of 47–57 $GtCO_2$-eq in 2030[19] (Section 4.2.2), it is no longer possible to limit warming to 1.5°C (>50%) with no or limited overshoot (*high confidence*). Instead, it would entail high overshoot (typically >0.1°C) and reliance on net negative CO_2 emissions with uncertain potential to return warming to 1.5°C (>50%) by the end of the century. It would also strongly increase mitigation challenges to limit warming to 2°C (>67%) (*high confidence*). GHG emissions reductions would need to abruptly increase after 2030 to an annual average rate of 1.4–2.0 $GtCO_2$-eq during the period 2030–2050, around 70% higher than in mitigation pathways assuming immediate action[1] to limit warming to 2°C (>67%). The higher post-2030 reduction rates would have to be obtained in an environment of continued buildup of fossil fuel infrastructure and less development of low-carbon alternatives until 2030. A lock-in to fossil fuel-intensive production systems (carbon lock-in) will increase the societal, economic and political strain of a rapid low-carbon transition after 2030 (*high confidence*).

The section builds on previous assessments in the IPCC's *Fifth Assessment Report* (Clarke et al. 2014) and the *IPCC Special Report on 1.5°C Warming* (Rogelj et al. 2018a). The literature assessed in these two reports has focused on delayed action until 2030 in the context of limiting warming to 2°C (den Elzen et al. 2010; van Vuuren and Riahi 2011; Luderer et al. 2013, 2016; Rogelj et al. 2013a; Kriegler et al. 2015; Riahi et al. 2015) and 1.5°C (Rogelj et al. 2013b; Luderer et al. 2018; Strefler et al. 2018). Here we provide an update of these assessments drawing on the most recent literature on global mitigation pathways. New studies have focused, *inter alia*, on constraining near-term developments by peak warming limits (Rogelj et al. 2019b; Riahi et al. 2021; Strefler et al. 2021b) and updating assumptions about near- and medium-term emissions developments based on national plans and long-term strategies (Roelfsema et al. 2020) (Section 4.2). Several studies have explored new types of pathways with accelerated action bridging between current policy plans and the goal of limiting warming below 2°C (Kriegler et al. 2018a; van Soest et al. 2021a) and looked at hybrid international policy regimes to phase in global collective action (Bauer et al. 2020).

3.5.1 Relationship Between Long-term Climate Goals and Near- to Medium-term Emissions Reductions

The close link between cumulative CO_2 emissions and warming has strong implications for the relationship between near-, medium-, and long-term climate action to limit global warming. The AR6 WGI Assessment has estimated a remaining carbon budget of 500 (400) $GtCO_2$ from the beginning of 2020 onwards for staying below 1.5°C with 50% (67%) likelihood, subject to additional uncertainties about historic warming and the climate response, and variations in warming from non-CO_2 climate forcers (Canadell and Monteiro 2019) (AR6 WGI Chapter 5, Section 5.5). For comparison, if current CO_2 emissions of more than 40 $GtCO_2$ are keeping up until 2030, more than 400 $GtCO_2$ will be emitted during 2021–2030, already exhausting the remaining carbon budget for 1.5°C by 2030.

The relationship between warming limits and near-term action is illustrated in Figure 3.29, using a set of 1.5°C–2°C scenarios with different levels of near-term action, overshoot and non-CO_2 warming contribution from a recent study (Riahi et al. 2021). In general, the more CO_2 is emitted until 2030, the less CO_2 can be emitted thereafter to stay within a remaining carbon budget and below a warming limit. Scenarios with immediate action to observe the warming limit give the longest time to exhaust the associated remaining carbon budget and reach net zero CO_2 emissions (see light blue lines in Figure 3.29 and Cross-Chapter Box 3 in this chapter). In comparison, following projected NDC emissions until 2030 would imply a more pronounced drop in emissions from 2030 levels to net zero to make up for the additional near-term emissions (see orange lines in Figure 3.29). If such a drop does not occur, the remaining carbon budget is exceeded and net negative CO_2 emissions are required to return global mean temperature below the warming limit (see black lines in Figure 3.29) (Clarke et al. 2014; Fuss et al. 2014; Rogelj et al. 2018a).

The relationship between warming limits and near-term action is also affected by the warming contribution of non-CO_2 greenhouse gases and other short-lived climate forcers (Section 3.3; AR6 WGI Section 6.7). The estimated budget values for limiting warming to 1.5°C–2°C already assume stringent reductions in non-CO_2 greenhouse gases and non-CO_2 climate forcing as found in 1.5°C–2°C pathways (Section 3.3 and Cross-Working Group Box 1 in this chapter; AR6 WGI Section 5.5 and Box 5.2 in Chapter 5). Further variations in non-CO_2 warming observed across 1.5°C–2°C pathways can vary the median estimate for the remaining carbon budget by 220 $GtCO_2$ (AR6 WGI Section 5.5). In 1.5°C–2°C pathways, the non-CO_2 warming contribution differs strongly between the near, medium and long term. Changes to the atmospheric composition of short-lived climate forcers (SLCFs) dominate the warming response in the near term (AR6 WGI Section 6.7). CO_2 reductions are combined with strong reductions in air pollutant emissions due to rapid reduction in fossil fuel combustion and in some cases the assumption of stringent air quality policies (Rao et al. 2017b; Smith et al. 2020c). As air pollutants exert a net-cooling effect,

[18] Original NDCs refer to those submitted to the UNFCCC in 2015 and 2016. See Section 4.2.

[19] In this section, the emissions range associated with NDCs announced prior to COP26 (or original NDCs) refer to the combined emissions ranges from the two cases of implementing only the unconditional elements of NDCs announced prior to COP26 (50–57 $GtCO_2$-eq) and implementing both unconditional and conditional elements of NDCs announced prior to COP26 (47–55 $GtCO_2$-eq), if not specified otherwise.

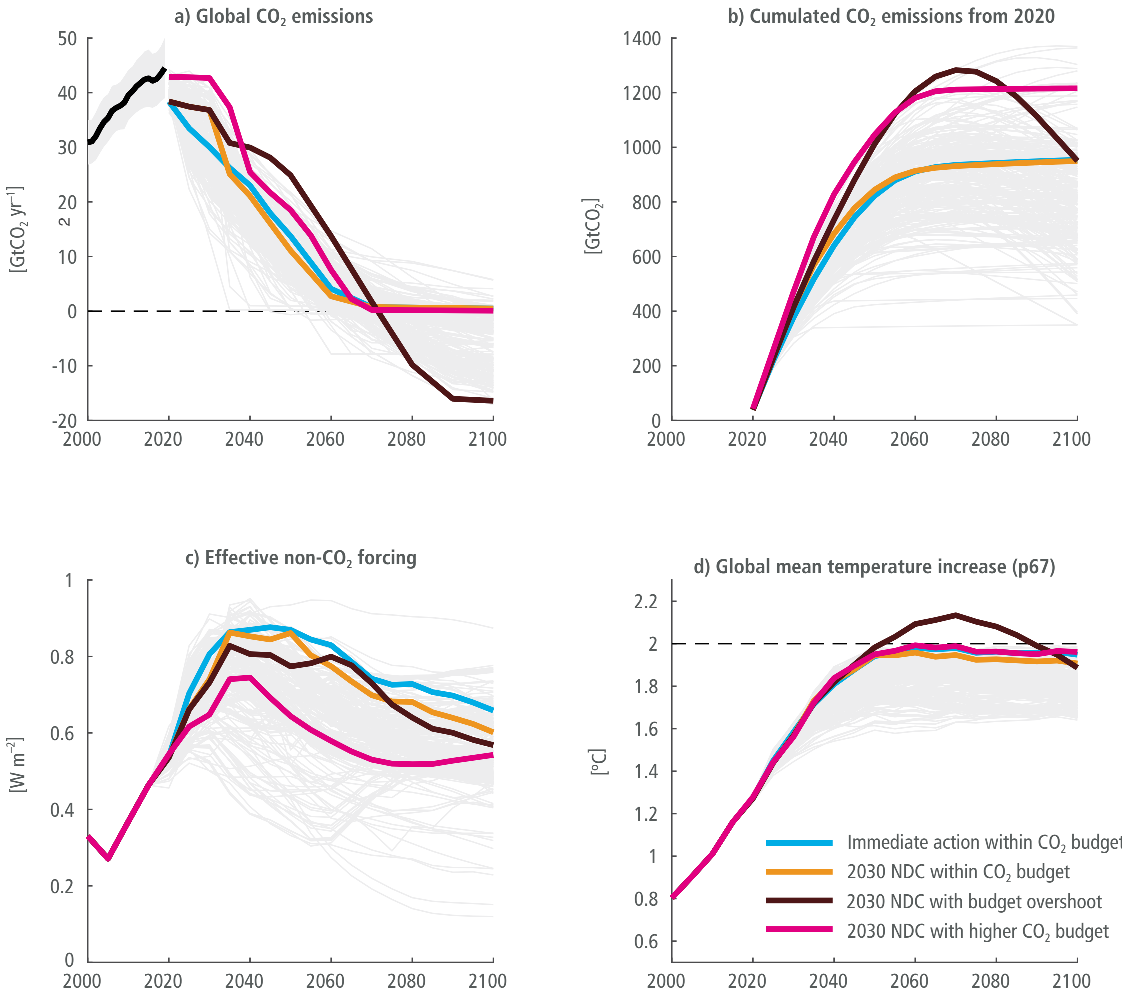


Figure 3.29 | Illustration of emissions and climate response in four mitigation pathways with different assumptions about near-term policy developments, global warming limit and non-CO_2 warming contribution drawn from Riahi et al. (2021). Shown are **(a)** CO_2 emissions trajectories, **(b)** cumulative CO_2 emissions, **(c)** effective non-CO_2 radiative forcing, and **(d)** the resulting estimate of the 67th percentile of global mean temperature response relative to 1850–1900. Light blue lines show a scenario that acts immediately on a remaining carbon budget of 900 $GtCO_2$ from 2020 without allowing net negative CO_2 emissions (i.e., temporary budget overshoot) (COFFEE 1.1, Scenario EN_NPi2020_900). Orange and black lines show scenarios drawn from the same model that follow the NDCs until 2030 and thereafter introduce action to stay within the same budget – in one case excluding net negative CO_2 emissions like before (orange lines; COFFEE 1.1., Scenario EN-INDCi2030_900) and in the other allowing for a temporary overshoot of the carbon budget until 2100 (black lines; COFFEE 1.1., Scenario EN-INDCi2030_900f). Light blue lines describe a scenario following the NDCs until 2030, and then aiming for a higher budget of 2300 $GtCO_2$ without overshoot (AIM/CGE 2.2, Scenario EN-INDCi2030_1200). It is drawn from another model which projects a lower anthropogenic non-CO_2 forcing contribution and therefore achieves about the same temperature outcome as the other two non-overshoot scenarios despite the higher CO_2 budget. Grey funnels include the trajectories from all scenarios that limit warming to 2°C (>67%) (category C3). Historical CO_2 emissions until 2019 are from Chapter SM.2.1 EDGAR v6.0.

their reduction drives up non-CO_2 warming in the near term, which can be attenuated by the simultaneous reduction of methane and black carbon (Shindell and Smith 2019; Smith et al. 2020b) (AR6 WGI Section 6.7). After 2030, the reduction in methane concentrations and associated reductions in tropospheric ozone levels tend to dominate so that a peak and decline in non-CO_2 forcing and non-CO_2-induced warming can occur before net zero CO_2 is reached (Figure 3.29) (Rogelj et al. 2018a). The more stringent the reductions in methane and other short-lived warming agents such as black carbon, the lower this peak and the earlier the decline of non-CO_2 warming, leading to a reduction of warming rates and overall warming in the near to medium term (Harmsen et al. 2020; Smith et al. 2020b). This is important for keeping warming below a tight warming limit that is already reached around mid-century as is the case in 1.5°C pathways (Xu and Ramanathan 2017). Early and deep reductions of methane emissions, and other short-lived warming agents such as black carbon, provide space for residual CO_2-induced warming until the point of net zero CO_2 emissions is reached (see purple lines in Figure 3.29). Such emissions reductions have also been advocated due to co-benefits for, for example, reducing air pollution (Rao et al. 2016; Shindell et al. 2017a, 2018; Shindell and Smith 2019; Rauner et al. 2020a; Vandyck et al. 2020).

The relationship between long-term climate goals and near-term action is further constrained by social, technological, economic and political factors (Cherp et al. 2018; van Sluisveld et al. 2018b; Aghion et al. 2019; Mercure et al. 2019; Trutnevyte et al. 2019b; Jewell and Cherp 2020). These factors influence path dependency and transition speed (Pahle et al. 2018; Vogt-Schilb et al. 2018). While detailed integrated assessment modelling of global mitigation pathways accounts for technology inertia (Bertram et al. 2015a; Mercure et al. 2018) and technology innovation and diffusion (Wilson et al. 2013; van Sluisveld et al. 2018a; Luderer et al. 2021), there are limitations in capturing socio-technical and political drivers of innovation, diffusion and transition processes (Gambhir et al. 2019; Köhler et al. 2019; Hirt et al. 2020; Keppo et al. 2021). Mitigation pathways show a wide range of transition speeds that have been interrogated in the context of socio-technical inertia (Gambhir et al. 2017; Kefford et al. 2018; Kriegler et al. 2018a; Brutschin et al. 2021) vs accelerating technological change and self-enforcing socio-economic developments (Creutzig et al. 2017; Zenghelis 2019) (Section 3.8). Diagnostic analysis of detailed IAMs found a lag of 8–20 years between the convergence of emissions pricing and the convergence of emissions response after a period of differentiated emission prices (Harmsen et al. 2021). This provides a measure of the inertia to changing policy signals in the model response. It is about half the time scale of 20–40 years observed for major energy transitions (Grubb et al. 2021). Hence, the mitigation pathways assessed here capture socio-technical inertia in reducing emissions, but the limited modelling of socio-political factors may alter the extent and persistence of this inertia.

3.5.2 Implications of Near-term Emission Levels for Keeping Long-term Climate Goals Within Reach

The implications of near-term climate action for long-term climate outcomes can be explored by comparing mitigation pathways with different near-term emissions developments aiming for the same climate target (Riahi et al. 2015; Vrontisi et al. 2018; Roelfsema et al. 2020). A particular example is the comparison of cost-effective pathways with immediate action to limit warming to 1.5°C–2°C with mitigation pathways pursuing more moderate mitigation action until 2030. After the adoption of the Paris Agreement, near-term action was often modelled to reflect conditional and unconditional elements of originally submitted NDCs (2015–2019) (Fawcett et al. 2015; Fujimori et al. 2016a; Kriegler et al. 2018a; Vrontisi et al. 2018; Roelfsema et al. 2020). The most recent modelling studies also include submission of updated NDCs or announcements of planned updates in the first half of 2021 (Network for Greening the Financial System 2021; Riahi et al. 2021). Emissions levels under NDCs announced prior to COP26 are assessed to range between 47–57 $GtCO_2$-eq in 2030 (Section 4.2.2). This assessed range corresponds well to 2030 emissions levels in 2°C mitigation pathways in the literature that are designed to follow the original or updated NDCs until 2030.[20] For the 139 scenarios of this kind that are collected in the AR6 scenario database and that still limit warming to 2°C (>67%), the 2030 emissions range is 53 (45–58) $GtCO_2$-eq (based on native model reporting) and 52.5 (47–56.5) $GtCO_2$-eq, respectively (based on harmonised emissions data for climate assessment (Annex III.2.5.1); median and 5–95th percentile). This close match allows a robust assessment of the implications of implementing NDCs announced prior to COP26 for post-2030 mitigation efforts and warming outcomes based on the literature and the AR6 scenarios database.

Without a strengthening of policies beyond those that are implemented by the end of 2020, GHG emissions are projected to rise beyond 2025, leading to a median global warming of 3.2 [2.2 to 3.5] °C by 2100. Modelled pathways that are consistent with NDCs announced prior to COP26 until 2030 and assume no increase in ambition thereafter have lower emissions, leading to a median global warming of 2.8°C [2.1–3.4°C] by 2100.

The assessed emission ranges from implementing the unconditional (unconditional and conditional) elements of NDCs announced prior to COP26 implies an emissions gap to cost-effective mitigation pathways of 19–26 (16–23) $GtCO_2$-eq in 2030 for limiting warming to 1.5°C (>50%) with no or limited overshoot and 10–16 (6–14) $GtCO_2$-eq in 2030 for limiting warming to 2°C (>67%) (Cross-Chapter Box 4 in Chapter 4). The emissions gap gives rise to a number of mitigation challenges (Kriegler et al. 2013a, 2018a,b; Luderer et al. 2013, 2018; Rogelj et al. 2013a; Fawcett et al. 2015; Riahi et al. 2015; Fujimori et al. 2016b; Strefler et al. 2018; Winning et al. 2019; SEI et al. 2020; UNEP 2020): (i) larger transitional challenges post-2030 to still remain under the warming limit, in particular higher CO_2 emissions reduction rates and technology transition rates required during 2030–2050; (ii) larger lock-in into carbon-intensive infrastructure and increased risk of stranded fossil fuel assets (Section 3.5.2.2); and (iii) larger reliance on CDR to reach net zero CO_2 more rapidly and compensate excess emissions in the second half of the century (Section 3.5.2.1). All these factors exacerbate the socio-economic strain of implementing the transition, leading to an increased risk of overshooting the warming and a higher risk of climate change impacts (Drouet et al. 2021).

The challenges are illustrated in Table 3.6 and Figure 3.30, surveying global mitigation pathways in the literature that were collected in the AR6 scenarios database. There is a clear trend of increasing peak warming with increasing 2030 GHG emission levels (Figure 3.30a,b). In particular, there is no mitigation pathway designed to follow the NDCs until 2030 that can limit warming to 1.5°C (>50%) with no or limited overshoot. Our assessment confirms the finding of the *IPCC Special Report on Global Warming of 1.5°C* (Rogelj et al. 2018) for the case of NDCs announced prior to COP26 that pathways following the NDCs until 2030 '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' (SR1.5 SPM). This assessment is now more robust than in SR1.5 as it is based on a larger set of 1.5°C–2°C pathways with better representation of current trends and plans covering a wider range of post-2030 emissions developments. In particular, a recent multi-model study limiting peak cumulative CO_2 emissions for a wide range of carbon budgets and immediate vs NDC-type action until 2030 established a feasibility frontier for the existence of such pathways across participating models (Riahi et al. 2021).

20 The intended design of mitigation pathways in the literature can be deduced from underlying publications and study protocols. This information was collected as part of this assessment to establish a categorisation of policy assumptions underpinning the mitigation pathways collected in the AR6 scenario database (Section 3.2 and Annex III.II.3.2.2).

3

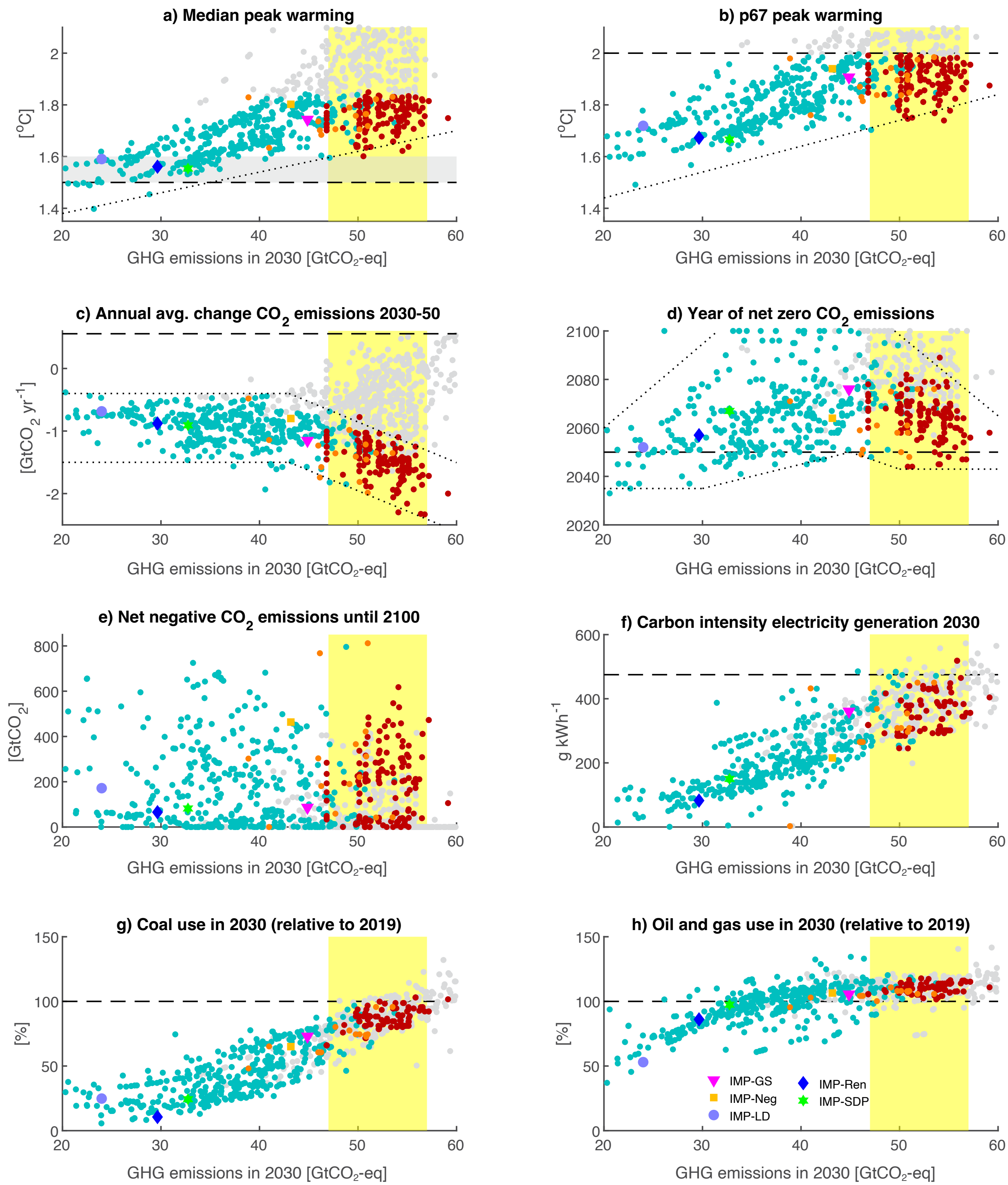


Figure 3.30 | Relationship between level of global GHG emissions in 2030 and selected indicators as listed in the panel titles for scenarios collected in the AR6 scenario database. Emissions data based on harmonised emissions used for the climate assessment. All scenarios that limit warming to 2°C (>67%) or lower are coloured blue or red (see p67 peak warming in panel (b)). The large majority of blue-coloured scenarios act immediately on the temperature target, while red-coloured scenarios depict all those that were designed to follow the NDCs or lesser action until 2030 and orange-coloured scenarios comprise a small set of pathways with additional regulatory action beyond NDCs (Section 3.5.3). Grey-coloured scenarios do not limit warming to 2°C (>67%) due to temporary overshoot or towards the end of the century. Large markers denote the five Illustrative Mitigation Pathways (IMPs) (legend in Panel (h); Section 3.2). Shaded yellow areas depict the estimated range of 2030 emissions from NDCs announced prior to COP26 (Section 4.2.2). Dotted lines are inserted in some panels to highlight trends in the dependency of selected output variables on 2030 GHG emissions levels (Section 3.5.2).

Table 3.6 | Comparison of key scenario characteristics for five scenario classes (see Table 3.2): (i) immediate action to limit warming to 1.5°C (>50%) with no or limited overshoot, (ii) near team action following the NDCs until 2030 and returning warming to below 1.5°C (>50%) by 2100 after a high overshoot, (iii) immediate action to limit warming to 2°C (>67%), (iv) near term action following the NDCs until 2030 followed by post-2030 action to limit warming to 2°C (>67%). Also shown are the characteristics for (v) the combined class of all scenarios that limit warming to 2°C (>67%). The classes (ii) and (iv) comprise the large majority of scenarios indicated by red dots, and the classes (i) and (iii) comprise the scenarios depicted by blue dots in Figure 3.30. Shown are median and interquartile ranges (in brackets) for selected global indicators. Emissions ranges are based on harmonized emissions data for the climate assessment with the exception of land use CO_2 emissions for which uncertainty in historic estimates is large. Numbers are rounded to the nearest 5, with the exception of cumulative CCS, BECCS, and net negative CO_2 emissions rounded to the nearest 10.

Global indicators	1.5°C	1.5°C (>50%) by 2100	2°C (>67%)		
	Immediate action, with no or limited overshoot (C1, 97 scenarios)	NDCs until 2030, with overshoot before 2100 (subset of 42 scenarios in C2)	Immediate action (C3a, 204 scenarios)	NDCs until 2030 (C3b; 97 scenarios)	All (C3; 311 scenarios)
Change in GHG emissions in 2030 (% rel to 2019)	–45 (–50,–40)	–5 (–5,0)	–25 (–35,–20)	–5 (–10,0)	–20 (–30,–10)
in 2050 (% rel to 2019)	–85 (–90,–80)	–75 (–85,–70)	–65 (–70,–60)	–70 (–70,–60)	–65 (–70,–60)
Change in CO_2 emissions in 2030 (% rel to 2019)	–50 (–60,–40)	–5 (–5,0)	–25 (–35,–20)	–5 (–5,0)	–20 (–30,–5)
in 2050 (% rel to 2019)	–100 (–105,–95)	–85 (–95,–80)	–70 (–80,–65)	–75 (–80,–65)	–75 (–80,–65)
Change in net land use CO_2 emissions in 2030 (% rel to 2019)	–100 (–105,–95)	–30 (–60,–20)	–90 (–105,–75)	–20 (–80,–20)	–80 (–100,–30)
in 2050 (% rel to 2019)	–150 (–200,–100)	–135 (–165,–120)	–135 (–185,–100)	–130 (–145,–115)	–135 (–180,–100)
Change in CH_4 emissions in 2030 (% rel to 2019)	–35 (–40,–30)	–5 (–5,0)	–25 (–35,–20)	–10 (–15,–5)	–20 (–25,–10)
in 2050 (% rel to 2019)	–50 (–60,–45)	–50 (–60,–45)	–45 (–50,–40)	–50 (–65,–45)	–45 (–55,–40)
Cumulative CCS until 2100 ($GtCO_2$)	670 (520,900)	670 (540,860)	610 (490,900)	530 (440,720)	590 (480,820)
of which BECCS ($GtCO_2$)	330 (250,560)	370 (280,590)	350 (240,450)	270 (240,400)	290 (240,430)
Cumulative net negative CO_2 emissions until 2100 ($GtCO_2$)	*220 (70,430)*	*380 (300,470)*	*30 (0,130)*	*60 (20,210)*	*40 (10, 180)*
Change in primary energy from coal in 2030 (% rel to 2019)	–75 (–80,–65)	–10 (–20,–5)	–50 (–65,–35)	–15 (–20,–10)	–35 (–55,–20)
in 2050 (% rel to 2019)	–95 (–100,–80)	–90 (–100,–85)	–85 (–100,–65)	–80 (–90,–70)	–85 (–95,–65)
Change in primary energy from coal without CCS in 2030 (% rel to 2019)	–75 (–80,–65)	–10 (–20,–10)	–50 (–65,–35)	–15 (–20,–10)	–35 (–55,–20)
in 2050 (% rel to 2019)	–100 (–100,–95)	–95 (–100,–95)	–95 (–100,–90)	–90 (–95,–85)	–95 (–100,–90)
Change in primary energy from oil in 2030 (% rel to 2019)	–10 (–25,0)	5 (5,10)	0 (–10,10)	10 (5,10)	5 (0,10)
in 2050 (% rel to 2019)	–60 (–75,–40)	–50 (–65,–35)	–30 (–45,–15)	–40 (–55,–20)	–30 (–50,–15)
Change in primary energy from oil without CCS in 2030 (% rel to 2019)	–5 (–20,0)	5 (5,10)	0 (–10,10)	10 (5,10)	5 (–5,10)
in 2050 (% rel to 2019)	–60 (–75,–45)	–50 (–65,–30)	–30 (–45,–15)	–40 (–55,–20)	–35 (–50,–15)
Change in primary energy from gas in 2030 (% rel to 2019)	–10 (–30,0)	15 (10,25)	10 (0,15)	15 (10,15)	10 (0,15)
in 2050 (% rel to 2019)	–45 (–60,–20)	–45 (–55,–30)	–10 (–35,15)	–30 (–45,–5)	–15 (–40,10)
Change in primary energy from gas without CCS in 2030 (% rel to 2019)	–20 (–30,–5)	15 (10,25)	5 (–5,10)	15 (10,15)	10 (0,15)
in 2050 (% rel to 2019)	–70 (–80,–60)	–60 (–70,–50)	–35 (–50,–20)	–40 (–60,–35)	–40 (–55,–20)
Change in primary energy from nuclear in 2030 (% rel to 2019)	40 (10,70)	10 (0,25)	35 (5,50)	10 (0,30)	25 (0,45)
in 2050 (% rel to 2019)	90 (15,295)	100 (45,130)	85 (30,200)	75 (30,120)	80 (30,140)
Change in primary energy from modern biomass in 2030 (% rel to 2019)	75 (55,130)	45 (20,75)	60 (35,105)	45 (20,80)	55 (35,105)
in 2050 (% rel to 2019)	290 (215,430)	230 (170,420)	240 (130,355)	260 (95,435)	250 (115,405)
Change in primary energy from non–biomass renewables in 2030 (% rel to 2019)	225 (155,270)	100 (85,145)	150 (115,190)	115 (85,130)	130 (90,170)
in 2050 (% rel to 2019)	725 (545,950)	665 (535,925)	565 (415,765)	625 (545,700)	605 (470,735)
Change in carbon intensity of electricity in 2030 (% rel to 2019)	–75 (–80,–70)	–30 (–40,–30)	–60 (–70,–50)	–35 (–40,–30)	–50 (–65,–35)
in 2050 (% rel to 2019)	–100 (–100,–100)	–100 (–100,–100)	–95 (–100,–95)	–100 (–100,–95)	–95 (–100,–95)
Change in carbon intensity of non–electric final energy consumption in 2030 (% rel to 2019)	–15 (–15,–10)	0 (–5,0)	–10 (–10,–5)	0 (–5,5)	–5 (–10,0)
in 2050 (% rel to 2019)	–50 (–55,–40)	–35 (–40,–30)	–30 (–35,–25)	–30 (–40,–20)	–30 (–35,–20)

The 2030 emissions levels in the NDCS announced prior to COP26 also tighten the remaining space to limit warming to 2°C (>67%). As shown in Figure 3.30b, the 67th percentile of peak warming reaches values above 1.7°C in pathways with 2030 emissions levels in this range. To still limit warming to 2°C (>67%), the global post-2030 GHG emission reduction rates would need to be abruptly raised in 2030 from 0–0.7 $GtCO_2$-eq yr^{-1} to an average of 1.4–2.0 $GtCO_2$-eq yr^{-1} during the period 2030–2050 (Figure 3.30c), around 70% higher than in immediate mitigation pathways confirming findings in the literature (Winning et al. 2019). Their average reduction rate of 0.6–1.4 $GtCO_2$ yr^{-1} would already be unprecedented at the global scale and, with a few exceptions, national scale for an extended period of time (Riahi et al. 2015). For comparison, the impact of COVID-19 on the global economy is projected to have lead to a decline of around 2.5–3 $GtCO_2$ of global CO_2 emissions from fossil fuels and industry in 2020 (Friedlingstein et al. 2020) (Section 2.2).

The increased post-2030 transition challenge in mitigation pathways with moderate near-term action is also reflected in the timing of reaching net zero CO_2 emissions (Figure 3.30d and Cross-Chapter Box 3 in this chapter). As 2030 emission levels and the cumulated CO_2 emissions until 2030 increase, the remaining time for dropping to net zero CO_2 and staying within the remaining carbon budget shortens (Figure 3.29). This gives rise to an inverted v-shape of the lower bound on the year of reaching net zero as a function of 2030 emissions levels. Reaching low emissions in 2030 facilitates reaching net zero early (left leg of the inverted v), but staying high until 2030 also requires reaching net zero CO_2 faster to compensate for higher emissions early on (right leg of the inverted v). Overall, there is a considerable spread of the timing of net zero CO_2 for any 2030 emissions level due to variation in the timing of spending the remaining carbon budget and the non-CO_2 warming contribution (Cross-Chapter Box 3 in this chapter).

There is also a profound impact on the underlying transition of energy and land use (Figure 3.30f–h and Table 3.6). Scenarios following NDCs until 2030 show a much smaller reduction in fossil fuel use, a slower growth in renewable energy use, and a smaller reduction in CO_2 and CH_4 land-use emissions in 2030 compared to immediate action scenarios. This is then followed by a much faster reduction of land-use emissions and fossil fuels, and a larger increase of nuclear energy, bioenergy and non-biomass renewable energy during the medium term in order to get close to the levels of the immediate action pathways in 2050. This is combined with a larger amount of net negative CO_2 emissions that are used to compensate the additional emissions before 2030. The faster transition during 2030–2050 is taking place from a greater investment in fossil fuel infrastructure and lower deployment of low-carbon alternatives in 2030, adding to the socio-economic challenges to realise the higher transition rates (Section 3.5.2.2). Therefore, these pathways also show higher mitigation costs, particularly during the period 2030–2050, than immediate action scenarios (Section 3.6.1 and Figure 3.34d) (Liu et al. 2016; Kriegler et al. 2018a; Vrontisi et al. 2018). Given these circumstances and the fact the modelling of socio-political and institutional constraints is limited in Integrated Assessment Models (IAMs) (Gambhir et al. 2019; Köhler et al. 2019; Hirt et al. 2020; Keppo et al. 2021), the feasibility of realising these scenarios is assessed to be lower (Gambhir et al. 2017; Napp et al. 2017; Brutschin et al. 2021) (cf. Section 3.8), increasing the risk of an overshoot of climate goals.

3.5.2.1 Overshoot and Net Negative CO_2 Emissions

If near- to medium-term emissions developments deplete the remaining carbon budget, the associated warming limit will be overshot. Some pathways that return warming to 1.5°C (>50%) by the end of the century show mid-century overshoots of up to 1.8°C median warming. The overshoot tends to be higher, the higher the 2030 emissions. Mitigation pathways with 2030 emissions levels in the NDCS announced prior to COP26 consistently overshoot 1.5°C by 0.15°C–0.3°C. This leads to higher risks from climate change impacts during the time of overshoot compared to pathways that limit warming to 1.5°C (>50%) with no or limited overshoot (Schleussner et al. 2016a; Mengel et al. 2018; Hofmann et al. 2019; Lenton et al. 2019; Tachiiri et al. 2019; Drouet et al. 2021). Furthermore, even if warming is reversed by net negative emissions, other climate changes such as sea level rise would continue in their current direction for decades to millennia (AR6 WGI Sections 4.6 and 5.6).

Returning warming to lower levels requires net negative CO_2 emissions in the second half of the century (Clarke et al. 2014; Fuss et al. 2014; Rogelj et al. 2018a). The amount of net negative CO_2 emissions in pathways limiting warming to 1.5°C–2°C climate goals varies widely, with some pathways not deploying net negative CO_2 emissions at all and others deploying up to –600 to –800 $GtCO_2$. The amount of net negative CO_2 emissions tends to increase with 2030 emissions levels (Figure 3.30e and Table 3.6). Studies confirmed the ability of net negative CO_2 emissions to reduce warming, but pointed to path dependencies in the storage of carbon and heat in the Earth System and the need for further research particularly for cases of high overshoot (Zickfeld et al. 2016, 2021; Keller et al. 2018a,b; Tokarska et al. 2019). The AR6 WGI assessed the reduction in global surface temperature to be approximately linearly related to cumulative CO_2 removal and, with lower confidence, that the amount of cooling per unit CO_2 removed is approximately independent of the rate and amount of removal (AR6 WGI TS.3.3.2). Still there remains large uncertainty about a potential asymmetry between the warming response to CO_2 emissions and the cooling response to net negative CO_2 emissions (Zickfeld et al. 2021). It was also shown that warming can adversely affect the efficacy of carbon dioxide removal measures and hence the ability to achieve net negative CO_2 emissions (Boysen et al. 2016).

Obtaining net negative CO_2 emissions requires massive deployment of carbon dioxide removal (CDR) in the second half of the century, on the order of 220 (160–370) $GtCO_2$ for each 0.1°C degree of cooling (based on the assessment of the *likely* range of the transient response to cumulative CO_2 emissions in AR6 WGI Section 5.5 in Chapter 5, not taking into account potential asymmetries in the temperature response to CO_2 emissions and removals). CDR is assessed in detail in Section 12.3 of this report (see also Cross-Chapter Box 8 in Chapter 12). Here we only point to the finding that CDR ramp-up rates and absolute deployment levels are tightly limited by techno-economic, social, political, institutional and sustainability constraints (Smith et al. 2016; Boysen et al. 2017; Fuss et al. 2018, 2020; Nemet et al. 2018; Hilaire et al. 2019; Jia et al. 2019) (Section 12.3). CDR therefore cannot be deployed arbitrarily to compensate any degree of overshoot. A fraction of models was not able to compute pathways that would follow the mitigation ambition in unconditional and conditional NDCs until 2030 and return warming to below 1.5°C by 2100 (Luderer et al. 2018; Roelfsema et al. 2020; Riahi et al. 2021). There exists a three-way trade-off between near-term emissions developments until 2030, transitional challenges during 2030–50, and long-term CDR deployment post-2050 (Sanderson et al. 2016; Holz et al. 2018; Strefler et al. 2018). For example, Strefler et al. (2018) find that if CO_2 emission levels stay at around 40 $GtCO_2$ until 2030, within the range of what is projected for NDCs announced prior to COP26, rather than being halved to 20 $GtCO_2$ until 2030, CDR deployment in the second half of the century would have to increase by 50–100%, depending on whether the 2030–2050 CO_2 emissions reduction rate is doubled from 6% to 12% or kept at 6% yr^{-1}. This three-way trade-off has also been identified at the national level (Pan et al. 2020).

In addition to enabling a temporary budget overshoot by net negative CO_2 emissions in the second half of the century, CDR can also be used to compensate – on an annual basis – residual CO_2 emissions from sources that are difficult to eliminate and to reach net zero CO_2 emissions more rapidly if deployed before this point (Kriegler et al. 2013b; Rogelj et al. 2018a). This explains its continued deployment in pathways that exclude overshoot and net negative CO_2 emissions (Riahi et al. 2021). However, given the time scales that would likely be needed to ramp-up CDR to gigatonne scale (Nemet et al. 2018), it can be expected to only make a limited contribution to reaching net zero CO_2 as fast as possible. In the vast majority (95%) of 1.5°C–2°C mitigation pathways assessed in this report, cumulative CDR deployment did not exceed 100 $GtCO_2$ until mid-century. This adds to the risk of excessively relying on CDR to compensate for weak mitigation action until 2030 by either facilitating massive net CO_2 emissions reduction rates during 2030–2050 or allowing a high temporary overshoot of 1.5°C until the end of the century. If international burden-sharing considerations are taken into account, the CDR penalty for weak action could increase further, in particular for developed countries (Fyson et al. 2020). Further assessment of CDR deployment in 1.5°C–2°C mitigation pathways is found in Section 3.4.7.

3.5.2.2 Carbon Lock-in and Stranded Assets

There already exists a substantial and growing carbon lock-in today, as measured by committed emissions associated with existing long-lived infrastructure (Section 2.7 and Figure 2.31). If existing fossil fuel infrastructure would continue to be operated as historically, it would entail CO_2 emissions exceeding the carbon budget for 1.5°C (Section 2.7.2 and Figure 2.32). However, owner-operators and societies may choose to retire existing infrastructure earlier than in the past, and committed emissions are thus contingent on the competitiveness of non-emitting alternative technologies and climate policy ambition. Therefore, in mitigation pathways, some infrastructure may become stranded assets. Stranded assets have been defined as 'assets that have suffered from unanticipated or premature write-downs, devaluations or conversion to liabilities' (Caldecott 2017).

A systematic map of the literature on carbon lock-in has synthesized quantification of stranded assets in the mitigation pathways literature, and showed that (i) coal power plants are the most exposed to risk of becoming stranded, (ii) delayed mitigation action increases stranded assets, and (iii) sectoral distribution and the amount of stranded assets differ between countries (Fisch-Romito et al. 2021). There is high agreement that existing fossil fuel infrastructure would need to be retired earlier than historically, used less, or retrofitted with CCS, to stay within the remaining carbon budgets of limiting warming to 1.5°C or 2°C (Johnson et al. 2016; Kefford et al. 2018; Pfeiffer et al. 2018; Cui et al. 2019; Fofrich et al. 2020; Rogelj et al. 2018a). Studies estimate that cumulative early retired power plant capacities by 2060 can be up to 600 GW for gas and 1700 GW for coal (Iyer et al. 2015a; Kefford et al. 2018), that only 42% of the total capital stock of both operating and planned coal-fired powers plants can be utilised to be compatible with the 2°C target (Pfeiffer et al. 2018), and that coal-fired power plants in scenarios consistent with keeping global warming below 2°C or 1.5°C retire one to three decades earlier than historically has been the case (Cui et al. 2019; Fofrich et al. 2020). After coal, electricity production based on gas is also projected to be phased out, with some capacity remaining as back-up (van Soest et al. 2017a). Kefford et al. (2018) find USD541 billion worth of stranded fossil fuel power plants could be created by 2060, with China and India the most exposed.

Some publications have suggested that stranded long-lived assets may be even more important outside of the power sector. While stranded power sector assets by 2050 could reach up to USD1.8 trillion in scenarios consistent with a 2°C target, Saygin et al. (2019) found a range of USD5–11 trillion in the buildings sector. Muldoon-Smith and Greenhalgh (2019) have even estimated a potential value at risk for global real estate assets up to USD21 trillion. More broadly, the set of economic activities that are potentially affected by a low-carbon transition is wide and includes also energy-intensive industries, transport and housing, as reflected in the concept of climate policy relevant sectors introduced in Battiston et al. (2017). The sectoral distribution and amount of stranded assets differ across countries (Fisch-Romito et al. 2021). Capital for fossil fuel production and distribution represents a larger share of potentially stranded assets in fossil fuel-producing countries such as the United States and Russia. Electricity generation would be a larger share of total stranded assets in emerging countries because this capital is relatively new compared to its operational lifetime. Conversely, buildings could represent a larger part of stranded capital in more developed countries and regions such as the USA, EU or even Russia because of high market value and low turnover rate.

Many quantitative estimates of stranded assets along mitigation pathways have focused on fossil fuel power plants in pathways characterised by mitigation ambition until 2030 corresponding to the NDCs followed by strengthened action afterwards to limit warming to 2°C (>67%) or lower (Bertram et al. 2015a; Iyer et al. 2015b; Lane et al. 2016; Farfan and Breyer 2017; van Soest et al. 2017a; Kriegler et al. 2018a; Luderer et al. 2018; Cui et al. 2019; Saygin et al.

2019; SEI et al. 2020). Pathways following NDCs announced prior to COP26 until 2030 do not show a significant reduction of coal, oil and gas use (Figure 3.30f–h and Table 3.6) compared to immediate action pathways. Stranded coal power assets are evaluated to be higher by a factor of two to three if action is strengthened after 2030 rather than now (Iyer et al. 2015b; Cui et al. 2019). There is high agreement that the later climate policies are implemented, the higher the expected stranded assets and the societal, economic and political strain of strengthening action. Associated price increases for carbon-intensive goods and transitional macro-economic costs have been found to scale with the emissions gap in 2030 (Kriegler et al. 2013a). At the aggregate level of the whole global economy, Rozenberg et al. (2015) showed that each year of delaying the start of mitigation decreases the required CO_2 intensity of new production by 20–50 gCO_2 per USD. Carbon lock-in can have a long-lasting effect on future emissions trajectories after 2030. Luderer et al. (2018) compared cost-effective pathways with immediate action to limit warming to 1.5°C–2°C with pathways following the NDCs until 2030 and adopting the pricing policy of the cost-effective pathways thereafter, and found that the majority of additional CO_2 emissions from carbon lock-in occur after 2030, reaching a cumulative amount of 290 (160–330) $GtCO_2$ by 2100 (Section 2.7.2). Early action and avoidance of investments in new carbon-intensive assets can minimise these risks.

3

The risk of stranded assets has implications for workers depending on those assets, asset owners, assets portfolio managers, financial institutions and the stability of the financial system. Chapter 6 assesses the risks and implications of stranded assets for energy systems (Section 6.7.3 and Box 6.11) and fossil fuels (Section 6.7.4). The implications of stranded assets for inequality and Just Transition are assessed in Chapter 17 (Section 17.3.2.3). Chapter 15 assesses the literature on those implications for the financial system as well as on coping options (Sections 15.5.2 and 15.6.1).

On the other hand, mitigation, by limiting climate change, reduces the risk of destroyed or stranded assets from the physical impacts of climate change on natural and human systems, from more frequent, intense or extended extreme events and from sea level rise (O'Neill et al. 2020a). The literature on mitigation pathways rarely includes an evaluation of stranded assets from climate change impacts. Unruh (2019) suggest that these are the real stranded assets of carbon lock-in and could prove much more costly.

3.5.3 Global Accelerated Action Towards Long-term Climate Goals

A growing literature explores long-term mitigation pathways with accelerated near-term action going beyond the NDCs (Graichen et al. 2017; Jiang et al. 2017; Kriegler et al. 2018a; Roelfsema et al. 2018; Fekete et al. 2021; van Soest et al. 2021a). Global accelerated action pathways are designed to transition more gradually from implemented policies and planned implementation of NDCs onto a 1.5°C–2°C pathway and at the same time alleviate the abrupt transition in 2030 that would be caused by following the NDCs until 2030 and strengthening towards limiting warming to 2°C thereafter (Section 3.5.2). Therefore, they have sometimes been called bridging scenarios/pathways in the literature (IEA 2011; Spencer et al. 2015; van Soest et al. 2021a). They rely on regionally differentiated regulatory and pricing policies to gradually strengthening regional and sectoral action beyond the mitigation ambition in the NDCs. There are limitations to this approach. The tighter the warming limit, the more likely it is that disruptive action becomes inevitable to achieve the speed of transition that would be required (Kriegler et al. 2018a). Cost-effective pathways already have abrupt shifts in deployments, investments and prices at the time a stringent warming limit is imposed, reflecting the fact that the overall response to climate change has so far been misaligned with long-term climate goals (Fawcett et al. 2015; Rogelj et al. 2016; Schleussner et al. 2016b; Geiges et al. 2020). Disruptive action can help to break lock-ins and enable transformative change (Vogt-Schilb et al. 2018).

The large literature on accelerating climate action was assessed in the *IPCC Special Report on Global Warming of 1.5°C* (de Coninck et al. 2018) and is taken up in this report primarily in Chapters 4, 13, and 14. Accelerating climate action and facilitating transformational change requires a perspective on socio-technical transitions (Geels et al. 2016a; Geels et al. 2016b; Geels 2020), a portfolio of policy instruments to manage technological and environmental change (Fischer and Newell 2008; Goulder and Parry 2008; Acemoglu et al. 2012, 2016), a notion of path dependency and policy sequencing (Pierson 2000; Meckling et al. 2017; Pahle et al. 2018) and the evolvement of polycentric governance layers of institutions and norms in support of the transformation (Dietz et al. 2003; Leach et al. 2007; Messner 2015). This subsection is focused on an assessment of the emerging quantitative literature on global accelerated action pathways towards 1.5°C–2°C, which to a large extent abstracts from the underlying processes and uses a number of stylised approaches to generate these pathways. A representative of accelerated action pathways has been identified as one of the Illustrative Mitigation Pathways (IMPs) in this assessment (*IMP-GS*, Figure 3.31).

One approach relies on augmenting initially moderate emissions-pricing policies with robust anticipation of ratcheting up climate action in the future (Spencer et al. 2015). If announcements of strong future climate policies are perceived to be credible, they can help to prevent carbon lock-in as investors anticipating high future costs of GHG emissions would reduce investment into fossil fuel infrastructure, such as coal power plants (Bauer et al. 2018b). However, the effectiveness of such announcements strongly hinges on their credibility. If investors believe that policymakers could drop them if anticipatory action did not occur, they may not undertake such action.

Another approach relies on international cooperation to strengthen near-term climate action. These studies build on international climate policy architectures that could incentivise a coalition of like-minded countries to raise their mitigation ambition beyond what is stated in their NDC (Graichen et al. 2017). Examples are the idea of climate clubs characterised by harmonised carbon and technology markets (Nordhaus 2015; Keohane et al. 2017; Paroussos et al. 2019; Pihl 2020) and the Powering Past Coal Alliance (PPCA) (Jewell et al. 2019). Paroussos et al. (2019) find economic benefits of joining a climate club despite the associated higher mitigation effort, in particular due

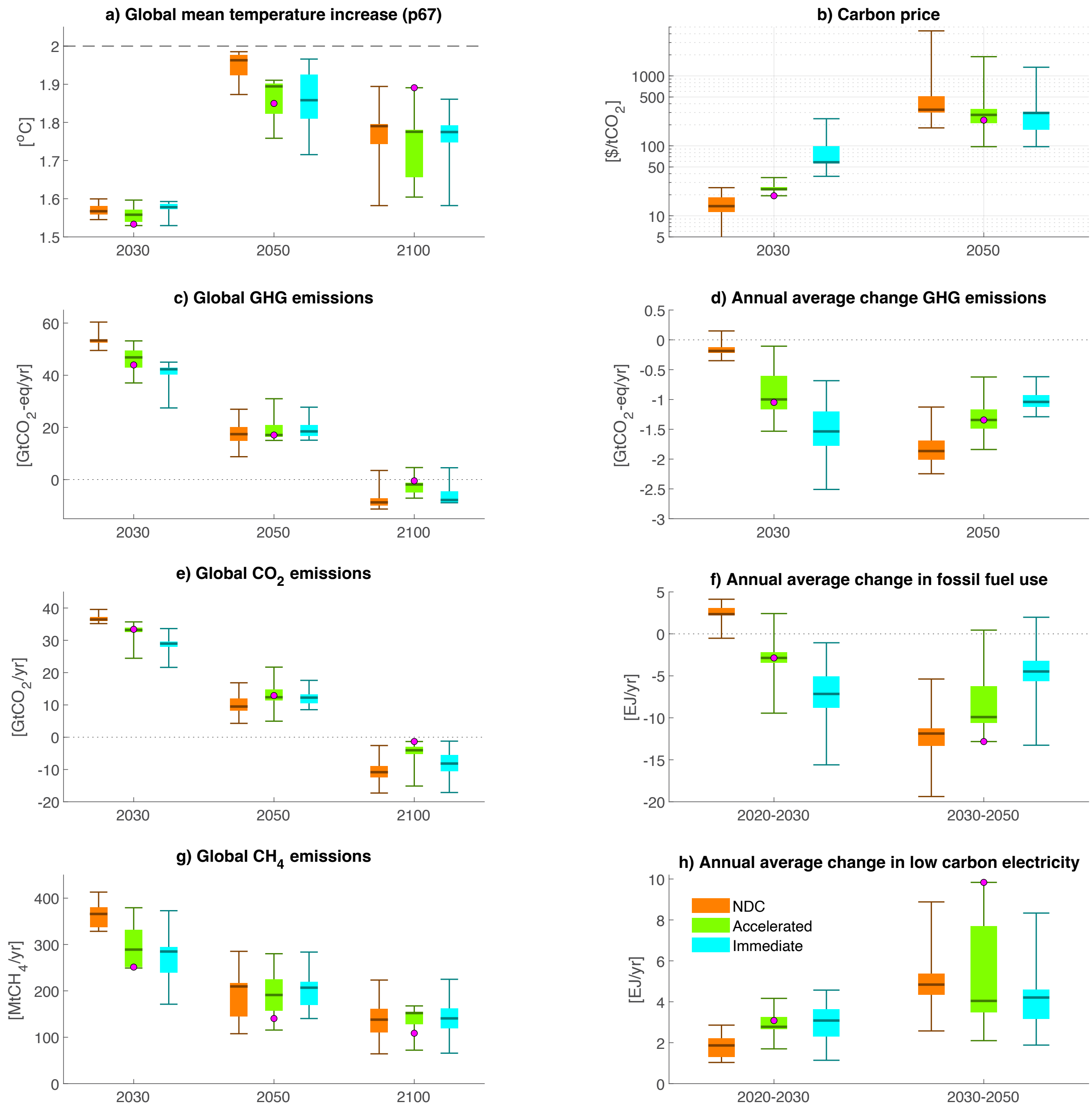


Figure 3.31 | Comparison of (i) pathways with immediate action to limit warming to 2°C (>67%) (Immediate, light blue), (ii) pathways following the NDCs until 2030 and limiting warming to 2°C (>67%) thereafter (NDC; orange), and (iii) pathways accelerating near-term action until 2030 beyond NDC ambition levels and limiting warming to 2°C (>67%) thereafter (accelerated) for selected indicators as listed in the panel titles, based on pathways from van Soest et al. (2021a). Low-carbon electricity comprises renewable and nuclear power. Indicator ranges are shown as box plots (full range, interquartile range, and median) for the years 2030, 2050 and 2100 (absolute values) and for the periods 2020–2030, 2030–2050 (change indicators). Ranges are based on nine models participating in van Soest et al. (2021a) with only seven models reporting emissions and climate results and eight models reporting carbon prices. The purple dot denotes the Illustrative Mitigation Pathway *GS* that was part of the study by van Soest et al.

to access to technology and climate finance. Graichen et al. (2017) find an additional reduction of 5–11 $GtCO_2$-eq compared to the mitigation ambition in the NDCs from the successful implementation of international climate initiatives. Other studies assess benefits from international transfers of mitigation outcomes (Stua 2017; Edmonds et al. 2021). Edmonds et al. (2021) find economic gains from sharing NDC emissions-reduction commitments compared to purely domestic implementation of NDCs. If reinvested in mitigation efforts, the study projects an additional reduction of 9 billion tonnes of CO_2 in 2030.

The most common approach relies on strengthening regulatory policies beyond current policy trends, also motivated by the finding that such policies have so far been employed more often than comprehensive carbon pricing (Kriegler et al. 2018a; Roelfsema et al. 2018; Fekete et al. 2021; IEA 2021a; van Soest et al. 2021a). Some studies have focused on generic regulatory policies such as low-carbon support policies, fossil fuel-sunset policies, and resource-efficiency policies (Bertram et al. 2015b; Hatfield-Dodds et al. 2017). Bertram et al. (2015b) found that a moderate carbon price combined with a coal moratorium and ambitious low-carbon support policies can limit efficiency losses until 2030 if emissions pricing is raised thereafter to limit warming to 2°C. They also showed that all three components are needed to achieve this outcome. Hatfield-Dodds et al. (2017) found that resource efficiency can lower 2050 emissions by an additional 15–20% while boosting near-term economic growth. The International Energy Agency (IEA 2021a) developed a detailed net zero scenario for the global energy sector characterised by a rapid phase-out of fossil fuels, a massive clean energy and electrification push, and the stabilisation of energy demand, leading to 10 $GtCO_2$ lower emissions from energy use in 2030 than in a scenario following the announced pledges.

The Paris Agreement has spurred the formulation of NDCs for 2030 and mid-century strategies around the world (cf. Chapter 4). This is giving researchers a rich empirical basis to formulate accelerated policy packages taking national decarbonisation pathways as a starting point (Graichen et al. 2017; Jiang et al. 2017; van Soest et al. 2017b; Waisman et al. 2019). The concept is to identify good practice policies that had demonstrable impact on pushing low-carbon options or reducing emissions in a country or region and then consider a wider roll out of these policies taking into account regional specificities (den Elzen et al. 2015; Fekete et al. 2015, 2021; Kriegler et al. 2018a; Kuramochi et al. 2018; Roelfsema et al. 2018). A challenge for this approach is to account for the fact that policy effectiveness varies with different political environments in different geographies. As a result, a global roll out of good practice policies to close the emissions gap will still be an idealised benchmark, but it is useful to understand how much could be gained from it.

Accelerated action pathways derived with this approach show considerable scope for narrowing the emissions gap between pathways reflecting the ambition level of the NDCs and cost-effective mitigation pathways in 2030. Kriegler et al. (2018a) find around 10 $GtCO_2$-eq lower emissions compared to original NDCs from a global roll out of good practice plus net zero policies and a moderate increase in regionally differentiated carbon pricing. Fekete et al. (2021) show that global replication of sector progress in five major economies would reduce GHG emissions in 2030 by about 20% compared to a current policy scenario. These findings were found in good agreement with a recent model comparison study based on results from nine integrated assessment models (IAMs) (van Soest et al. 2021a). Based on these three studies, implementing accelerated action in terms of a global roll out of regulatory and moderate pricing policies is assessed to lead to global GHG emissions of 48 (38–52) $GtCO_2$-eq in 2030 (median and 5–95th percentile based on 10 distinct modelled pathways). This closes the implementation gap for the NDCs, and in addition falls below the emissions range implied by implementing unconditional and conditional elements of NDCs by 2–9 $GtCO_2$-eq. However, it does not close the emissions gap to immediate action pathways that limit warming to 2°C (>67%), and, based on our assessment in Section 3.5.2, emission levels above 40 $GtCO_2$-eq in 2030 still have a very low prospect for limiting warming to 1.5°C (>50%) with no or limited overshoot.

Figure 3.31 shows the intermediate position of accelerated action pathways derived by van Soest et al. (2021a) between pathways that follow the NDCs until 2030 and immediate action pathways limiting warming to 2°C (>67%). Accelerated action is able to reduce the abrupt shifts in emissions, fossil fuel use and low-carbon power generation in 2030 and also limits peak warming more effectively than NDC pathways. But primarily due to the moderate carbon price assumptions (Figure 3.31b), the reductions in emissions and particular fossil fuel use are markedly smaller than what would be obtained in the case of immediate action. The assessment shows that accelerated action until 2030 can have significant benefits in terms of reducing the mitigation challenges from following the NDCs until 2030. But putting a significant value on GHG emissions reductions globally remains a key element of moving onto 1.5°C–2°C pathways. The vast majority of pathways that limit warming to 2°C (>67%) or lower, independently of their differences in near-term emission developments, converge to a global mitigation regime putting a significant value on GHG emission reductions in all regions and sectors.

3.6 Economics of Long-term Mitigation and Development Pathways, Including Mitigation Costs and Benefits

A complete appraisal of economic effects and welfare effects at different temperature levels would include the macroeconomic impacts of investments in low-carbon solutions and structural change away from emitting activities, co-benefits and adverse side effects of mitigation, (avoided) climate damages, as well as (reduced) adaptation costs, with high temporal, spatial and social heterogeneity using a harmonised framework. If no such complete appraisal in a harmonised framework exists, key elements are emerging from the literature, and assessed in the following subsections: on aggregated economy-wide global mitigation costs (Section 3.6.1), on the economic benefits of avoiding climate impacts (Section 3.6.2), on economic benefits and costs associated with mitigation co-benefits and co-harms (Section 3.6.3) and on the distribution of economic implications between economic sectors and actors (Section 3.6.4).

3

3.6.1 Economy-wide Implications of Mitigation

3.6.1.1 Global Economic Effects of Mitigation and Carbon Values in Mitigation Pathways

Box 3.5 | Concepts and Modelling Frameworks Used for Quantifying Macroeconomic Effects of Mitigation

Most studies that have developed mitigation pathways have used a cost-effectiveness analysis (CEA) framework, which aim to compare the costs of different mitigation strategies designed to meet a given climate change mitigation goal (e.g., an emission-reduction target or a temperature stabilisation target) but does not represent economic impacts from climate change itself, nor the associated economic benefits of avoided impacts. Other studies use modelling frameworks that represent the feedback of damages from climate change on the economy in a cost-benefit analysis (CBA) approach, which balances mitigation costs and benefits. This second type of study is represented in Section 3.6.2.

The marginal abatement cost of carbon, also called carbon price, is determined by the mitigation target under consideration: it describes the cost of reducing the last unit of emissions to reach the target at a given point in time. Total macroeconomic mitigation costs (or gains) aggregate the economy-wide impacts of investments in low-carbon solutions and structural changes away from emitting activities. The total macroeconomic effects of mitigation pathways are reported in terms of variations in economic output or consumption levels, measured against a reference scenario, also called baseline, at various points in time or discounted over a given time period. Depending on the study, the reference scenario reflects specific assumptions about patterns of socio-economic development and assumes either no-climate policies or the climate policies in place or planned at the time the study was carried out. When available in the AR6 scenarios database, this second type of reference scenario, with trends from implemented policies until the end of 2020, has been chosen for computation of mitigation costs. In the vast majority of studies that have produced the body of work on the cost of mitigation assessed here, and in particular in all studies that have submitted global scenarios to the AR6 scenarios database except (Schultes et al. 2021), the feedbacks of climate change impacts on the economic development pathways are not accounted for. This omission of climate impacts leads to overly optimistic economic projections in the reference scenarios, in particular in reference scenarios with no or limited mitigation action where the extent of global warming is the greatest. Mitigation cost estimates computed against no or limited policy reference scenarios therefore omit economic benefits brought by avoided climate change impact along mitigation pathways, and should be interpreted with care (Grant et al. 2020). When aggregate economic benefits from avoided climate change impacts are accounted for, mitigation is a welfare-enhancing strategy (Section 3.6.2).

If GDP or consumption in mitigation pathways are below the reference scenario levels, they are reported as losses or macroeconomic costs. Such cost estimates give an indication of how economic activity slows relative to the reference scenario; they do not necessarily describe, in absolute terms, a reduction of economic output or consumption levels relative to previous years along the pathway. Aggregate mitigation costs depend strongly on the modelling framework used and the assumptions about the reference scenario against which mitigation costs are measured, in particular whether the reference scenario is, or not, on the efficiency frontier of the economy. If the economy is assumed to be at the efficiency frontier in the reference scenario, mitigation inevitably leads to actual costs, at least in the short-run until the production frontier evolves with technical and structural change. Starting from a reference scenario that is not on the efficiency frontier opens the possibility to simultaneously reduce emissions and obtain macroeconomic gains, depending on the design and implementation of mitigation policies. A number of factors can result in reference scenarios below the efficiency frontier, for instance distorting labour taxes and/or fossil fuel subsidies, misallocation or under-utilisation of production factors such as involuntary unemployment, imperfect information or non-rational behaviours. Although these factors are pervasive, the modelling frameworks used to construct mitigation pathways are often limited in their ability to represent them (Köberle et al. 2021).

The absolute level of economic activity and welfare also strongly depends on the socio-economic pathway assumptions regarding, *inter alia*, evolutions in demography, productivity, education levels, inequality, and technical change and innovation. The GDP or consumption indicators reported in the database of scenarios, and synthesized below, represent the absolute level of aggregate economic activity or consumption but do not reflect welfare and well-being (Roberts et al. 2020), that notably depend on human-needs satisfaction, distribution within society and inequality (Section 3.6.4).

Chapter 1 and Annex III.I give further details of the economic concepts and modelling frameworks, including their limitations, used in this report, respectively.

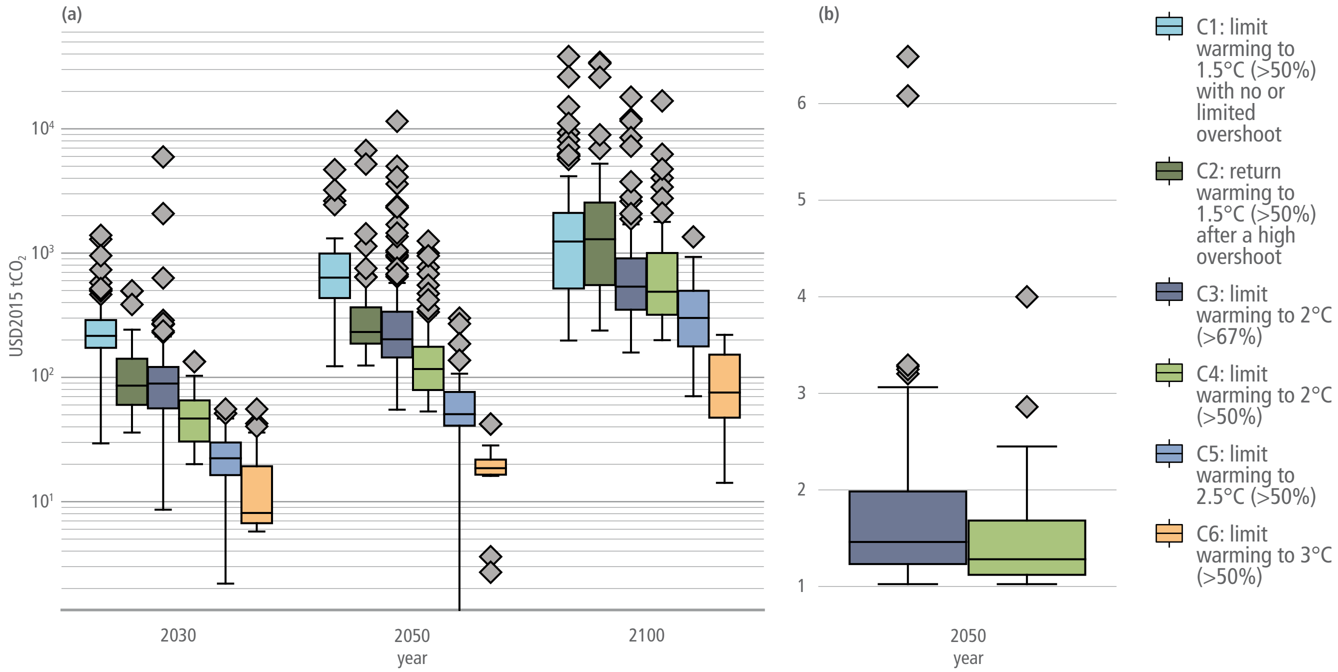


Figure 3.32 | Marginal abatement cost of carbon in 2030, 2050 and 2100 for mitigation pathways with immediate global mitigation action (a), and ratio in 2050 between pathways that correspond to NDCs announced prior to COP26 in 2030 and strengthen action after 2030 and pathways with immediate global mitigation action, for C3 and C4 temperature categories (b).

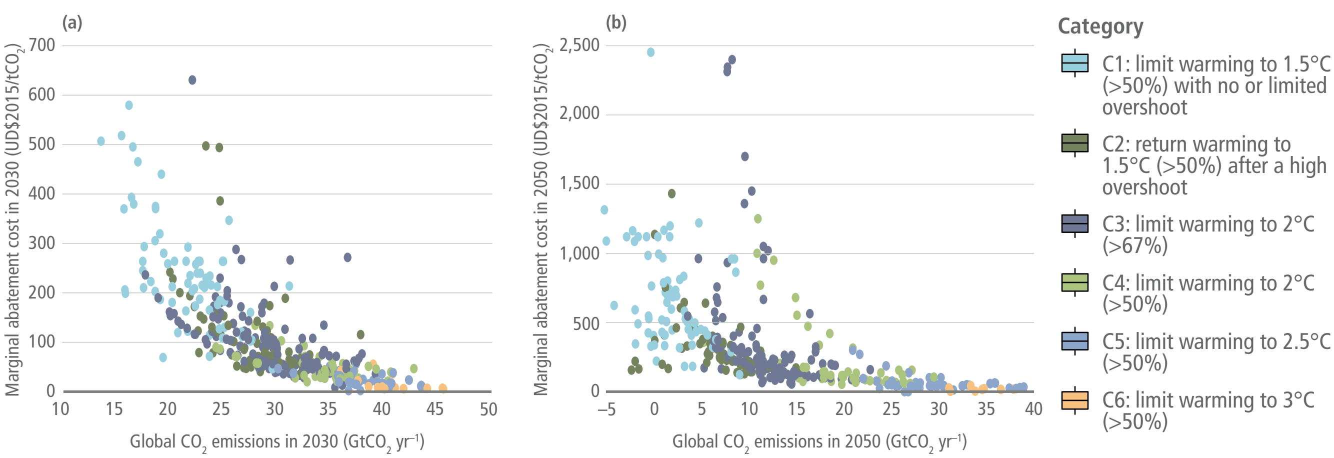


Figure 3.33 | Marginal abatement cost of carbon with respect to CO_2 emissions for mitigation pathways with immediate global mitigation action, in 2030 (a) and 2050 (b).

Estimates for the marginal abatement cost of carbon in mitigation pathways vary widely, depending on the modelling framework used and socio-economic, technological and policy assumptions. However, it is robust across modelling frameworks that the marginal abatement cost of carbon increases for lower temperature categories, with a higher increase in the short term than in the longer term (Figure 3.32, left panel) (*high confidence*). The marginal abatement cost of carbon increases non-linearly with the decrease of CO_2 emissions level, but the uncertainty in the range of estimates also increases (Figure 3.33). Mitigation pathways with low-energy consumption patterns exhibit lower carbon values (Méjean et al. 2019; Meyer et al. 2021). In the context of the COVID-19 pandemic recovery, Kikstra et al. (2021a) also show that a low-energy-demand recovery scenario reduces carbon prices for a 1.5°C-consistent pathway by 19% compared to a scenario with energy demand trends restored to pre-pandemic levels.

For optimisation modelling frameworks, the time profile of marginal abatement costs of carbon depends on the discount rate, with lower discount rates implying higher carbon values in the short term but lower values in the long term (Emmerling et al. 2019) (see also 'Discounting' in Annex I: Glossary, and Annex III.I.2). In that case, the discount rate also influences the shape of the emissions trajectory, with low discount rates implying more emissions reduction in the short term and, for low-temperature categories, limiting CDR and temperature overshoot.

Pathways that correspond to NDCs announced prior to COP26 in 2030 and strengthen action after 2030 imply higher marginal abatement costs of carbon in the longer run than pathways with stronger immediate global mitigation action (Figure 3.32b) (*high confidence*).

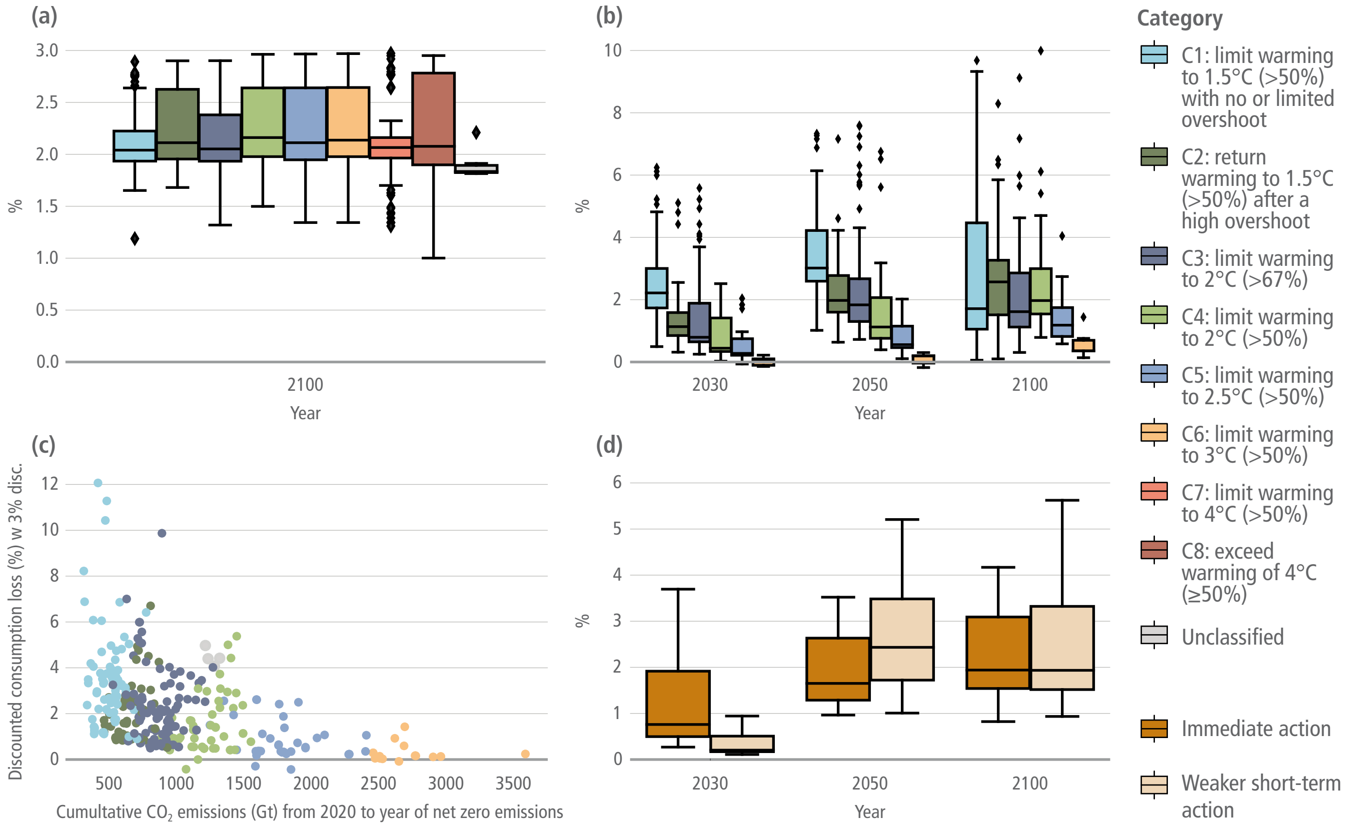


Figure 3.34 | (a) Mean annual global consumption growth rate over 2020–2100 for the mitigation pathways in the AR6 scenarios database. (b) Global GDP loss compared to baselines (not accounting for climate change damages) in 2030, 2050 and 2100 for mitigation pathways with immediate global action. **(c)** Total discounted consumption loss (with a 3% discount rate) in mitigation scenarios with respect to their corresponding baseline (not accounting for climate change damages) as a function of cumulative CO_2 emissions until date of net zero CO_2. **(d)** Comparison of GDP losses compared to baselines (not accounting for climate change damages) in 2030, 2050 and 2100 for pairs of scenarios depicting immediate action pathways and delayed action pathways. Source: AR6 Scenarios Database.

Aggregate economic activity and consumption levels in mitigation pathways are primarily determined by socio-economic development pathways but are also influenced by the stringency of the mitigation goal and the policy choices to reach the goal (*high confidence*). Mitigation pathways in temperature categories C1 and C2 entail losses in global consumption with respect to their baselines – not including benefits of avoided climate change impacts nor co-benefits or co-harms of mitigation action – that correspond to an annualised reduction of consumption growth by 0.04 (median value) (interquartile range [0.02–0.06]) percentage points over the century. For pathways in temperature categories C3 and C4 this reduction in global consumption growth is 0.03 (median value) (interquartile range [0.01–0.05]) percentage points over the century. In the majority of studies that focus on the economic effects of mitigation without accounting for climate damages, global economic growth and consumption growth is reduced compared to baseline scenarios (that omit damages from climate change), but mitigation pathways do not represent an absolute decrease of economic activity level (Figure 3.34b,c).

However, the possibility for increased economic activity following mitigation action, and conversely the risk of large negative economic effects, are not excluded. Some studies find that mitigation increases the speed of economic growth compared to baseline scenarios (Pollitt and Mercure 2018; Mercure et al. 2019). These studies are based on a macroeconomic modelling framework that represent baselines below the efficiency frontier, based on non-equilibrium economic theory, and assume that mitigation is undertaken in such a way that green investments do not crowd out investment in other parts of the economy – and therefore offers an economic stimulus. In the context of the recovery from the COVID-19 crisis, it is estimated that a green investment push would initially boost the economy while also reducing GHG emissions (IMF 2020; Pollitt et al. 2021). Conversely, several studies find that only a GDP non-growth/degrowth or post-growth approach enable reaching climate stabilisation below 2°C (Hardt and O'Neill 2017; D'Alessandro et al. 2020; Hickel and Kallis 2020; Nieto et al. 2020), or to minimise the risks of reliance on high energy-GDP decoupling, large-scale CDR and large-scale renewable energy deployment (Keyßer and Lenzen 2021). Similarly, feedbacks of financial system risk amplifying shocks induced by mitigation policy and lead to a higher impact on economic activity (Stolbova et al. 2018).

Mitigation costs increase with the stringency of mitigation (Hof et al. 2017; Vrontisi et al. 2018) (Figure 3.34b,c), but are reduced when energy demand is moderated through energy efficiency and lifestyle changes (Fujimori et al. 2014; Bibas et al. 2015; Liu et al. 2018; Méjean et al. 2019), when sustainable transport policies are implemented (Zhang et al. 2018c), and when international technology cooperation is fostered (Schultes et al. 2018; Paroussos et al. 2019). Mitigation costs also depend on assumptions on availability and costs of technologies (Clarke et al. 2014; Bosetti et al. 2015; Dessens et al. 2016; Creutzig et al.

2018; Napp et al. 2019; Giannousakis et al. 2021), on the representation of innovation dynamics in modelling frameworks (Hoekstra et al. 2017; Rengs et al. 2020) (Chapter 16), as well as the representation of investment dynamics and financing mechanisms (Iyer et al. 2015c; Mercure et al. 2019; Battiston et al. 2021). In particular, endogenous and induced innovation reduce technology costs over time, create path dependencies and reduce the macroeconomic cost of reaching a mitigation target (Section 1.7.1.2). Mitigation costs also depend on socio-economic assumptions (Hof et al. 2017; van Vuuren et al. 2020).

Mitigation pathways with early emissions reductions represent higher mitigation costs in the short-run but bring long-term gains for the economy compared to delayed transition pathways (*high confidence*). Pathways with earlier mitigation action bring higher long-term GDP than pathways reaching the same end-of-century temperature with weaker early action (Figure 3.34d). Comparing counterfactual history scenarios, Sanderson and O'Neill (2020) also find that delayed mitigation action leads to higher peak costs. Rogelj et al. (2019b) and Riahi et al. (2021) also show that pathways with earlier timing of net zero CO_2 lead to higher transition costs but lower long-term mitigation costs, due to dynamic effects arising from lock-in avoidance and learning effects. For example, Riahi et al.(2021) find that for a 2°C target, the GDP losses (compared to a reference scenario without impacts from climate change) in 2100 are 5–70% lower in pathways that avoid net negative CO_2 emissions and temperature overshoot than in pathways with overshoot. Accounting also for climate change damage, van der Wijst et al. (2021a) show that avoiding net negative emissions leads to a small increase in total discounted mitigation costs over 2020–2100, between 5% and 14% in their medium assumptions, but does not increase mitigation costs when damages are high and when using a low discount rate, and becomes economically attractive if damages are not fully reversible. The modelled cost-optimal balance of mitigation action over time strongly depends on the discount rate used to compute or evaluate mitigation pathways: lower discount rates favour earlier mitigation, reducing both temperature overshoot and reliance on net negative carbon emissions (Emmerling et al. 2019; Riahi et al. 2021). Mitigation pathways with weak early action corresponding to NDCs announced prior to COP26 in 2030 and strengthening action after 2030 to reach end-of-century temperature targets imply limited mitigation costs in 2030, compared to immediate global action pathways, but faster increase in costs post-2030, with implications for intergenerational equity (Aldy et al. 2016; Liu et al. 2016; Vrontisi et al. 2018). Emissions trading policies reduce global aggregate mitigation costs, in particular in the context of achieving NDCs (Fujimori et al. 2015, 2016a; Böhringer et al. 2021; Edmonds et al. 2021), and change the distribution of mitigation costs between regions and countries (Section 3.6.1.2).

3.6.1.2 Regional Mitigation Costs and Effort-sharing Regimes

The economic repercussions of mitigation policies vary across countries (Aldy et al. 2016; Hof et al. 2017): regional variations exist in institutions, economic and technological development, and mitigation opportunities. For a globally uniform carbon price, carbon-intensive and energy-exporting countries bear the highest economic costs because of a deeper transformation of their economies and of trade losses in the fossil markets (Stern et al. 2012; Tavoni et al. 2015; Böhringer et al. 2021). This finding is confirmed in Figure 3.35. Since carbon-intensive countries are often poorer, uniform global carbon prices raise equity concerns (Tavoni et al. 2015). On the other hand, the climate economic benefits of mitigating climate change will be larger in poorer countries (Cross-Working Group Box 1 in this chapter). This reduces policy regressivity but does not eliminate it (Taconet et al. 2020; Gazzotti et al. 2021). Together with co-benefits, such as health benefits of improved air quality, the economic benefits of mitigating climate change are likely to outweigh mitigation costs in many regions (Li et al. 2018, 2019; Scovronick et al. 2021).

Regional policy costs depend on the evaluation framework (Budolfson et al. 2021), policy design, including revenue recycling, and on international coordination, especially among trade partners. By fostering technological change and finance, climate cooperation can

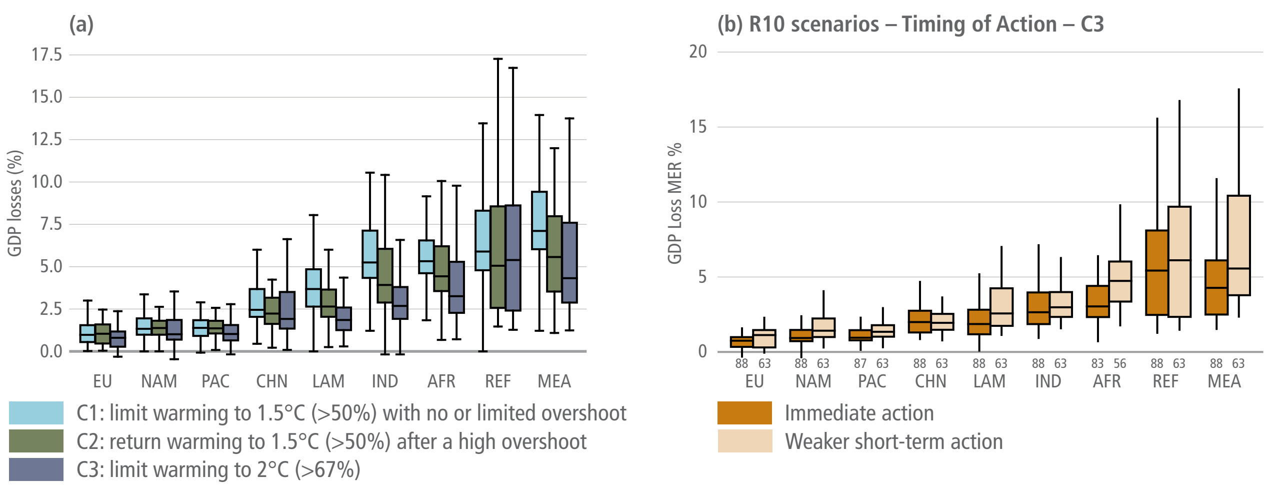


Figure 3.35 | a: regional mitigation costs in the year 2050 (expressed as GDP losses between mitigation scenarios and corresponding baselines, not accounting for climate change damages), under the assumption of immediate global action with uniform global carbon pricing and no international transfers, by climate categories for the 2°C (>67%) and 1.5°C (>50%) (with and without overshoot) categories. Right panel: policy costs in 2050 (as in panel a) for 2°C (>67%) climate category C3 for scenario pairs that represent either immediate global action ('immediate') or delayed global action ('delayed') with weaker action in the short term, strengthening to reach the same end-of-century temperature target.

generate economic benefits, both in large developing economies such as China and India (Paroussos et al. 2019) and industrialised regions such as Europe (Vrontisi et al. 2020). International coordination is a major driver of regional policy costs. Delayed participation in global mitigation efforts raises participation costs, especially in carbon-intensive economies (Figure 3.35a. Trading systems and transfers can deliver cost savings and improve equity (Rose et al. 2017a). On the other hand, measures that reduce imports of energy-intensive goods such as carbon-border tax adjustment may imply costs outside of the policy jurisdiction and have international equity repercussions, depending on how they are designed (Böhringer et al. 2012, 2017; Cosbey et al. 2019) (Section 13.6.6).

An equitable global emission-trading scheme would require very large international financial transfers, in the order of several hundred billion USD per year (Tavoni et al. 2015; Bauer et al. 2020; van den Berg et al. 2020). The magnitude of transfers depends on the stringency of the climate goals and on the burden-sharing principle. Some interpretations of equitable burden sharing compliant with the Paris Agreement leads to negative carbon allowances for developed countries and some developing countries by mid-century (van den Berg et al. 2020), more stringent than cost-optimal pathways. International transfers also depend on the underlying socio-economic development (Leimbach and Giannousakis 2019), as these drive the mitigation costs of meeting the Paris Agreement (Rogelj et al. 2018b). By contrast, achieving equity without international markets would result in a large discrepancy in regional carbon prices, up to a factor of 100 (Bauer et al. 2020). The efficiency-sovereignty trade-off can be partly resolved by allowing for limited differentiation of regional carbon prices: moderate financial transfers substantially reduce inefficiencies by narrowing the carbon price spread (Bauer et al. 2020).

3.6.1.3 Investments in Mitigation Pathways

Figures 3.36 and 3.37 show increased investment needs in the energy sector in lower temperature categories, and a major shift away from fossil fuel generation and extraction towards electricity, including for system enhancements for electricity transmission, distribution and storage, and low-carbon technologies. Investment needs in the electricity sector are 2.3 trillion USD2015 yr^{-1} over 2023–2050 on average for C1 pathways, 2 trillion USD for C2 pathways, 1.7 trillion USD for C3, 1.2 trillion USD for C4 and 0.9–1.1 billion USD for C5/C6/C7 (mean values for pathways in each temperature category). The regional pattern of power sector investments broadly mirrors the global picture. However, the bulk of investment requirements are in medium- and low-income regions. These results from the AR6 scenarios database corroborate the findings from McCollum et al. (2018a), Zhou et al. (2019) and Bertram et al. (2021).

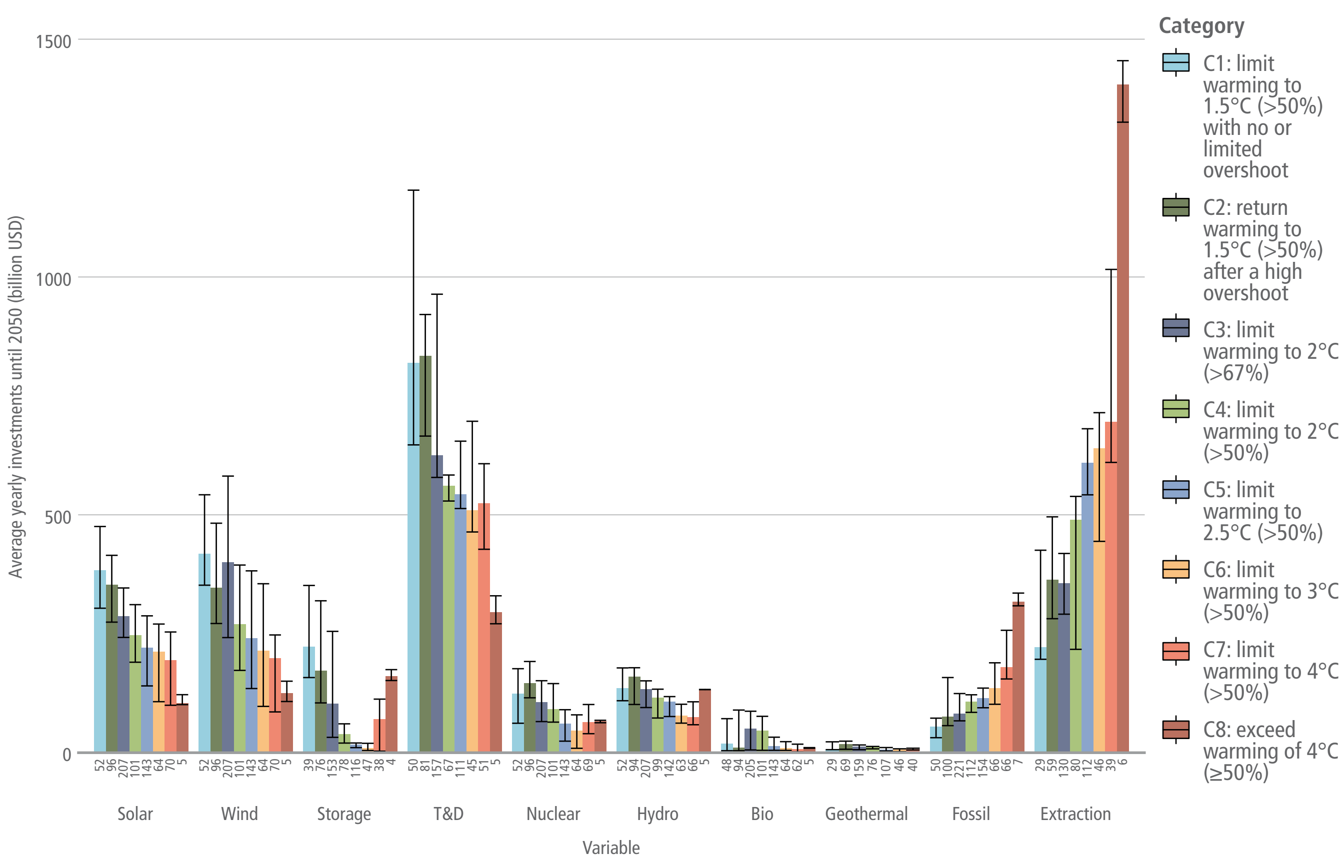


Figure 3.36 | Global average yearly investments from 2023–2052 for nine electricity supply subcomponents and for extraction of fossil fuels (in billion USD2015), in pathways by temperature categories. T&D: transmission and distribution of electricity. Bars show the median values (number of pathways at the bottom), and whiskers show the interquartile ranges.

3

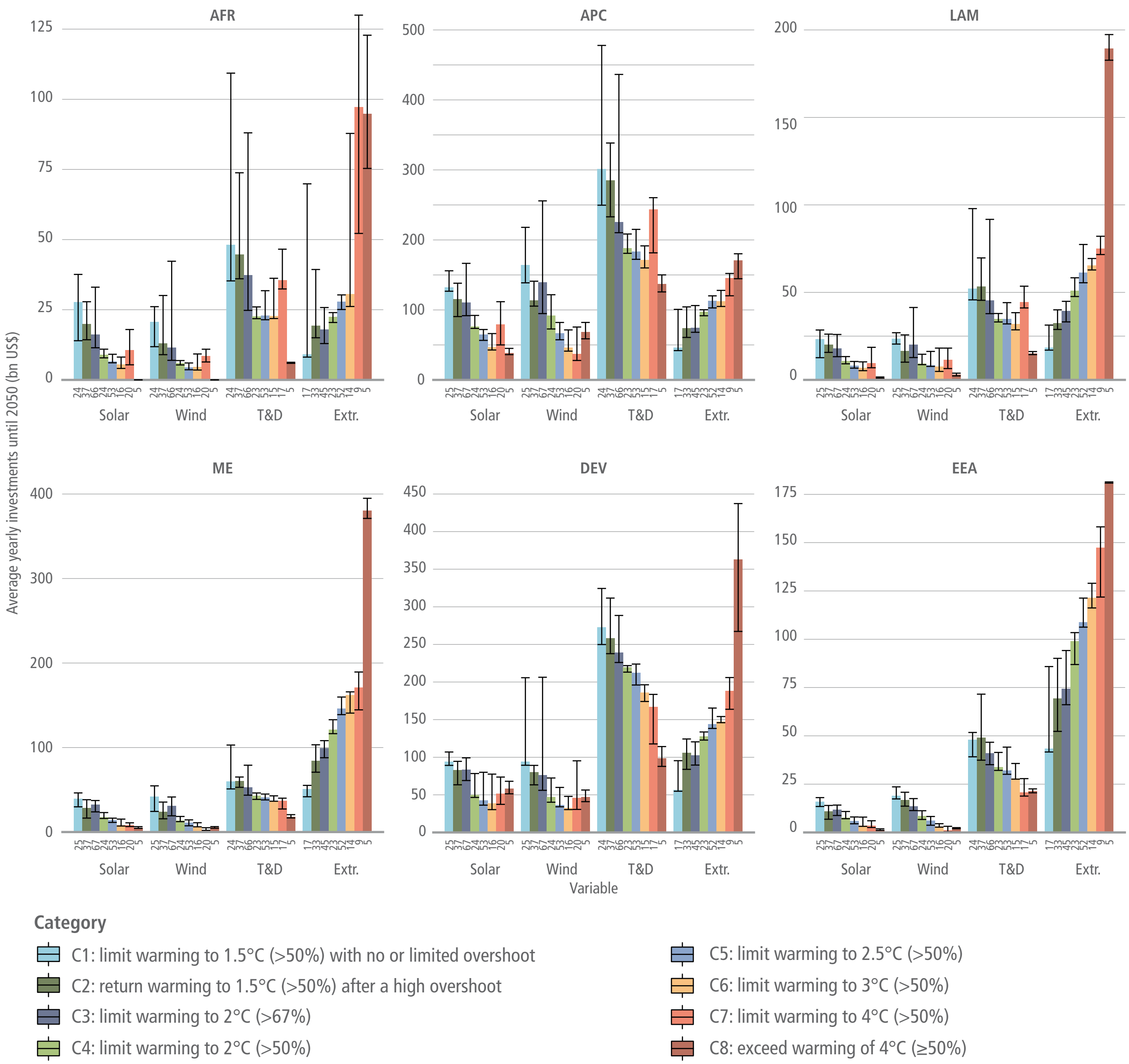


Figure 3.37 | Average yearly investments from 2023–2052 for the four subcomponents of the energy system representing the larger amounts (in billion USD2015), by aggregate regions, in pathways by temperature categories. T&D: transmissions and distribution of electricity. Extr.: extraction of fossil fuels. Bars show the median values (number of pathways at the bottom), and whiskers show the interquartile ranges. For definition of regional classifications used see Annex II Table 1.

In the context of the COVID-19 pandemic recovery, Kikstra et al. (2021a) show that a low-energy-demand recovery scenario reduces energy investments required until 2030 for a 1.5°C consistent pathway by 9% (corresponding to reducing total required energy investment by USD1.8 trillion) compared to a scenario with energy demand trends restored to pre-pandemic levels.

Few studies extend the scope of the investment needs quantification beyond the energy sector. Fisch-Romito and Guivarch (2019) and Ó Broin and Guivarch (2017) assess investment needs for transportation infrastructures and find lower investment needs in low-carbon pathways, due to a reduction in transport activity and a shift towards less road construction, compared to high-carbon pathways. Rozenberg and Fay (2019) estimate the funding needs to close the service gaps in water and sanitation, transportation, electricity, irrigation, and flood protection in thousands of scenarios, showing that infrastructure investment paths compatible with full decarbonisation in the second half of the century need not cost more than more-polluting alternatives. Investment needs are estimated between 2% to 8% of GDP, depending on the quality and quantity of services targeted, the timing of investments, construction costs, and complementary policies.

Chapter 15 also reports investment requirements in global mitigation pathways in the near term, compares them to recent investment trends, and assesses financing issues.

3.6.2 Economic Benefits of Avoiding Climate Change Impacts

Cross-Working Group Box 1 | Economic Benefits from Avoided Climate Impacts Along Long-term Mitigation Pathways

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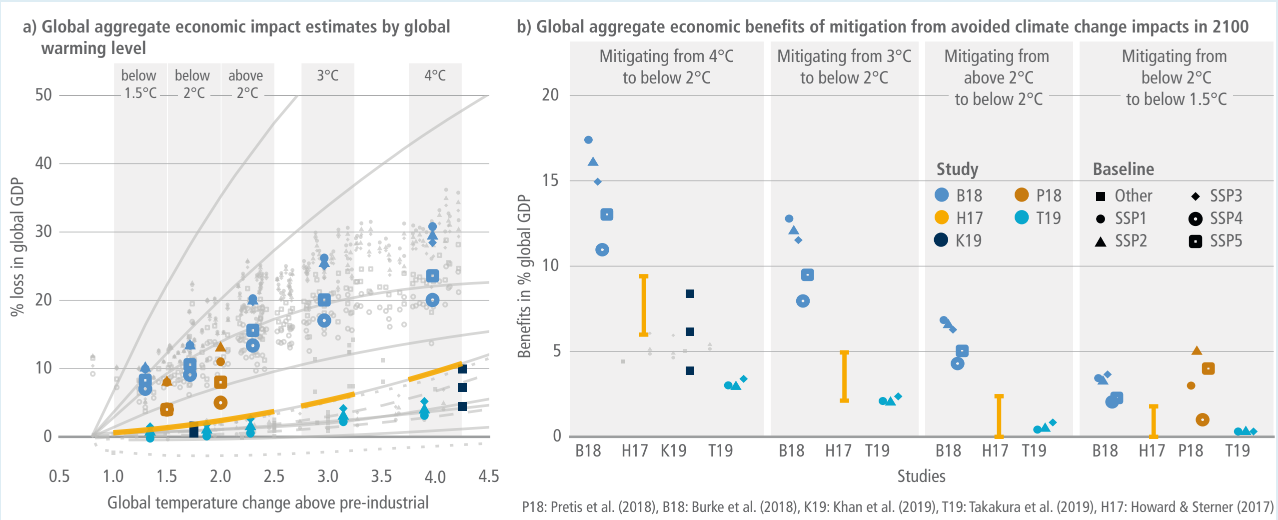
Mitigation reduces the extent of climate change and its impacts on ecosystems, infrastructure, and livelihoods. This box summarises elements from the AR6 WGII report on aggregate climate change impacts and risks, putting them into the context of mitigation pathways. AR6 WGII provides an assessment of current lines of evidence regarding potential climate risks with future climate change, and therefore, the avoided risks from mitigating climate change. Regional and sectoral climate risks to physical and social systems are assessed (AR6 WGII Chapters 2–15). Over 100 of these are identified as Key Risks (KRs) and further synthesised by WGII Chapter 16 into eight overarching Representative Key Risks (RKRs) relating to low-lying coastal systems; terrestrial and ocean ecosystems; critical physical infrastructure, networks and services; living standards; human health; food security; water security; and peace and mobility (AR6 WGII Section 16.5.2). The RKR assessment finds that risks increase with global warming level, and also depend on socio-economic development conditions, which shape exposure and vulnerability, and adaptation opportunities and responses. 'Reasons For Concern', another WGII aggregate climate-impacts risk framing, are also assessed to increase with climate change, with increasing risk for unique and threatened systems, extreme weather events, distribution of impacts, global aggregate impacts, and large-scale singular events (AR6 WGII Chapter 16). For human systems, in general, the poor and disadvantaged are found to have greater exposure level and vulnerability for a given hazard. With some increase in global average warming from today expected regardless of mitigation efforts, human and natural systems will be exposed to new conditions and additional adaptation will be needed (AR6 WGII Chapter 18). The range of dates for when a specific warming level could be reached depends on future global emissions, with significant overlap of ranges across emissions scenarios due to climate system response uncertainties (AR6 WGI Tables 4.2 and 4.5). The speed at which the climate changes is relevant to adaptation timing, possibilities, and net impacts.

The AR6 WGII also assesses the growing literature estimating the global aggregate economic impacts of climate change and the social cost of carbon dioxide and other greenhouse gases (AR6 WGII Cross-Working Box ECONOMIC: Estimating Global Economic Impacts from Climate Change and the Social Cost of Carbon in AR6 WGII Chapter 16). The former represents aggregate estimates that inform assessment of the economic benefits of mitigation. This literature is characterised by significant variation in the estimates, including for today's level of global warming, due primarily to fundamental differences in methods, but also differences in impacts included, representation of socio-economic exposure, consideration of adaptation, aggregation approach, and assumed persistence of damages. The AR6 WGII's assessment identifies different approaches to quantification of aggregated economic impacts of climate change, including: physical modelling of impact processes, such as projected mortality rates from climate risks such as heat, vector- or waterborne diseases that are then monetised; structural economic modelling of impacts on production, consumption, and markets for economic sectors and regional economies; and statistical estimation of impacts based on observed historical responses to weather and climate. The AR6 WGII finds that variation in estimated global economic impacts increases with warming in all methodologies, indicating higher risk in terms of economic impacts at higher temperatures (*high confidence*). Many estimates are non-linear with marginal economic impacts increasing with temperature, although some show declining marginal economic impacts with temperature, and functional forms cannot be determined for all studies. The AR6 WGII's assessment finds that the lack of comparability between methodologies does not allow for identification of robust ranges of global economic impact estimates (*high confidence*). Further, AR6 WGII identifies evaluating and reconciling differences in methodologies as a research priority for facilitating use of the different lines of evidence (*high confidence*). However, there are estimates that are higher than AR5, indicating that global aggregate economic impacts could be higher than previously estimated (*low confidence* due to the lack of comparability across methodologies and lack of robustness of estimates) (AR6 WGII Cross-Working Box ECONOMIC).

Conceptually, the difference in aggregate economic impacts from climate change between two given temperature levels represents the aggregate economic benefits arising from avoided climate change impacts due to mitigation action. A subset of the studies whose estimates were evaluated by AR6 WGII (5 of 15) are used to derive illustrative estimates of aggregate economic benefits in 2100 arising

Cross-Working Group Box 1 (continued)



Cross-Working Group Box 1, Figure 1 | Global aggregate economic benefits of mitigation from avoided climate change impacts in 2100 corresponding to shifting from a higher temperature category (4°C (3.75°C–4.25°C), 3°C (2.75°C–3.25°C), or above 2°C (2°C–2.5°C), to below 2°C (1.5°C–2°C), as well as from below 2°C to below 1.5°C (1°C–1.5°C)), from the five studies discussed in the text. Panel **(a)** is adapted from AR6 WGII Cross-Working Group Box ECONOMIC, Figure 1, showing global aggregate economic impact estimates (% global GDP loss relative to GDP without additional climate change) by temperature change level. All estimates are shown in grey. Estimates used for the computation of estimated benefits in 2100 in panel (b) are coloured for the selected studies, which provide results for different temperature change levels. See the AR6 WGII AR6 WGII Cross-Working Group Box ECONOMIC for discussion and assessment of the estimates in panel (a) and the differences in methodologies. For B18 and T19, median estimates in the cluster are considered. Shape distinguishes the baseline scenarios. Temperature ranges are highlighted. HS17 estimates are based on their preferred model –50th percentile of non-catastrophic damage. Panel **(b)** shows the implied aggregate economic benefits in 2100 of a lower temperature increase. Economic benefits for point estimates are computed as a difference, while economic benefits from the curve HS17 are computed as ranges from the segment differences.

from avoided climate change (Howard and Sterner 2017; Burke et al. 2018; Pretis et al. 2018; Kahn et al. 2019; Takakura et al. 2019). Burke et al. (2018), Pretis et al. (2018) and Kahn et al. (2019) are examples of statistical estimations of historical relationships between temperature and economic growth, whereas Takakura et al. (2019) is an example of structural modelling, which evaluates selected impact channels (impacts on agriculture productivity, undernourishment, heat-related mortality, labour productivity, cooling/heating demand, hydro-electric and thermal power generation capacity and fluvial flooding) with a general equilibrium model. Howard and Sterner (2017) and Rose et al. (2017b) estimate damage functions that can be used to compute the economic benefits of mitigation from avoiding a given temperature level for a lower one. Howard and Sterner (2017) estimate a damage function from a meta-analysis of aggregate economic impact studies, while Rose et al. (2017b) derive global functions by temperature and socio-economic drivers from stylised aggregate cost-benefit-analysis (CBA) integrated assessment models (IAMs) using diagnostic experiments. Cross-Working Group Box 1, Figure 1 summarises the global aggregate economic benefits in 2100 of avoided climate change impacts from individual studies corresponding to shifting from a higher temperature category (above 3°C, below 3°C or below 2.5°C) to below 2°C, as well as from below 2°C to below 1.5°C. Benefits are positive and increase with the temperature gap for any given study, and this result is robust across socio-economic scenarios. The Figure provides evidence of a wide range of quantifications, and illustrates the important differences associated with methods. Panel a puts the studies used to calculate aggregate economic benefits arising from avoided impacts into the context of the broader set of studies assessed in WGII (Section 16.6.2 of this report, AR6 WGII Cross-Working Group Box ECONOMIC,). However, economic benefits in 2100 arising from avoided impacts cannot be directly computed from damage estimates across this broader set of studies, due to inconsistencies – different socio-economic assumptions, scenario designs, and counterfactual reference scenarios across studies. Furthermore, these types of estimates cannot be readily compared to mitigation cost estimates. The comparison would require a framework that ensures consistency in assumptions and dynamics and allows for consideration of benefits and costs along the entire pathway.

Aggregate benefits from avoided impacts expressed in GDP terms, as in Figure 1, do not encompass all avoided climate risks, adaptation possibilities, and do not represent their influence on well-being and welfare (AR6 WGII Cross-Working Group Box ECONOMIC). Methodological challenges for economic impact estimates include representing uncertainty and variability, capturing interactions and spillovers, considering distributional effects, representing micro- and macro-adaptation processes, specifying non-gradual damages and non-linearities, and improving understanding of potential long-run growth effects. In addition, the economic benefits aggregated

Cross-Working Group Box 1 (continued)

at the global scale provide limited insights into regional heterogeneity. Global economic impact studies with regional estimates find large differences across regions in absolute and percentage terms, with developing and transitional economies typically more vulnerable. Furthermore, (avoided) impacts for poorer households and poorer countries can represent a smaller share in aggregate quantifications expressed in GDP terms or monetary terms, compared to their influence on well-being and welfare (Hallegatte et al. 2020; Markhvida et al. 2020). Finally, as noted by AR6 WGII, other lines of evidence regarding climate risks, beyond monetary estimates, should be considered in decision-making, including Key Risks and Reasons for Concern.

Cost-benefit analyses (CBA) aim to balance all costs and benefits in a unified framework (Nordhaus, 2008). Estimates of economic benefits from avoided climate change impacts depend on the types of damages accounted for, the assumed exposure and vulnerability to these damages as well as the adaptation capacity, which in turn are based on the development pathway assumed (Cross-Working Group Box 1 in this chapter). CBA IAMs raised criticism, in particular for omitting elements of dynamic realism, such as inertia, induced innovation and path dependence, in their representation of mitigation (Grubb et al. 2021), and for underestimating damages from climate change, missing non-monetary damages, the uncertain and heterogeneous nature of damages and the risk of catastrophic damages (Stern 2013, 2016; Diaz and Moore 2017; NASEM 2017; Pindyck 2017; Stoerk et al. 2018; Stern and Stiglitz 2021). Emerging literature has started to address those gaps, and integrated into cost-benefit frameworks the account of heterogeneity of climate damage and inequality (Dennig et al. 2015; Budolfson et al. 2017; Fleurbaey et al. 2019; Kornek et al. 2021), damages with higher persistence, including damages on capital and growth (Moyer et al. 2014; Dietz and Stern 2015; Moore and Diaz 2015; Guivarch and Pottier 2018; Ricke et al. 2018; Piontek et al. 2019), risks of tipping points (Cai et al. 2015, 2016; Lontzek et al. 2015; Lemoine and Traeger 2016; van der Ploeg and de Zeeuw 2018; Cai and Lontzek 2019; Nordhaus 2019; Yumashev et al. 2019; Taconet et al. 2021) and damages to natural capital and non-market goods (Tol 1994; Sterner and Persson 2008; Bastien-Olvera and Moore 2020; Drupp and Hänsel 2021).

Each of these factors, when accounted for in a CBA framework, tends to increase the welfare benefit of mitigation, thus leading to stabilisation at a lower temperature in optimal mitigation pathways. The limitations in CBA modelling frameworks remain significant, their ability to represent all damages incomplete, and the uncertainty in estimates remains large. However, emerging evidence suggests that, even without accounting for co-benefits of mitigation on other sustainable development dimensions (see Section 3.6.3 for further details about on co-benefits), global benefits of pathways that limit warming to 2°C outweigh global mitigation costs over the 21st century: depending on the study, the reason for this result lies in assumptions of economic damages from climate change in the higher end of available estimates (Moore and Diaz 2015; Ueckerdt et al. 2019; Brown and Saunders 2020; Glanemann et al. 2020), in the introduction of risks of tipping points (Cai and Lontzek 2019), in the consideration of damages to natural capital and non-market goods (Bastien-Olvera and Moore 2020) or in the combination of updated representations of carbon cycle and climate modules, updated damage estimates and/or updated representations of economic and mitigation dynamics (Dietz and Stern 2015; Hänsel et al. 2020; Wei et al. 2020; van der Wijst et al. 2021b). In the studies cited above that perform a sensitivity analysis, this result is found to be robust to a wide range of assumptions on social preferences (in particular, on inequality aversion and pure rate-of-time preference) and holds except if assumptions of economic damages from climate change are in the lower end of available estimates and the pure rate-of-time preference is in the higher range of values usually considered (typically above 1.5%). However, although such pathways bring net benefits over time (in terms of aggregate discounted present value), they involve distributional consequences and transition costs (Brown et al. 2020; Brown and Saunders 2020) (Sections 3.6.1.2 and 3.6.4).

The standard discounted utilitarian framework dominates CBA, thus often limiting the analysis to the question of discounting. CBA can be expanded to accommodate a wider variety of ethical values to assess mitigation pathways (Fleurbaey et al. 2019). The role of ethical values with regard to inequality and the situation of the worse off (Adler et al. 2017), risk (van den Bergh and Botzen 2014; Drouet et al. 2015), and population size (Scovronick et al. 2017; Méjean et al. 2020) has been explored. In most of these studies, the optimal climate policy is found to be more stringent than the one obtained using a standard discounted utilitarian criterion.

Comparing economic costs and benefits of mitigation raises a number of methodological and fundamental difficulties. Monetising the full range of climate change impacts is extremely hard, if not impossible (AR6 WGII Chapter 16), as is aggregating costs and benefits over time and across individuals when values are heterogeneous (Chapter 1; AR5 WGIII Chapter 3). Other approaches should thus be considered in supplement for decision-making (Chapter 1 and Section 1.7), in particular cost-effectiveness approaches that analyse how to achieve a defined mitigation objective at least cost or while also reaching other societal goals (Koomey 2013; Kaufman et al. 2020; Köberle et al. 2021; Stern and Stiglitz 2021). In cost-effectiveness studies too, incorporating benefits from avoided climate damages influences the results and leads to more stringent mitigation in the short term (Drouet et al. 2021; Schultes et al. 2021).

3.6.3 Aggregate Economic Implication of Mitigation Co-benefits and Trade-offs

Mitigation actions have co-benefits and trade-offs with other sustainable development dimensions (Section 3.7) beyond climate change, which imply welfare effects and economic effects, as well as other implications beyond the economic dimension. The majority of quantifications of mitigation costs and benefits synthesized in Sections 3.6.1 and 3.6.2 do not account for these economic benefits and costs associated with co-benefits and trade-offs along mitigation pathways.

Systematic reviews of the literature on co-benefits and trade-offs from mitigation actions have shown that only a small portion of articles provide economic quantifications (Deng et al. 2017; Karlsson et al. 2020). Most economic quantifications use monetary valuation approaches. Improved air quality, and associated health effects, are the co-benefit category dominating the literature (Markandya et al. 2018; Vandyck et al. 2018; Scovronick et al. 2019; Howard et al. 2020; Karlsson et al. 2020b; Rauner et al. 2020a,b), but some studies cover other categories, including health effects from diet change (Springmann et al. 2016b) and biodiversity impacts (Rauner et al. 2020a). Regarding health effects from air quality improvement and from diet change, co-benefits are shown to be of the same order of magnitude as mitigation costs (Thompson et al. 2014; Springmann et al. 2016a,b; Markandya et al. 2018; Scovronick et al. 2019b; Howard et al. 2020; Rauner et al. 2020a,b; Liu et al. 2021; Yang et al. 2021). Co-benefits from improved air quality are concentrated sooner in time than economic benefits from avoided climate change impacts (Karlsson et al. 2020), such that when accounting both for positive health impacts from reduced air pollution and for the negative climate effect of reduced cooling aerosols, optimal GHG mitigation pathways exhibit immediate and continual net economic benefits (Scovronick et al. 2019a). However, AR6 WGI Chapter 6 (Section 6.7.3) shows a delay in air pollution reduction benefits when they come from climate change mitigation policies compared with air pollution reduction policies.

Achieving co-benefits is not automatic but results from coordinated policies and implementation strategies (Clarke et al. 2014; McCollum et al. 2018a). Similarly, avoiding trade-offs requires targeted policies (van Vuuren et al. 2015; Bertram et al. 2018). There is limited evidence of such pathways, but the evidence shows that mitigation pathways designed to reach multiple Sustainable Development Goals instead of focusing exclusively on emissions reductions, result in limited additional costs compared to the increased benefits (Cameron et al. 2016; McCollum et al. 2018b; Fujimori et al. 2020a; Sognnaes et al. 2021).

3.6.4 Structural Change, Employment and Distributional Issues Along Mitigation Pathways

Beyond aggregate effects at the economy-wide level, mitigation pathways have heterogeneous economic implications for different sectors and different actors. Climate-related factors are only one driver of the future structure of the economy, of the future of employment, and of future inequality trends, as overarching trends in demographics, technological change (innovation, automation, etc.), education and institutions will be prominent drivers. For instance, Rao et al. (2019b) and Benveniste et al. (2021) have shown that income inequality projections for the 21st century vary significantly, depending on socio-economic assumptions related to demography, education levels, social public spending and migrations. However, the sections below focus on climate-related factors, both climate-mitigation actions themselves and the climate change impacts avoided along mitigation pathways, effects on structural change, including employment, and distributional effects.

3.6.4.1 Economic Structural Change and Employment in Long-term Mitigation Pathways

Mitigation pathways entail transformation of the energy sector, with structural change away from fossil energy and towards low-carbon energy (Section 3.3), as well as broader economic structural change, including industrial restructuring and reductions in carbon-intensive activities in parallel to extensions in low-carbon activities.

Mitigation affects work through multiple channels, which impacts geographies, sectors and skill categories differently (Fankhaeser et al. 2008; Bowen et al. 2018; Malerba and Wiebe 2021). Aggregate employment impacts of mitigation pathways mainly depend on the aggregate macroeconomic effect of mitigation (Sections 3.6.1 and 3.6.2) and of mitigation policy design and implementation (Freire-González 2018) (Section 4.2.6.3). Most studies that quantify overall employment implications of mitigation policies are conducted at the national or regional scales (Section 4.2.6.3), or sectoral scales (e.g., see Chapter 6 for energy sector jobs). The evidence is limited at the multinational or global scale, but studies generally find small differences in aggregate employment in mitigation pathways compared to baselines: the sign of the difference depends on the assumptions and modelling frameworks used and the policy design tested, with some studies or policy design cases leading to small increases in employment (Chateau and Saint-Martin 2013; Pollitt et al. 2015; Barker et al. 2016; Garcia-Casals et al. 2019; Fujimori et al. 2020a; Vrontisi et al. 2020; Malerba and Wiebe 2021) and other studies or policy design cases leading to small decreases (Chateau and Saint-Martin 2013; Vandyck et al. 2016). The small variations in aggregate employment hide substantial reallocation of jobs across sectors, with jobs creation in some sectors and jobs destruction in others. Mitigation action through thermal renovation of buildings, installation and maintenance of low-carbon generation, and the expansion of public transit lead to job creation, while jobs are lost in fossil fuel extraction, energy supply and energy-intensive sectors in mitigation pathways (von Stechow et al. 2015, 2016; Barker et al. 2016; Fuso Nerini et al. 2018; Perrier and Quirion 2018; Pollitt and Mercure 2018; Dominish et al. 2019; Garcia-Casals et al. 2019). In the energy sector, job losses in the fossil fuel sector are found to be compensated by gains in wind and solar jobs, leading to a net increase in energy sector jobs in 2050 in a mitigation pathway compatible with stabilisation of the temperature increase below 2°C (Pai et al. 2021). Employment effects also differ by geographies, with energy-importing regions benefiting from net job creations but energy-exporting regions experiencing very small gains or suffering from net job destruction (Barker et al. 2016; Pollitt and Mercure 2018; Garcia-Casals et al. 2019; Malerba and Wiebe 2021). Coal phase-out raises acute issues of just transition for the coal-dependent countries (Spencer et al. 2018; Jakob et al. 2020) (Section 4.5 and Box 6.2).

Mitigation action also affects employment through avoided climate change impacts. Mitigation reduces the risks to human health and associated impacts on labour and helps protect workers from the occupational health and safety hazards imposed by climate change (Kjellstrom et al. 2016, 2018, 2019; Levi et al. 2018; Day et al. 2019) (AR6 WGII Chapter 16).

3.6.4.2 Distributional Implications of Long-term Mitigation Pathways

Mitigation policies can have important distributive effects between and within countries, either reducing or increasing economic inequality and poverty, depending on policy instruments' design and implementation (see Section 3.6.1.2 for an assessment of the distribution of mitigation costs across regions in mitigation pathways; Sections 3.7 and 4.2.2.6, and Box 3.6 for an assessment of the fairness and ambition of NDCs; and Section 4.5 for an assessment of national mitigation pathways along the criteria of equity, including Just Transition, as well as Section 17.4.5 for equity in a Just Transition). For instance, emissions taxation has important distributive effects, both between and within income groups (Cronin et al. 2018b; Klenert et al. 2018; Pizer and Sexton 2019; Douenne 2020; Steckel et al. 2021). These effects are more significant in some sectors, such as transport, and depend on country-specific consumption structures (Dorband et al. 2019; Fullerton and Muehlegger 2019; Ohlendorf et al. 2021). However, revenues from emissions taxation can be used to lessen their regressive distributional impacts or even turn the policy into a progressive policy reducing inequality and/or leading to gains for lower-income households (Cameron et al. 2016; Jakob and Steckel 2016; Fremstad and Paul 2019; Fujimori et al. 2020b; Böhringer et al. 2021; Budolfson et al. 2021; Soergel et al. 2021b; Steckel et al. 2021). Mitigation policies may affect the poorest through effects on energy and food prices (Hasegawa et al. 2015; Fujimori et al. 2019). Markkanen and Anger-Kraavi (2019) and Lamb et al. (2020) synthesize evidence from the existing literature on social co-impacts of climate change mitigation policy and their implications for inequality. They show that most policies can compound or lessen inequalities depending on contextual factors, policy design and policy implementation, but that negative inequality impacts of climate policies can be mitigated (and possibly even prevented), when distributive and procedural justice are taken into consideration in all stages of policymaking, including policy planning, development and implementation, and when focusing on the carbon intensity of lifestyles, sufficiency and equity, well-being and decent living standards for all (Section 13.6).

Mitigation pathways also affect economic inequalities between and within countries, and poverty, through the reduction of climate change impacts that fall more heavily on low-income countries, communities and households, and exacerbate poverty (AR6 WGII Chapters 8 and 16). Higher levels of warming are projected to generate higher inequality between countries as well as within them (AR6 WGII Chapter 16). Through avoiding impacts, mitigation thus reduces economic inequalities and poverty (*high confidence*).

A few studies consider both mitigation policies' distributional impacts and avoided climate change impacts on inequalities along mitigation pathways. Rezai et al. (2018) find that unmitigated climate change impacts increase inequality, whereas mitigation has the potential to reverse this effect. Considering uncertainty in socio-economic assumptions, emission pathways, mitigation costs, temperature response, and climate damage, Taconet et al. (2020) show that the uncertainties associated with socio-economic assumptions and damage estimates are the main drivers of future inequalities between countries and that in most cases mitigation policies reduce future inequalities between countries. Gazzotti et al. (2021) show that inequality persists in 2°C-consistent pathways due to regressivity of residual climate damages. However, the evidence on mitigation pathways' implications for global inequality and poverty remains limited, and the modelling frameworks used have limited ability to fully represent the different dimensions of inequality and poverty and all the mechanisms by which mitigation affects inequality and poverty (Rao et al. 2017a; Emmerling and Tavoni 2021; Jafino et al. 2021).

3.7 Sustainable Development, Mitigation and Avoided Impacts

3.7.1 Synthesis Findings on Mitigation and Sustainable Development

Rapid and effective climate mitigation is a necessary part of sustainable development (*high confidence*) (Cross-Chapter Box 5 in Chapter 4), but the latter can only be realised if climate mitigation becomes integrated with sustainable development policies (*high confidence*). Targeted policy areas must include healthy nutrition, sustainable consumption and production, inequality and poverty alleviation, air quality and international collaboration (*high confidence*). Lower energy demand enables synergies between mitigation and sustainability, with lower reliance on CDR (*high confidence*).

This section covers the long-term interconnection of sustainable development and mitigation, taking forward the holistic vision of sustainable development described in the SDGs (Brandi 2015; Leal Filho et al. 2018). Recent studies have explored the aggregated impact of mitigation for multiple sustainable-development dimensions (Hasegawa et al. 2014; Bertram et al. 2018; Fuso Nerini et al. 2018; Grubler et al. 2018; McCollum et al. 2018b; Soergel et al. 2021a; van Vuuren et al. 2019). For instance, Figure 3.38 shows selected mitigation co-benefits and trade-offs based on a subset of models and scenarios, since so far many IAMs do not have a comprehensive coverage of SDGs (Rao et al. 2017a; van Soest et al. 2019). Figure 3.38 shows that mitigation *likely* leads to increased forest cover (SDG 15 – life on land) and reduced mortality from ambient PM2.5 pollution (SDG 3 – good health and well-being) compared to reference scenarios. However, mitigation policies can also cause higher food prices and an increased population at risk of hunger (SDG 2 – zero hunger) and relying on solid fuels (SDG 3 – good health and well-being; and SDG 7 – affordable and clean energy) as side effects. These trade-offs can be compensated through targeted support measures and/or additional sustainable development policies (Cameron et al. 2016; Bertram et al. 2018; Fujimori et al. 2019; Soergel et al. 2021a).

The synthesis of the interplay between climate mitigation and sustainable development is shown in Figure 3.39. Panel a shows the reduction in population affected by climate impacts at 1.5°C compared to 3°C according to sustainability domains (Byers et al. 2018). Reducing warming reduces the population impacted by all impact categories shown (*high confidence*). The left panel does not take into account any side effects of mitigation efforts or policies to reduce warming: only reductions in climate impacts. This underscores that mitigation is an integral basis for comprehensive sustainable development (Watts et al. 2015).

Panels b and c of Figure 3.39 show the effects of 1.5°C mitigation policies compared to current national policies: narrow mitigation policies (averaged over several models, middle panel), and policies integrating sustainability considerations (right panel of Figure 3.39, based on the Illustrative Mitigation Pathway 'Shifting Pathways' (***IMP-SP***) (Soergel et al. 2021a)). Note that neither middle nor right panels include climate impacts.

Areas of co-benefits include human health, ambient air pollution and other specific kinds of pollution, while areas of trade-off include food access, habitat loss and mineral resources (*medium confidence*). For example, action consistent with 1.5°C in the absence of energy-demand reduction measures require large quantities of CDR, which, depending on the type used, are likely to negatively impact both food availability and areas for biodiversity (Fujimori et al. 2018; Ohashi et al. 2019; Roelfsema et al. 2020).

Mitigation to 1.5°C reduces climate impacts on sustainability (left). Policies integrating sustainability and mitigation (right) have far fewer trade-offs than narrow mitigation policies (middle).

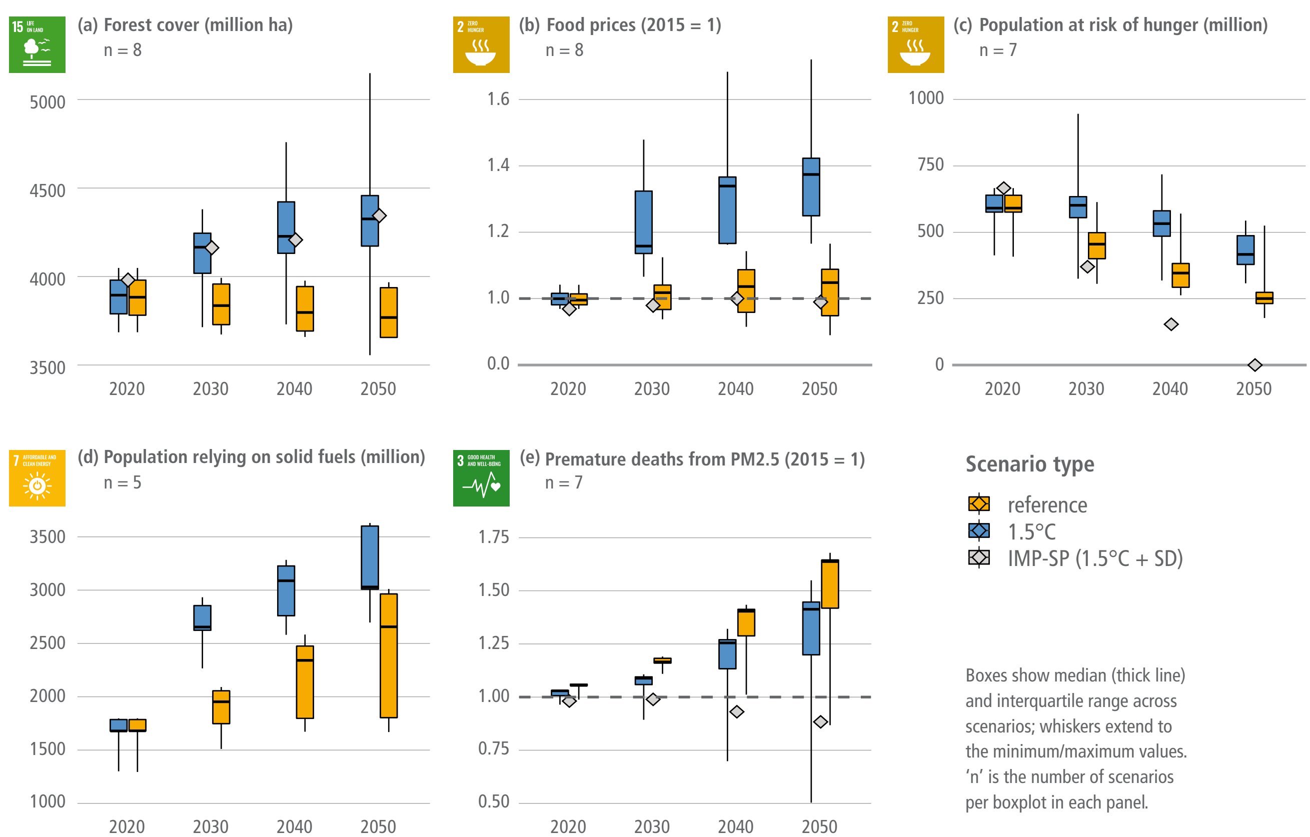


Figure 3.38 | Effect of climate change mitigation on different dimensions of sustainable development: shown are mitigation scenarios compatible with the 1.5°C target (blue) and reference scenarios (yellow). Blue box plots contain scenarios that include narrow mitigation policies from different studies (see below). This is compared to a sustainable development scenario (*SP*, Soergel et al. (2021a), grey diamonds) integrating mitigation and SD policies (e.g., zero hunger in 2050 by assumption). Scenario sources for box plots: single scenarios from: (i) Fujimori et al. (2020a); (ii) Soergel et al. (2021a); multi-model scenario set from CD-LINKS (McCollum et al. 2018b; Fujimori et al. 2019; Roelfsema et al. 2020). For associated methods, see also Cameron et al. (2016) and Rafaj et al. (2021). The reference scenario for Fujimori et al. (2020a) is no-policy baseline; for all other studies, it includes current climate policies. In the 'Food prices' and 'Risk of hunger' panels, scenarios from CD-LINKS include a price cap of USD200 tCO_2-eq for land-use emissions (Fujimori et al. 2019). For the other indicators, CD-LINKS scenarios without price cap (Roelfsema et al. 2020) are used due to SDG indicator availability. In the 'Premature deaths' panel, a well-below 2°C scenario from Fujimori et al. (2020a) is used in place of a 1.5°C scenario due to data availability, and all scenarios are indexed to their 2015 values due to a spread in reported levels between models. SDG icons were created by the United Nations.

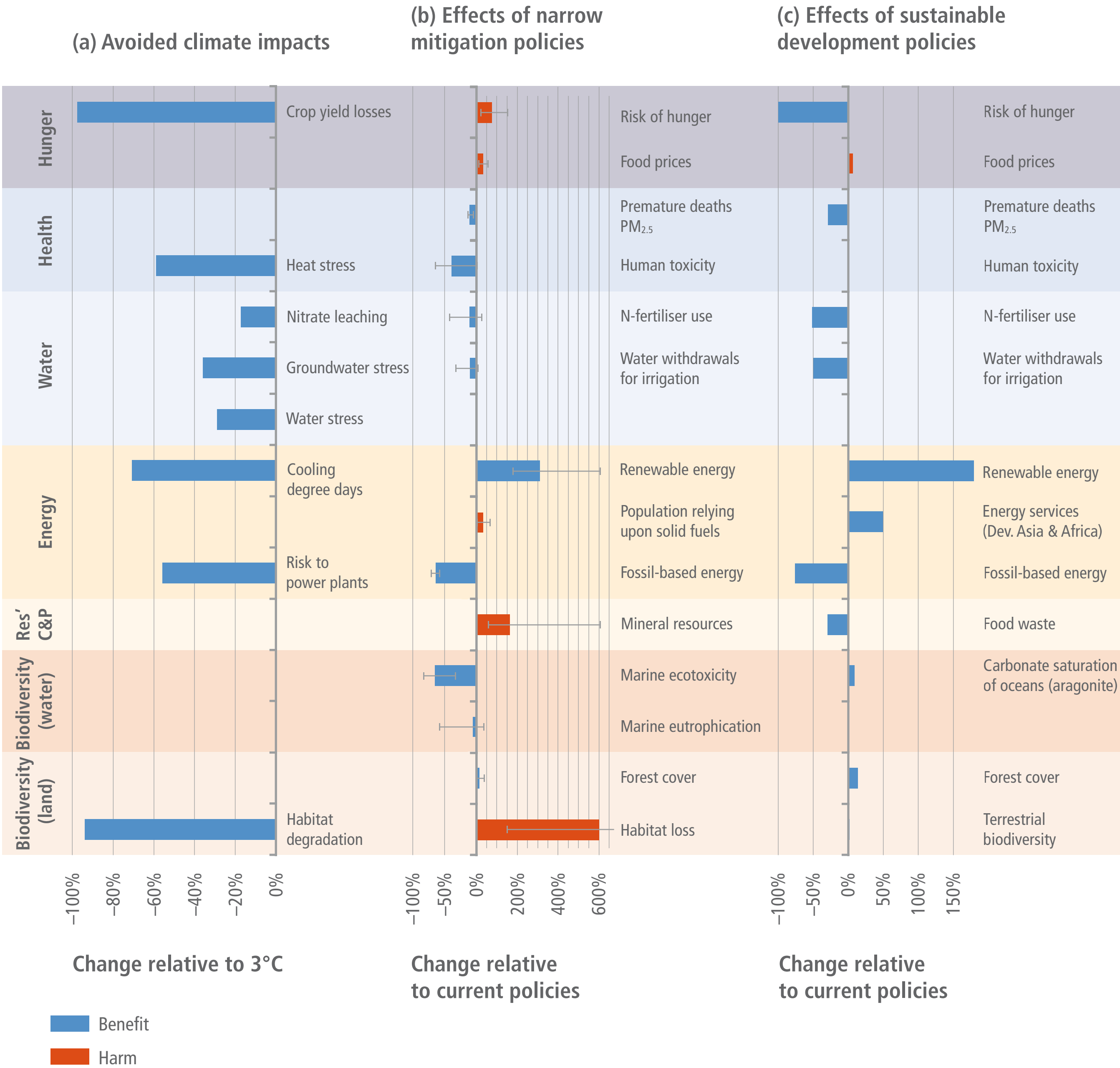


Figure 3.39 | Sustainable development effects of mitigation to 1.5°C. Panel (a): benefits of mitigation from avoided impacts. **Panel (b):** sustainability co-benefits and trade-offs of narrow mitigation policies (averaged over multiple models). **Panel (c):** sustainability co-benefits and trade-offs of mitigation policies integrating Sustainable Development Goals. Scale: 0% means no change compared to 3°C (left) or current policies (middle and right). Blue values correspond to proportional improvements, red values to proportional worsening. Note: only the left panel considers climate impacts on sustainable development; the middle and right panels do not. 'Res' C&P' stands for Responsible Consumption and Production (SDG 12). Data are from Byers et al. (2018) (left), *SP*/Soergel et al. (2021a) (right). Methods used in middle panel: for biodiversity, Ohashi et al. (2019); for ecotoxicity and eutrophication, Arvesen et al. (2018) and Pehl et al. (2017); for energy access, Cameron et al. (2016). 'Energy services' on the right is a measure of useful energy in buildings and transport. 'Food prices' and 'Risk of hunger' in the middle panel are the same as in Figure 3.38.

3.7.1.1 Policies Combining Mitigation and Sustainable Development

These findings indicate that holistic policymaking integrating sustainability objectives alongside mitigation will be important in attaining Sustainable Development Goals (van Vuuren et al. 2015, 2018; Bertram et al. 2018; Fujimori et al. 2018; Hasegawa et al. 2018; Liu et al. 2020a; Honegger et al. 2021; Soergel et al. 2021a). Mitigation policies which target direct sector-level regulation, early mitigation action, and lifestyle changes have beneficial sustainable development outcomes across air pollution, food, energy and water (Bertram et al. 2018).

These policies include ones around stringent air quality (Kinney 2018; Rafaj et al. 2018; Soergel et al. 2021a); efficient and safe demand-side technologies, especially cook stoves (Cameron et al. 2016); lifestyle changes (Bertram et al. 2018; Grubler et al. 2018; Soergel et al. 2021a); industrial and sectoral policy (Bertram et al. 2018); agricultural and food policies (including food waste) (van Vuuren et al. 2019; Soergel et al. 2021a); international cooperation (Soergel et al. 2021a); as well as economic policies described in Section 3.6. Recent research shows that mitigation is compatible with reductions in inequality and poverty (Box 3.6).

Lower demand – for example, for energy and land-intensive consumption such as meat – represents a synergistic strategy for achieving ambitious climate mitigation without compromising Sustainable Development Goals (*high confidence*) (Bertram et al. 2018; Grubler et al. 2018; van Vuuren et al. 2018; Kikstra et al. 2021b; Soergel et al. 2021a). This is especially true for reliance on BECCS (Hickel et al. 2021; Keyßer and Lenzen 2021). Options that reduce agricultural demand (e.g., dietary change, reduced food waste) can have co-benefits for adaptation through reductions in demand for land and water (Bertram et al. 2018; Grubler et al. 2018; IPCC 2019a; Soergel et al. 2021a).

While the impacts of climate change on agricultural output are expected to increase the population at risk of hunger, there is evidence suggesting population growth will be the dominant driver of hunger and undernourishment in Africa in 2050 (Hall et al. 2017). Meeting SDG 5, relating to gender equality and reproductive rights, could substantially lower population growth, leading to a global population lower than the 95% prediction range of the UN projections (Abel et al. 2016). Meeting SDG 5 (gender equality, including via voluntary family planning (O'Sullivan 2018)) could thus minimise the risks to SDG 2 (zero hunger) that are posed by meeting SDG 13 (climate action).

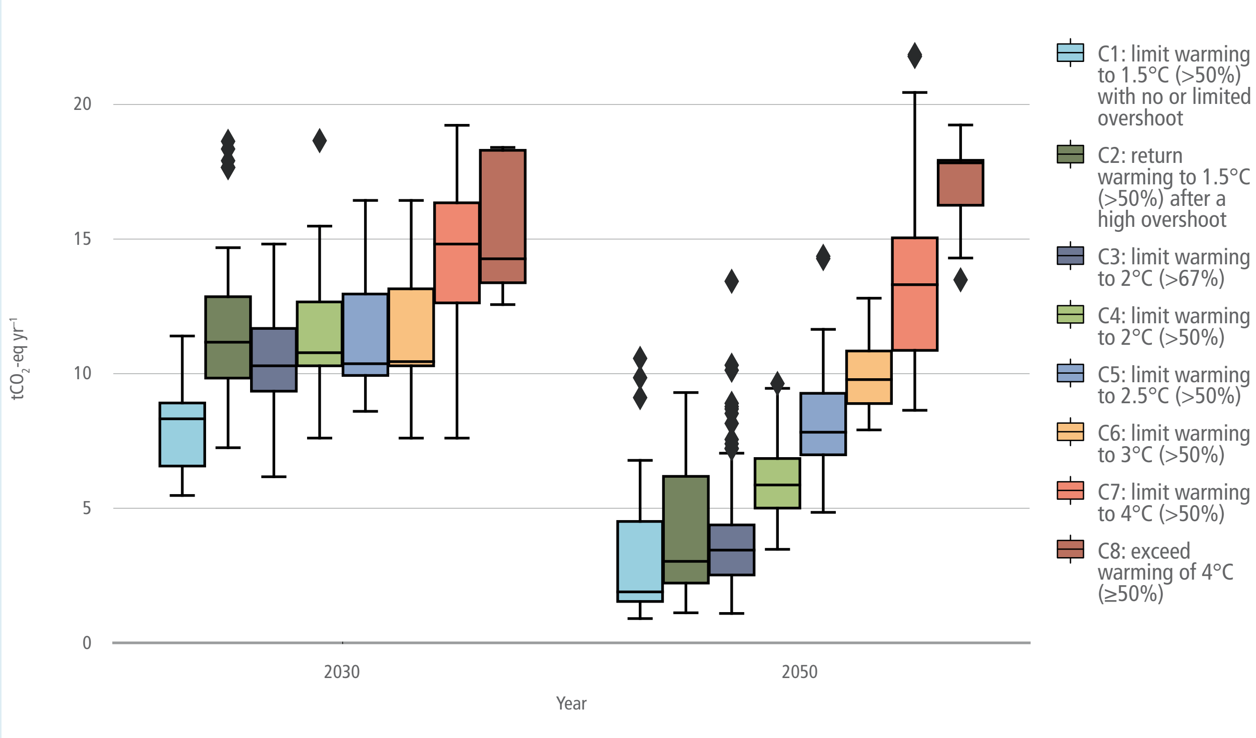
Box 3.6 | Poverty and Inequality

There is high confidence (*medium evidence*, *high agreement*) that the eradication of extreme poverty and universal access to energy can be achieved without resulting in significant GHG emissions (Tait and Winkler 2012; Chakravarty and Tavoni 2013; Pachauri et al. 2013; Pachauri 2014; Rao 2014; Hubacek et al. 2017b; Poblete-Cazenave et al. 2021). There is also high agreement in the literature that a focus on well-being and decent living standards for all can reduce disparities in access to basic needs for services concurrently with climate mitigation (Section 5.2). Mitigation pathways in which national redistribution of carbon-pricing revenues is combined with international climate finance, achieve poverty reduction globally (Fujimori et al. 2020b; Soergel et al. 2021b). Carbon-pricing revenues in mitigation pathways consistent with limiting temperature increase to 2°C could also contribute to finance investment needs for basic infrastructure (Jakob et al. 2016) and the achievement of the SDGs (Franks et al. 2018).

Several studies conclude that reaching higher income levels globally, beyond exiting extreme poverty, and achieving more qualitative social objectives and well-being, are associated with higher emissions (Ribas et al. 2017, 2019; Hubacek et al. 2017b; Fischetti 2018; Scherer et al. 2018). Studies give divergent results on the effect of economic inequality reduction on emissions, with either an increase or a decrease in emissions (Berthe and Elie 2015; Lamb and Rao 2015; Grunewald et al. 2017; Hubacek et al. 2017a,b; Jorgenson et al. 2017; Knight et al. 2017; Mader 2018; Rao and Min 2018; Liu et al. 2019; Sager 2019; Baležentis et al. 2020; Liobikienė 2020; Liobikienė and Rimkuvienė 2020; Liu et al. 2020b; Millward-Hopkins and Oswald 2021). However, the absolute effect of economic inequality reduction on emissions remains moderate, under the assumptions tested. For instance, Sager (2019) finds that a full redistribution of income leading to equality among US households in a counterfactual scenario for 2009 would raise emissions by 2.3%; and Rao and Min (2018) limit to 8% the maximum plausible increase in emissions that would accompany the reduction of the global Gini coefficient from its current level of 0.55 to a level of 0.3 by 2050. Similarly, reduced income inequality would lead to a global energy-demand increase of 7% (Oswald et al. 2021). Reconciling mitigation and inequality reduction objectives requires policies that take into account both objectives at all stages of policymaking (Markkanen and Anger-Kraavi 2019), including focusing on the carbon intensity of lifestyles (Scherer et al. 2018), attention to sufficiency and equity (Fischetti 2018), and targeting the consumption of the richest and highest-emitting households (Otto et al. 2019).

In modelled mitigation pathways, inequality in per-capita emissions between regions are generally reduced over time, and the reduction is generally more pronounced in lower-temperature pathways (Box 3.6, Figure 1). Already in 2030, if NDCs from the Paris Agreement, announced prior to COP26, are fully achieved, inequalities in per-capita GHG emissions between countries would be reduced (Benveniste et al. 2018).

Box 3.6 (continued)



Box 3.6, Figure 1 | Difference in per-capita emissions of Kyoto gases between the highest emitting and the lowest emitting of the 10 regions, in 2030 and 2050, by temperature category of pathways.

Through avoiding impacts of climate change, which fall more heavily on low-income countries, communities and households, and exacerbate poverty, mitigation reduces inequalities and poverty (Section 3.6.4.2).

The remainder of this section covers specific domains of sustainable development: food (Section 3.7.2), water (Section 3.7.3), energy (Section 3.7.4), health (Section 3.7.5), biodiversity (Section 3.7.6) and multi-sector – cities, infrastructure, industry, production and consumption (Section 3.7.7). These represent the areas with the strongest research connecting mitigation to sustainable development. The links to individual SDGs are given within these sections. Each domain covers the benefits of avoided climate impacts and the implications (synergies and trade-offs) of mitigation efforts.

3.7.2 Food

The goal of SDG 2 is to achieve 'zero-hunger' by 2030. According to the UN (2015), over 25% of the global population currently experience food insecurity and nearly 40% of these experience severe food insecurity, a situation worsened by the COVID-19 pandemic (Paslakis et al. 2021).

3.7.2.1 Benefits of Avoided Climate Impacts Along Mitigation Pathways

Climate change will reduce crop yields, increase food insecurity, and negatively influence nutrition and mortality (*high confidence*) (AR6 WGII Chapter 5). Climate mitigation will thus reduce these impacts, and hence reduce food insecurity (*high confidence*). The yield reduction of global food production will increase food insecurity and influence nutrition and mortality (Hasegawa et al. 2014; Springmann et al. 2016a). For instance, Springmann et al. (2016a) estimate that climate change could lead to 315,000–736,000 additional deaths by 2050, though these could mostly be averted by stringent mitigation efforts. Reducing warming reduces the impacts of climate change, including extreme climates, on food production and risk of hunger (Hasegawa et al. 2014, 2021b).

3.7.2.2 Implications of Mitigation Efforts Along Pathways

Recent studies explore the effect of climate change mitigation on agricultural markets and food security (Havlík et al. 2014; Hasegawa et al. 2018; Doelman et al. 2019; Fujimori et al. 2019). Mitigation policies aimed at achieving 1.5°C–2°C, if not managed properly, could negatively affect food security through changes in land and food prices (*high confidence*), leading to increases in the population at risk of hunger by 80–280 million people compared to baseline scenarios. These studies assume uniform carbon prices on AFOLU sectors (with some sectoral caps) and do not account for climate impacts on food production.

Mitigating climate change while ensuring that food security is not adversely affected requires a range of different strategies and interventions (*high confidence*). Fujimori et al. (2018) explore possible economic solutions to these unintended impacts of mitigation (e.g., agricultural subsidies, food aid, and domestic reallocation of income) with an additional small (<0.1%) change in global GDP. Targeted food-security support is needed to shield impoverished and vulnerable people from the risk of hunger that could be caused by the economic effects of policies narrowly focussed on climate objectives. Introducing more biofuels and careful selection of bioenergy feedstocks could also reduce negative impacts (FAO, IFAD, UNICEF, WFP and WHO, 2017). Reconciling bioenergy demands with food and biodiversity, as well as competition for land and water, will require changes in food systems – agricultural intensification, open trade, less consumption of animal products and reduced food losses – and advanced biotechnologies (Henry et al. 2018; Xu et al. 2019).

There are many other synergistic measures for climate mitigation and food security. Agricultural technological innovation can improve the efficiency of land use and food systems, thus reducing the pressure on land from increasing food demand (Foley et al. 2011; Popp et al. 2014; Obersteiner et al. 2016; Humpenöder et al. 2018; Doelman et al. 2019). Furthermore, decreasing consumption of animal products could contribute to SDG 3.4 by reducing the risk of non-communicable diseases (Garnett 2016).

Taken together, climate changes will reduce crop yields, increase food insecurity and influence nutrition and mortality (*high confidence*) (see 3.7.2.1). However, if measures are not properly designed, mitigating climate change will also negatively impact on food consumption and security. Additional solutions to negative impacts associated with climate mitigation on food production and consumption include a transition to a sustainable agriculture and food system that is less resource intensive, more resilient to a changing climate, and in line with biodiversity and social targets (Kayal et al. 2019).

3.7.3 Water

Water is relevant to SDG 6 (clean water and sanitation), SDG 15 (life on land), and SDG Targets 12.4 and 3.9 (water pollution and health). This section discusses water quantity, water quality, and water-related extremes. See Section 3.7.5 for water-related health effects.

3.7.3.1 Benefits of Avoided Climate Impacts Along Mitigation Pathways

Global precipitation, evapotranspiration, runoff and water availability increase with warming (Hanasaki et al. 2013; Greve et al. 2018) (AR6 WGII Chapter 4). Climate change also affects the occurrence of and exposure to hydrological extremes (*high confidence*) (Arnell and Lloyd-Hughes 2014; Asadieh and Krakauer 2017; Dottori et al. 2018; Naumann et al. 2018; IPCC 2019a; Do et al. 2020) (AR6 WGII Chapter 4). Climate models project increases in precipitation intensity (*high confidence*), local flooding (*medium confidence*), and drought risk (*very high confidence*) (Arnell and Lloyd-Hughes 2014; Asadieh and Krakauer 2017; Dottori et al. 2018; IPCC 2019a) (AR6 WGII Chapter 4).

The effect of climate change on water availability and hydrological extremes varies by region (*high confidence*) due to differences in the spatial patterns of projected precipitation changes (Hanasaki et al. 2013; Schewe et al. 2014; Schlosser et al. 2014; Asadieh and Krakauer 2017; Dottori et al. 2018; Naumann et al. 2018; Koutroulis et al. 2019) (AR6 WGII Chapter 4). Global exposure to water stress is projected to increase with increased warming, but increases will not occur in all regions (Hanasaki et al. 2013; Schewe et al. 2014; Arnell and Lloyd-Hughes 2014; Gosling and Arnell 2016; IPCC 2019a).

Limiting warming could reduce water-related risks (*high confidence*) (O'Neill et al. 2017b; Byers et al. 2018; Hurlbert et al. 2019) (AR6 WGII Chapter 4) and the population exposed to increased water stress (Hanasaki et al. 2013; Arnell and Lloyd-Hughes 2014; Schewe et al. 2014; Gosling and Arnell 2016; IPCC 2019a).

The effect of climate change on water depends on the climate model, the hydrological model, and the metric (*high confidence*) stress Hanasaki et al. (2013); Arnell and Lloyd-Hughes (2014); Schewe et al. (2014); Schlosser et al. (2014); Gosling and Arnell (2016); IPCC (2019a).

However, the effect of socio-economic development could be larger than the effect of climate change (*high confidence*) (Arnell and Lloyd-Hughes 2014; Schlosser et al. 2014; Graham et al. 2020).

Climate change can also affect water quality (both thermal and chemical) (Liu et al. 2017), leading to increases in stream temperature and nitrogen loading in rivers (Ballard et al. 2019).

3.7.3.2 Implications of Mitigation Efforts Along Pathways

The effects of mitigation on water demand depends on the mitigation technologies deployed (*high confidence*) (Chaturvedi et al. 2013a,b; Hanasaki et al. 2013; Kyle et al. 2013; Hejazi et al. 2014; Bonsch et al. 2016; Jakob and Steckel 2016; Mouratiadou et al. 2016; Fujimori et al. 2017; Maïzi et al. 2017; Bijl et al. 2018; Cui et al. 2018; Graham et al. 2018; Parkinson et al. 2019). Some mitigation options could increase water consumption (volume removed and not returned) while decreasing withdrawals (total volume of water removed, some of which may be returned) (Kyle et al. 2013; Fricko et al. 2016; Mouratiadou et al. 2016; Parkinson et al. 2019). Bioenergy and BECCS can increase water withdrawals and water consumption (*high confidence*) (Chaturvedi et al. 2013a; Kyle et al. 2013; Hejazi et al. 2014; Bonsch et al. 2016; Jakob and Steckel 2016; Mouratiadou et al. 2016; Fujimori et al. 2017; Maïzi et al. 2017; Séférian et al. 2018; Yamagata et al. 2018; Parkinson et al. 2019) (AR6 WGII Chapter 4). DACCS (Fuhrman et al. 2020) and CCS (Kyle et al. 2013; Fujimori et al. 2017) could increase water demand; however, the implications of CCS depend on the cooling technology and when capture occurs (Magneschi et al. 2017; Maïzi et al. 2017; Giannaris et al. 2020). Demand-side mitigation (e.g., dietary change, reduced food waste, reduced energy demand) can reduce water demand (Bajželj et al. 2014; Aleksandrowicz et al. 2016; Green et al. 2018; Springmann et al. 2018). Introducing specific measures (e.g., environmental flow requirements, improved efficiency, priority rules) can reduce water withdrawals (Bertram et al. 2018; Bijl et al. 2018; Parkinson et al. 2019).

The effect of mitigation on water quality depends on the mitigation option, its implementation, and the aspect of quality considered (*high confidence*) (Ng et al. 2010; Flörke et al. 2019; Sinha et al. 2019; Smith et al. 2019; Fuhrman et al. 2020; Karlsson et al. 2020; McElwee et al. 2020).

3.7.4 Energy

Energy is relevant to SDG 7 (affordable and clean energy). Access to sufficient levels of reliable, affordable and renewable energy is essential for sustainable development. Currently, over 1 billion people still lack access to electricity (Ribas et al. 2019).

3.7.4.1 Benefits of Avoided Climate Impacts Along Mitigation Pathways

Climate change alters the production of energy through changes in temperature (hydropower, fossil fuel, nuclear, solar, bioenergy, transmission and pipelines), precipitation (hydropower, fossil fuel, nuclear and bioenergy), windiness (wind and wave), and cloudiness (solar) (*high confidence*). Increases in temperature reduce efficiencies of thermal power plants (e.g., fossil fuel and nuclear plants) with air-cooled condensers by 0.4–0.7% per °C increase in ambient temperature (Cronin et al. 2018a; Simioni and Schaeffer 2019; Yalew, S.G. et al. 2020). Potentials and costs for renewable energy technologies are also affected by climate change, though with considerable regional variation and uncertainty (Gernaat et al. 2021). Biofuel yields could increase or decrease depending on the level of warming, changes in precipitation, and the effect of CO_2 fertilisation (Calvin et al. 2013; Kyle et al. 2014; Gernaat et al. 2021). Coastal energy facilities could potentially be impacted by sea level rise (Brown et al. 2014).

The energy sector uses large volumes of water (Fricko et al. 2016), making it highly vulnerable to climate change (Tan and Zhi 2016) (*high confidence*). Thermoelectric and hydropower sources are the most vulnerable to water stress (van Vliet et al. 2016). Restricted water supply to these power sources can affect grid security and affordable energy access (Koch et al. 2014; Ranzani et al. 2018; Zhang et al. 2018d).The hydropower facilities from high mountain areas of Central Europe, Iceland, Western USA/Canada, and Latin America (Hock et al. 2019), as well as Africa and China (Bartos and Chester 2015; Gaupp et al. 2015; Tarroja et al. 2016; Conway et al. 2017; Byers et al. 2018; Eyer and Wichman 2018; Ranzani et al. 2018; Savelsberg et al. 2018; Zhang et al. 2018d; Zhou et al. 2018; Wang et al. 2019) have experienced changes in seasonality and availability.

3.7.4.2 Implications of Mitigation Efforts Along Pathways

Extending energy access to all in line with SDG7 is compatible with strong mitigation consistent with the Paris Agreement (*high confidence*). The Low Energy Demand (LED) scenario projects that these twin goals can be achieved by relying heavily on energy efficiency and rapid social transformations (Grubler et al. 2018). The IEA's Sustainable Development Scenario (IEA 2020a) achieves development outcomes but with higher average energy use, and bottom-up modelling suggests that decent living standards could be provided to all in 2040–2050 with roughly 150 EJ, or 40% of current final energy use (Millward-Hopkins et al. 2020; Kikstra et al. 2021b). The trade-offs between climate mitigation and increasing energy consumption of the world's poorest are negligible (Rao and Min 2018; Scherer et al. 2018).

The additional energy demand to meet the basic cooling requirement in the Global South is estimated to be much larger than the electricity needed to provide basic residential energy services universally via clean and affordable energy, as defined by SDG 7 (IEA 2019; Mastrucci et al. 2019) (*high confidence*). If conventional air-conditioning systems are widely deployed to provide cooling, energy use could rise significantly (van Ruijven et al. 2019; Bezerra et al. 2021; Falchetta and Mistry 2021), thus creating a positive feedback further increasing cooling demand. However, the overall emissions are barely altered by the changing energy demand composition with reductions in heating demand occurring simultaneously (Isaac and van Vuuren 2009; Labriet et al. 2015; McFarland et al. 2015; Clarke et al. 2018). Some mitigation scenarios show price increases of clean cooking fuels, slowing the transition to clean cooking fuels (SDG 7.1) and leaving a billion people in 2050 still reliant on solid fuels in South Asia (Cameron et al. 2016).

In contrast, future energy infrastructure could improve reliability, thus lowering dependence on high-carbon, high-air pollution back-up diesel generators (Farquharson et al. 2018) that are often used to cope with unreliable power in developing countries (Maruyama Rentschler et al. 2019). There can be significant reliability issues where mini-grids are used to electrify rural areas (Numminen and Lund 2019). A stable, sustainable energy transition policy that considers national sustainable development in the short and long term is critical in driving a transition to an energy future that addresses the trilemma of energy security, equity, and sustainability (La Viña et al. 2018).

3.7.5 Health

SDG 3 (good health and well-being) aims to ensure healthy lives and promote well-being for all at all ages. Climate change is increasingly causing injuries, illnesses, malnutrition, threats to mental health and well-being, and deaths (AR6 WGII Chapter 7). Mitigation policies and technologies to reduce GHG emissions are often beneficial for human health on a shorter time scale than benefits in terms of slowing climate change (Limaye et al. 2020). The financial value of health benefits from improved air quality alone is projected to exceed the costs of meeting the goals of the Paris Agreement (Markandya et al. 2018).

3.7.5.1 Benefits of Avoided Climate Impacts Along Mitigation Pathways

The human health chapter of the WGII contribution to the AR6 concluded that climate change is increasingly affecting a growing number of health outcomes, with negative net impacts at the global scale and positive impacts only in a few limited situations. There are few estimates of economic costs of increases in climate-sensitive health outcomes. In the USA in 2012, the financial burden in terms of deaths, hospitalisations, and emergency department visits for ten climate-sensitive events across 11 states were estimated to be 10 (2.7–24.6) billion USD2018 (Limaye et al. 2019).

3.7.5.2 Implications of Mitigation Efforts Along Pathways

Transitioning toward equitable, low-carbon societies has multiple co-benefits for health and well-being (AR6 WGII Chapter 7). Health benefits can be gained from improvements in air quality through transitioning to renewable energy and active transport (e.g., walking and cycling); shifting to affordable low-meat, plant-rich diets; and green buildings and nature-based solutions, such as green-and-blue urban infrastructure, as shown in Figure 3.40 (Iacobucci 2016).

The avoided health impacts associated with climate change mitigation can substantially offset mitigation costs at the societal level (Ščasný et al. 2015; Schucht et al. 2015; Chang et al. 2017; Markandya et al. 2018). Models of health co-benefits show that a 1.5°C pathway could result in 152 million ± 43 million fewer premature deaths worldwide between 2020 and 2100 in comparison to a business-as-usual scenario, particularly due to reductions in exposure to PM2.5 (Shindell et al. 2018; Rauner et al. 2020a; Rafaj et al. 2021). Some of the most substantial health, well-being, and equity benefits associated with climate action derive from investing in basic infrastructure: sanitation, clean drinking water, clean energy, affordable healthy diets, clean public transport, and improved air quality from transformative solutions across economic sectors including agriculture, energy, transport and buildings (Chang et al. 2017).

The health co-benefits of the NDCs for 2040 were compared for two scenarios, one consistent with the goal of the Paris Agreement and the SDGs and the other also placing health as a central focus of the policies (i.e., health in all climate policies scenario) (Hamilton et al. 2021), for Brazil, China, Germany, India, Indonesia, Nigeria, South Africa, the UK, and the USA. Modelling of the energy, food and agriculture, and transport sectors, and associated risk factors

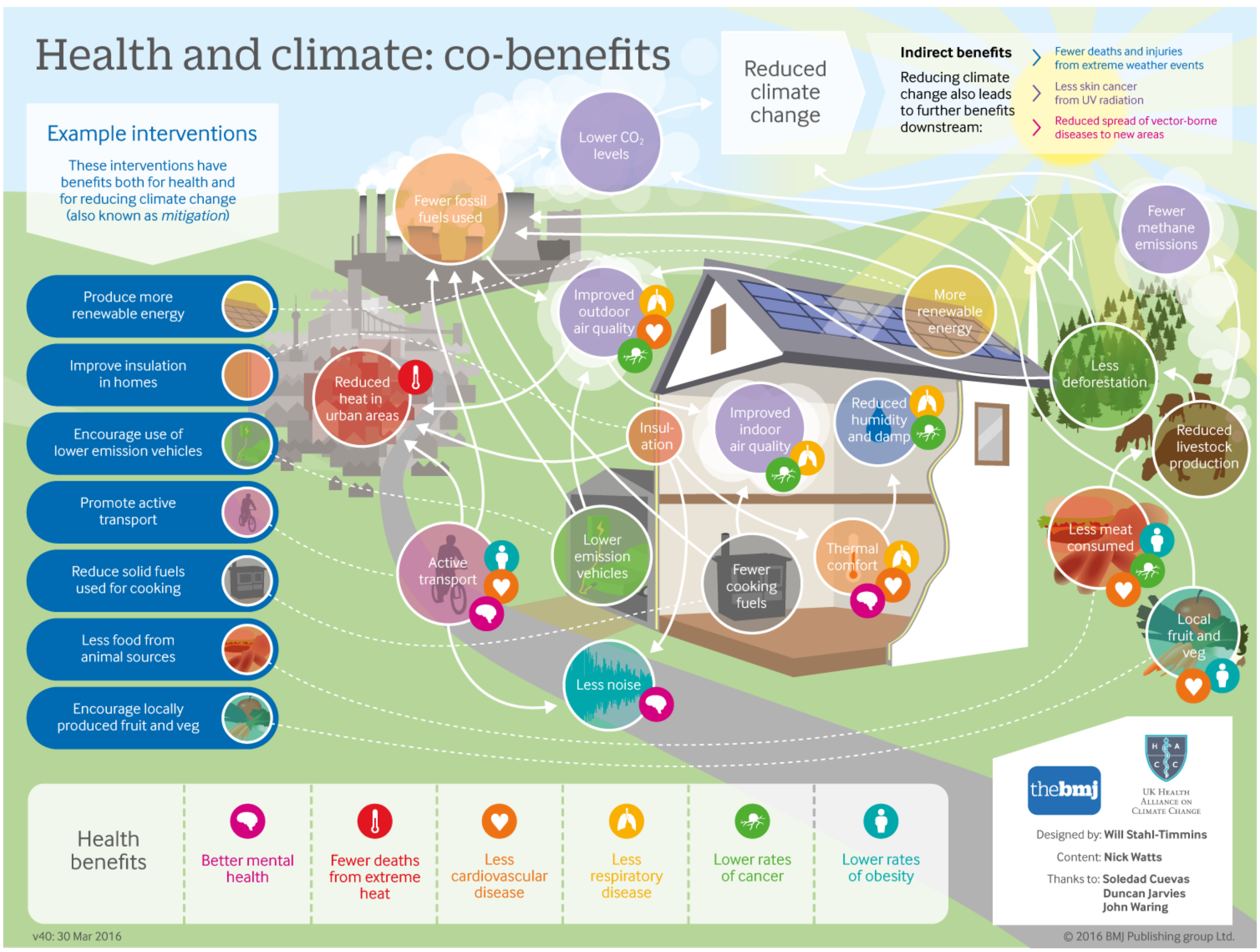


Figure 3.40 | Diagram showing the co-benefits between health and mitigation. Source: with permission from Iacobucci 2016.

related to mortality, suggested the sustainable pathways scenario could result in annual reductions of 1.18 million air pollution-related deaths, 5.86 million diet-related deaths, and 1.15 million deaths due to physical inactivity. Adopting the more ambitious health in all climate policies scenario could result in further reductions of 462,000 annual deaths attributable to air pollution, 572,000 annual deaths attributable to diet, and 943,000 annual deaths attributable to physical inactivity. These benefits were attributable to the mitigation of direct GHG emissions and the commensurate actions that reduce exposure to harmful pollutants, as well as improved diets and safe physical activity.

Cost-benefit analyses for climate mitigation in urban settings that do not account for health may underestimate the potential cost savings and benefits (Hess et al. 2020). The net health benefits of controlling air pollution as part of climate mitigation efforts could reach trillions of dollars annually, depending on the air quality policies adopted globally (Markandya et al. 2018; Scovronick et al. 2019b). Air pollution reductions resulting from meeting the Paris Agreement targets were estimated to provide health co-benefits-to-mitigation ratios of between 1.4 and 2.5 (Markandya et al. 2018). In Asia, the benefit of air pollution reduction through mitigation measures was estimated to reduce premature mortality by 0.79 million, with an associated health benefit of USD2.8 trillion versus mitigation costs of USD840 billion, equating to 6% and 2% of GDP, respectively (Xie et al. 2018). Similarly, stabilising radiative forcing to 3.4 W m^{-2} in South Korea could cost USD1.3–8.5 billion in 2050 and could lead to a USD23.5 billion cost reduction from the combined benefits of avoided premature mortality, health expenditures, and lost work hours (Kim et al. 2020). The health co-benefits related to physical exercise and reduced air pollution largely offset the costs of implementing low-CO_2-emitting urban mobility strategies in three Austrian cities (Wolkinger et al. 2018).

Just in the USA, over the next 50 years, a 2°C pathway could prevent roughly 4.5 million premature deaths, about 3.5 million hospitalisations and emergency room visits, and approximately 300 million lost workdays (Shindell 2020). The estimated yearly benefits of USD700 billion were more than the estimated cost of the energy transition.

3.7.6 Biodiversity (Land and Water)

Biodiversity covers life below water (SDG 14) and life on land (SDG 15). Ecosystem services are relevant to the goals of zero hunger (SDG 2), good health and well-being (SDG 3), clean water and sanitation (SDG 6) and responsible consumption and production (SDG 12), as well as being essential to human existence (IPBES 2019).

3.7.6.1 Benefits of Avoided Climate Impacts Along Mitigation Pathways

Terrestrial and freshwater aquatic ecosystems

Climate change is a major driver of species extinction and terrestrial and freshwater ecosystems destruction (*high confidence*) (AR6 WGII Chapter 2). Analysis shows that approximately half of all species with long-term records have shifted their ranges in elevation and about two thirds have advanced their timing of spring events (Parmesan and Hanley 2015). Under 3.2°C warming, 49% of insects, 44% of plants and 26% of vertebrates are projected to be at risk of extinction. At 2°C, this falls to 18% of insects, 16% of plants and 8% of vertebrates and at 1.5°C, to 6% of insects, 8% of plants and 4% of vertebrates (Warren et al. 2018). Incidents of migration of invasive species, including pests and diseases, are also attributable to climate change, with negative impacts on food security and vector-borne diseases. Moreover, if climate change reduces crop yields, cropland may expand – a primary driver of biodiversity loss – in order to meet food demand (Molotoks et al. 2020). Land restoration and halting land degradation under all mitigation scenarios has the potential for synergy between mitigation and adaptation.

Marine and coastal ecosystems

Marine ecosystems are being affected by climate change and growing non-climate pressures including temperature change, acidification, land-sourced pollution, sedimentation, resource extraction and habitat destruction (*high confidence*) (Bindoff et al. 2019; IPCC 2019b). The impacts of climate drivers and their combinations vary across taxa (AR6 WGII Chapter 3). The danger or warming and acidification to coral reefs, rocky shores and kelp forests is well established (*high confidence*) (AR6 WGII Chapter 3). Migration towards optimal thermal and chemical conditions (Burrows et al. 2019) contributes to large-scale redistribution of fish and invertebrate populations, and major impacts on global marine biomass production and maximum sustainable yield (Bindoff et al. 2019).

3.7.6.2 Implications of Mitigation Efforts Along Pathways

Mitigation measures have the potential to reduce the progress of negative impacts on ecosystems, although it is *unlikely* that all impacts can be mitigated (*high confidence*) (Ohashi et al. 2019). The specifics of mitigation achievement are crucial, since large-scale deployment of some climate mitigation and land-based CDR measures could have deleterious impacts on biodiversity (Santangeli et al. 2016; Hof et al. 2018).

Climate change mitigation actions to reduce or slow negative impacts on ecosystems are *likely* to support the achievement of SDGs 2, 3, 6, 12, 14 and 15. Some studies show that stringent and constant GHG mitigation practices bring a net benefit to global biodiversity even if land-based mitigation measures are also adopted (Ohashi et al. 2019), as opposed to delayed action which would require much more widespread use of BECCS. Scenarios based on demand reductions of energy and land-based production are expected to avoid many such consequences, due to their minimised reliance on BECCS (Conijn et al. 2018; Grubler et al. 2018; Bowles et al. 2019; Soergel et al. 2021a). Stringent mitigation that includes reductions in demand for animal-based foods and food waste could also relieve pressures on land use and biodiversity (*high confidence*), both directly by reducing agricultural land requirements (Leclère et al. 2020) and indirectly by reducing the need for land-based CDR (van Vuuren et al. 2018).

As environmental conservation and sustainable use of the Earth's terrestrial species and ecosystems are strongly related, recent studies

3

have evaluated interconnections among key aspects of land and show a pathway to the global sustainable future of land (Popp et al. 2014; Erb et al. 2016; Obersteiner et al. 2016; Humpenöder et al. 2018). Most studies agree that many biophysical options exist to achieve global climate mitigation and sustainable land use in future. Conserving local biodiversity requires careful policy design in conjunction with land-use regulations and societal transformation in order to minimise the conversion of natural habitats.

3.7.7 Cities and Infrastructure

This subsection focuses upon SDG 9 (industry, innovation and infrastructure) and SDG 11 (sustainable cities and communities).

3.7.7.1 Benefits of Avoided Climate Impacts Along Mitigation Pathways

By 2100, urban population will be almost double and more urban areas will be built (Jiang and O'Neill 2017), although COVID-19 may modify these trends (Kii 2021). Urbanisation will amplify projected air temperature changes in cities, including amplifying heatwaves (AR6 WGI Chapter 10, Box 10.3). Benefits of climate mitigation in urban areas include reducing heat, air pollution and flooding. Industrial infrastructure and production-consumption supply networks also benefit from avoided impacts.

3.7.7.2 Implications of Mitigation Efforts Along Pathways

Many co-benefits to urban mitigation actions (Chapter 8, Section 8.2.1) improve the liveability of cities and contribute to achieving SDG 11. In particular, compact urban form, efficient technologies and infrastructure can play a valuable role in mitigation by reducing energy demand (Creutzig et al. 2016; Güneralp et al. 2017), thus averting carbon lock-in, while reducing land sprawl and hence increasing carbon storage and biodiversity (D'Amour et al. 2017). Benefits of mitigation include air quality improvements from decreased traffic and congestion when private vehicles are displaced by other modes; health benefits from increases in active travel; and lowered urban heat island effects from green-blue infrastructures (Section 8.2.1).

However, increasing urban density or enlarging urban green spaces can increase property prices and reduce affordability (Section 8.2.1). Raising living conditions for slum dwellers and people living in informal settlements will require significant materials and energy; however, regeneration can be conducted in ways that avoid carbon-intense infrastructure lock-in (Chapters 8 and 9). Cities affect other regions through supply chains (Marinova et al. 2020).

Sustainable production, consumption and management of natural resources are consistent with, and necessary for, mitigation (Chapters 5 and 11). Demand-side measures can lower requirements for upstream material and energy use (Chapter 5). In terms of industrial production, transformational changes across sectors will be necessary for mitigation (Sections 11.3 and 11.4).

Addressing multiple SDG arenas requires new systemic thinking in the areas of governance and policy, such as those proposed by Sachs et al. (2019).

3.8 Feasibility of Socio/Techno/Economic Transitions

The objective of this section is to discuss concepts of feasibility in the context of the low-carbon transition and pathways. We aim to identify drivers of low-carbon scenarios feasibility and to highlight enabling conditions which can ameliorate feasibility concerns.

3.8.1 Feasibility Frameworks for the Low-carbon Transition and Scenarios

Effectively responding to climate change and achieving sustainable development requires overcoming a series of challenges to transition away from fossil-based economies. Feasibility can be defined in many ways (Chapter 1). The political science literature (Majone 1975a,b; Gilabert and Lawford-Smith 2012) distinguishes the feasibility of 'what' (i.e., emission reduction strategies), 'when and where' (i.e., in the year 2050, globally) and 'whom' (i.e., cities). It distinguishes desirability from political feasibility (von Stechow et al. 2015): the former represents a normative assessment of the compatibility with societal goals (i.e., SDGs), while the latter evaluates the plausibility of what can be attained given the prevailing context of transformation (Nielsen et al. 2020). Feasibility concerns are context and time dependent and malleable: enabling conditions can help overcome them. For example, public support for carbon taxes has been hard to secure but appropriate policy design and household rebates can help dissipate opposition (Murray and Rivers 2015; Carattini et al. 2019).

Regarding scenarios, the feasibility 'what' question is the one most commonly dealt with in the literature, though most of the studies have focused on expanding low-carbon system, and yet political constraints might arise mostly from phasing out fossil fuel-based ones (Spencer et al. 2018; Fattouh et al. 2019). The 'when and where' dimension can also be related to the scenario assessment, but only insofar that the models generating them can differentiate time and geographical contextual factors. Distinguishing mitigation potential by regional institutional capacity has a significant influence on the costs of stabilising climate (Iyer et al. 2015c). The 'whom' question is the most difficult to capture by scenarios, given the multitude of actors involved as well as their complex interactions. The focus of socio-technical transition sciences on the co-evolutionary processes can shed light on the dynamics of feasibility (Nielsen et al. 2020).

The when-where-whom distinction allows depicting a feasibility frontier beyond which implementation challenges prevent mitigation action (Jewell and Cherp 2020). Even if the current feasibility frontier appears restraining in some jurisdictions, it is context-dependent and dynamic as innovation proceeds and institutional capacity builds up (Nielsen et al. 2020). The question is whether the feasibility frontier can move faster than the pace at which the carbon budget is being exhausted. Jewell et al. (2019) show that the emission savings from the pledges of premature retirement of coal plants is 150 times less than globally committed emissions from existing coal power plants. The pledges come from countries with high institutional capacity and relatively low shares of coal in electricity. Other factors currently limiting the capacity to steer transitions at the necessary speed include the electoral-market orientation of politicians (Willis 2017), the status-quo orientation of senior public officials (Geden 2016), path dependencies created by 'instrument constituencies' (Béland and Howlett 2016), or the impacts of deliberate inconsistencies between talk, decisions and actions in climate policy (Rickards et al. 2014). All in all, a number of different delay mechanisms in both science and policy have been identified to potentially impede climate goal achievement (Karlsson and Gilek 2020) (Chapter 13).

In addition to its contextual and dynamic nature, feasibility is a multi-dimensional concept. The IPCC SR1.5 distinguishes six dimensions of feasibility: geophysical, environmental-ecological, technological, economic, socio-cultural and institutional. At the individual option level, different mitigation strategies face various barriers as well as enablers (see Chapter 6 for the option-level assessment). However, a systemic transformation involves interconnections of a wide range of indicators. Model-based assessments are meant to capture the integrative elements of the transition and of associated feasibility challenges. However, the translation of model-generated pathways into feasibility concerns (Rogelj et al. 2018b) has developed only recently. Furthermore, multiple forms of knowledge can be mobilised to support strategic decision-making and complement scenario analysis (Turnheim and Nykvist 2019). We discuss both approaches next.

3.8.2 Feasibility Appraisal of Low-carbon Scenarios

Evaluating the feasibility of low-carbon pathways can take different forms. In the narrowest sense, there is feasibility pertaining the reporting of model-generated scenarios: here an infeasible scenario is one which cannot meet the constraints embedded implicitly or explicitly in the models which attempted to generate it. Second, there is a feasibility that relates to specific elements or overall structure characterising the low-carbon transition compared to some specified benchmark.

3.8.2.1 Model Solvability

In order to be generated, scenarios must be coherent with the constraints and assumptions embedded in the models (i.e., deployment potential of given technologies, physical and geological limits) and in the scenario design (i.e., carbon budget). Sometimes, models cannot solve specific scenarios. This provides a first, coarse indication of feasibility concerns. Specific vetting criteria can be imposed, such as carbon-price values above which scenarios should not be reported, as in Clarke et al. (2009). However, model solvability raises issues of aggregation in model ensembles. Since model solving is not a random process, but a function of the characteristics of the models, analysing only reported outcomes leads to statistical biases (Tavoni and Tol 2010).

Although model-feasibility differs distinctly from feasibility in the real world, it can indicate the relative challenges of low-carbon scenarios – primarily when performed in a model ensemble of sufficient size. Riahi et al. (2015) interpreted infeasibility across a large number of models as an indication of increased risk that the transformation may not be attainable due to technical or economic concerns. All models involved in a model comparison of 1.5°C targets (Rogelj et al. 2018b) (Table S1) were able to solve under favourable underlying socio-economic assumptions (SSP1), but none for the more challenging SSP3. This interpretation of feasibility was used to highlight the importance of socio-economic drivers for attaining climate stabilisation. Gambhir et al. (2017) constrained the models to historically observed rates of change and found that it would no longer allow to solve for 2°C, highlighting the need for rapid technological change.

3.8.2.2 Scenario Feasibility

Evaluating the feasibility of scenarios involves several steps (Figure 3.41). First, one needs to identify which dimensions of feasibility to focus on. Then, for each dimension, one needs to select relevant indicators for which sufficient empirical basis exists and which are an output of models (or at least of a sufficient number of them). Then, thresholds marking different levels of feasibility concerns are defined based on available literature, expert elicitations and empirical analysis based on appropriately chosen historical precedents. Finally, scenario feasibility scores are obtained for each indicator, and where needed aggregated up in time or dimensions, as a way to provide an overall appraisal of feasibility trade-offs, depending on the timing, disruptiveness and scale of transformation.

Most of the existing literature has focused on the technological dimensions, given the technology focus of models and the ease of comparison. The literature points to varied findings. Some suggest that scenarios envision technological progress consistent with historical benchmarks (Wilson et al. 2013; Loftus et al. 2015). Others that scenarios exceed historically observed rates of low-carbon technology deployment and of energy demand transformation globally (van der Zwaan et al. 2013; Napp et al. 2017; Cherp et al. 2021; Semieniuk et al. 2021), but not for all countries (Cherp et al. 2021). The reason for these discrepancies depends on the unit of analysis and the indicators used. Comparing different kinds of historical indicators, (van Sluisveld et al. 2015) find that indicators that look into the absolute change of energy systems remain within the range of historical growth frontiers for the next decade, but increase to unprecedented levels before mid-century. Expert assessments provide another way of benchmarking scenarios, though they have shown to be systematically biased (Wiser et al. 2021) and to underperform empirical methods (Meng et al. 2021). van Sluisveld et al. (2018a) find that scenarios and experts align for baseline scenarios but differ for low-carbon ones. Scenarios rely more on conventional technologies based on existing infrastructure (such as nuclear and CCS) than what is forecasted by experts. Overall, the technology assessment of the feasibility space highlights that Paris-compliant transformations would have few precedents, but not zero (Cherp et al. 2021).

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

Figure 3.41 | Steps involved in evaluating the feasibility of scenarios. Source: adapted with permission from Brutschin et al. 2021.

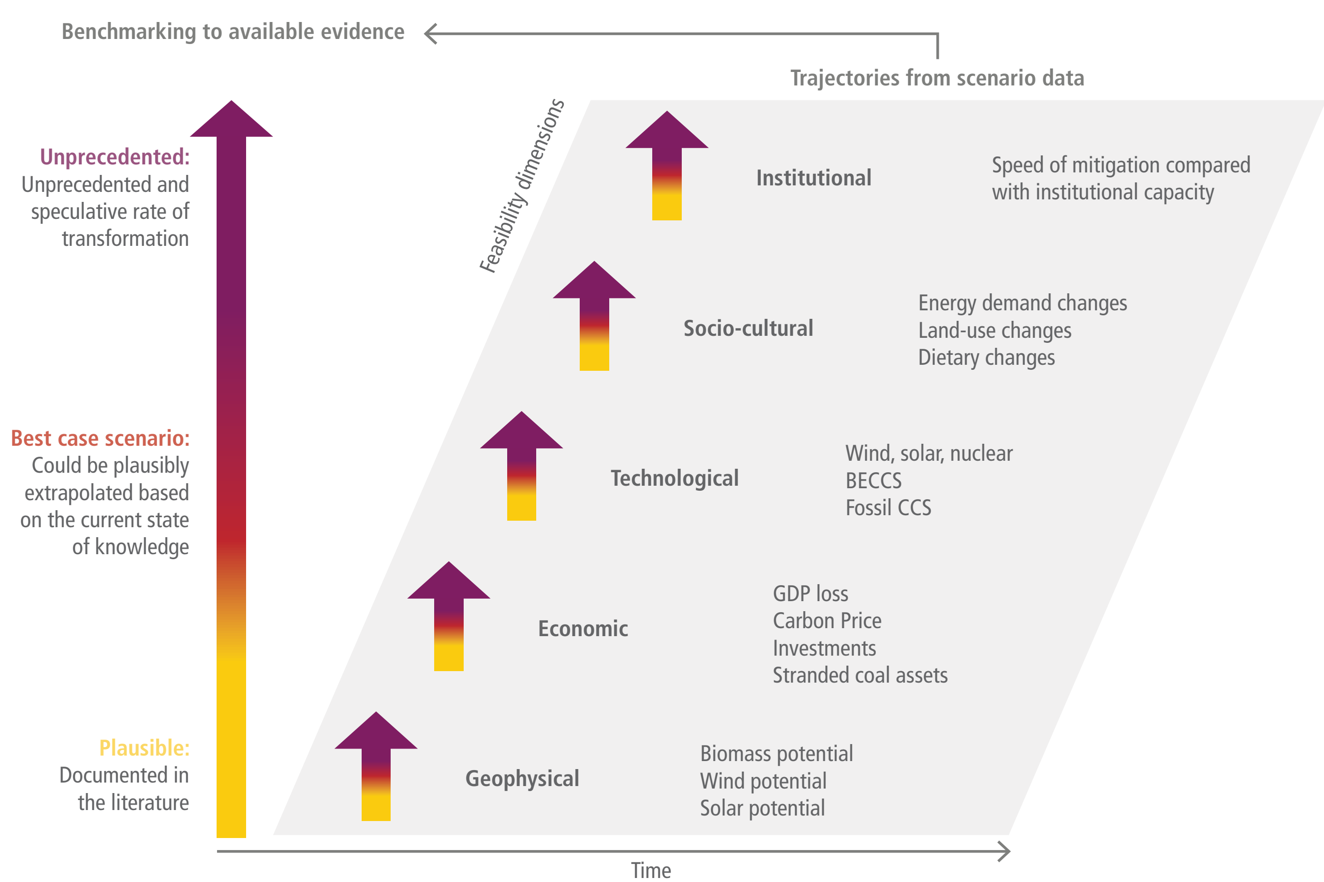


Figure 3.42 | Example of multi-dimensional feasibility analysis and indicators used in the IPCC AR6 scenarios. The approach defines relevant indicators characterising the key dimensions of feasibility. Indicators capture the timing, scale and disruptiveness challenges. Low-, medium- and high-feasibility concerns are defined based on historical trends and available literature. Details about indicator and threshold values can be found in Annex III.II.2.3.

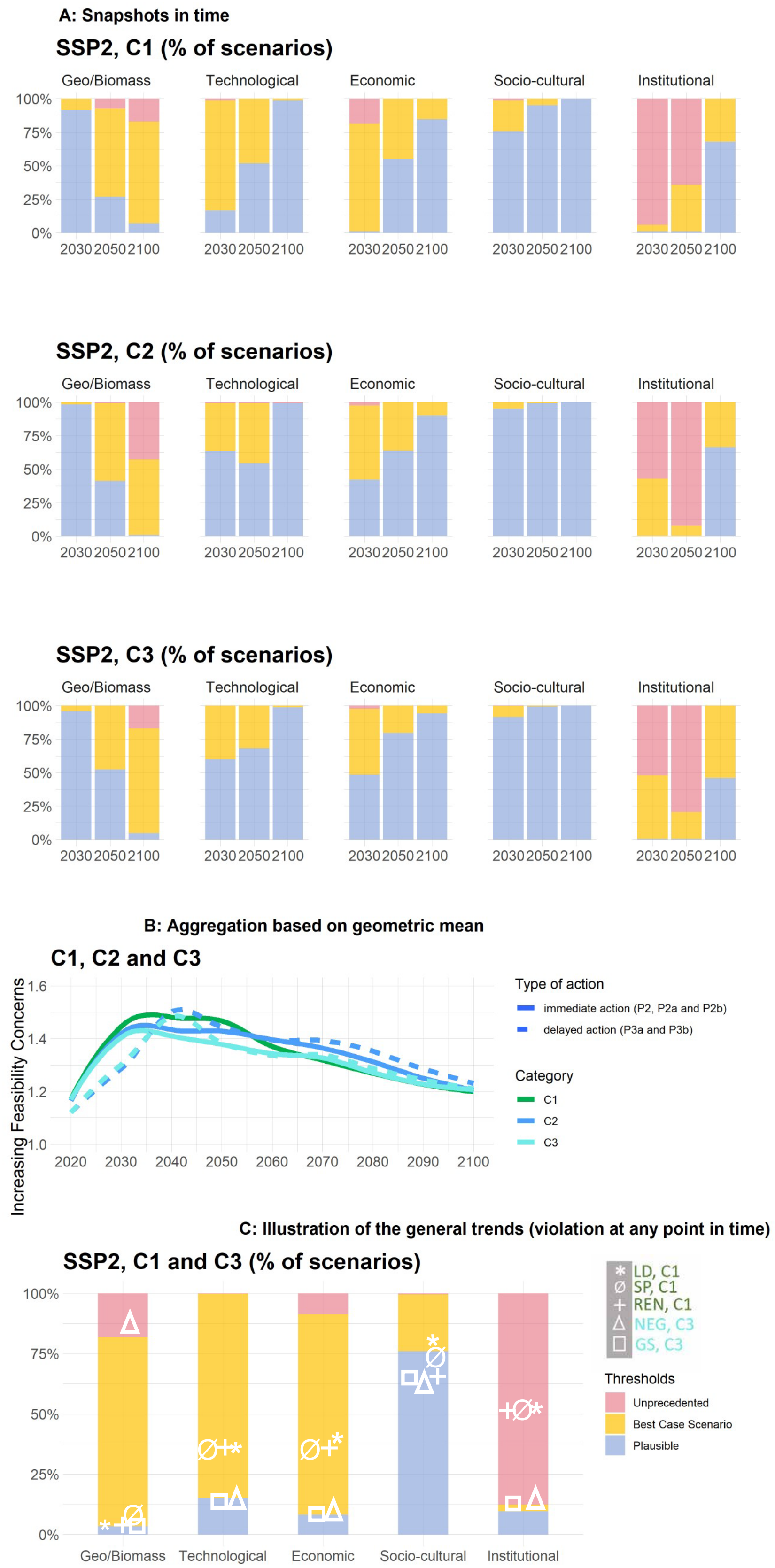


Figure 3.43 | Feasibility characteristics of the Paris-consistent scenarios in the AR6 scenarios database : Feasibility corridors for the AR6 scenarios database, applying the methodology by (Brutschin et al. 2021). (a) The fraction of scenarios falling within three categories of feasibility concerns (plausible, best case, unprecedented), for different times (2030, 2050, 2100), different climate categories consistent with the Paris Agreement and five dimensions. **(b)** Composite feasibility score (obtained by geometric mean of underlying indicators) over time for scenarios with immediate and delayed global mitigation efforts, for different climate categories (C1, C2, C3. Note: no C1 scenario has delayed participation). **(c)** The fraction of scenarios which in any point in time over the century exceed the feasibility concerns, for C1 and C3 climate categories. Overlayed are the Illustrative Mitigation Pathways (*IMP-LP*, *IMP-SP*, *IMP-Ren*: C1 category; *IMP-Neg*, *IMP-GS*: C3 category).

Recent approaches have addressed multiple dimensions of feasibility, an important advancement since social and institutional aspects are as, if not more, important than technology ones (Jewell and Cherp 2020). Feasibility corridors of scenarios based on their scale, rate of change and disruptiveness have been identified (Kriegler et al. 2018b; Warszawski et al. 2021). The reality check shows that many 1.5°C-compatible scenarios violate the feasibility corridors. The ones that didn't are associated with a greater coverage of the available mitigation levers (Warszawski et al. 2021).

Brutschin et al. (2021) proposed an operational framework covering all six dimensions of feasibility. They developed a set of multi-dimensional metrics capturing the timing, disruptiveness and the scale of the transformative change within each dimension (as in Kriegler et al. 2018b). Thresholds of feasibility risks of different intensity are obtained through the review of the relevant literature and empirical analysis of historical data. Novel indicators include governance levels (Andrijevic et al. 2020a). The 17 bottom-up indicators are then aggregated up across time and dimension, as a way to highlight feasibility trade-offs. Aggregation is done via compensatory approaches such as the geometric mean. This is employed, for instance, for the Human Development Index. A conceptual example of this approach as applied to the IPCC AR6 scenarios database is shown in Figure 3.42 and further described in the Annex III.II.2.3.

In Figure 3.43, we show the results of applying the methodology of Brutschin et al. (2021) to the AR6 scenarios database. The charts highlight the dynamic nature of feasibility risks, which are mostly concentrated in the decades before mid-century except for geophysical risks driven by CO_2 removals later in the century. Different dimensions pose differentiated challenges: for example, institutional feasibility challenges appear to be the most relevant, in line with the qualitative literature. Thus, feasibility concerns might be particularly relevant in countries with weaker institutional capacity. Figure 3.43 also highlights the key roles of policy and technology as enabling factors. In particular (panel b), internationally coordinated and immediate emission reductions allow to smooth out feasibility concerns and reduce long-term challenges compared to delayed policy action, as a result of a more gradual transition and lower requirements of CO_2 removals. For the same climate objective, different Illustrative Mitigation Pathways entail somewhat different degrees and distributions of implementation challenges (panel c).

3.8.3 Feasibility in Light of Socio-technical Transitions

The limitations associated with quantitative low-carbon transition pathways stem from a predominant reliance on techno-economic considerations with a simplified or non-existent representation of the socio-political and institutional agreement. Accompanying the required deployment of low-carbon technologies will be the formation of new socio-technical systems (Bergek et al. 2008). With a socio-technical system being defined as a cluster of elements comprising of technology, regulation, user practices and markets, cultural meaning, infrastructure, maintenance networks, and supply networks (Hofman et al. 2004; Geels and Geels 2005); the inter-relationship between technological systems and social systems must be comprehensively understood. It is of vital importance that the process of technical change must be considered in its institutional and social context so as to ascertain potential transition barriers which in turn provide an indication of pathway feasibility. In order to address the multitudinous challenges associated with low-carbon transition feasibility and governance, it has been opined that the robustness of evaluating pathways may be improved by the bridging of differing quantitative-qualitative analytical approaches (Haxeltine et al. 2008; Foxon et al. 2010; Hughes 2013; Wangel et al. 2013; Li et al. 2015; Turnheim et al. 2015; Geels et al. 2016a,b, 2020; Moallemi et al. 2017; De Cian et al. 2020; Li and Strachan 2019). The rationale for such analytical bridging is to rectify the issue that in isolation each disciplinary approach can only generate a fragmented comprehension of the transition pathway with the consequence being an incomplete identification of associated challenges in terms of feasibility. Concerning low-carbon transition pathways generated by IAMs, it has been argued that a comprehensive analysis should include social scientific enquiry (Geels et al. 2016a, 2020; van Sluisveld et al. 2018b). The normative analysis of IAM pathways assists in the generation of a vision or the formulation of a general plan with this being complemented by socio-technical transition theory (Geels et al. 2016a). Such an approach thereby allowing for the socio-political feasibility and the social acceptance and legitimacy of low-carbon options to be considered. Combining computer models and the multi-level perspective can help identify 'transition bottlenecks' (Geels et al. 2020). Similarly, increased resolution of integrated assessment models' actors has led to more realistic narratives of transition in terms of granularity and behaviour (McCollum et al. 2017; van Sluisveld et al. 2018b). Increased data availability of actual behaviour from smart technology lowers the barriers to representing behavioural change in computer simulations, and thus better represents crucial demand-side transformations (Creutzig et al. 2018). Increasing the model resolution is a meaningful way forward. However, integrating a much broader combination of real-life aspects and dynamics into models could lead to an increased complexity that could restrict them to smaller fields of applications (De Cian et al. 2020).

Other elements of feasibility relate to social justice, which could be essential to enhance the political and public acceptability of the low-carbon transition. Reviewing the literature, one study finds that employing social justice as an orienting principle can increase the political feasibility of low-carbon policies (Patterson et al. 2018). Three elements are identified as key: (i) protecting vulnerable people from climate change impacts, (ii) protecting people from disruptions of transformation, (iii) enhancing the process of envisioning and implementing an equitable post-carbon society.

3.8.4 Enabling Factors

There is strong agreement that the climate policy institutional framework as well as technological progress have a profound impact on the attainability of low-carbon pathways. Delaying international cooperation reduces the available carbon budget and locks into carbon-intensive infrastructure exacerbating implementation challenges (Keppo and Rao 2007; Bosetti et al. 2009; Boucher et al. 2009; Clarke et al. 2009; Krey and Riahi 2009; van Vliet et al. 2009;

Knopf et al. 2011; Jakob et al. 2012; Luderer et al. 2013; Rogelj et al. 2013a; Aboumahboub et al. 2014; Kriegler et al. 2014a; Popp et al. 2014; Riahi et al. 2015; Gambhir et al. 2017; Bertram et al. 2021). Similarly, technological availability influences the feasibility of climate stabilisation, though differently for different technologies (Kriegler et al. 2014a; Iyer et al. 2015a; Riahi et al. 2015).

One of the most relevant factors affecting mitigation pathways and their feasibility is the rate and kind of socio-economic development. For example, certain socio-economic trends and assumptions about policy effectiveness preclude achieving stringent mitigation futures (Rogelj et al. 2018b). The risk of failure increases markedly in high-growth, unequal and/or energy-intensive worlds such as those characterised by the shared socio-economic pathways SSP3, SSP4 and SSP5. On the other hand, socio-economic development conducive to mitigation relieves the energy sector transformation from relying on large-scale technology development: for example, the amount of biomass with CCS in SSP1 is one third of that in SSP5. The reason why socio-economic trends matter so much is that they both affect the CO_2 emissions in counterfactual scenarios as well as the mitigation capacity (Riahi et al. 2017; Rogelj et al. 2018b). Economic growth assumptions are the most important determinant of scenario emissions (Marangoni et al. 2017). Degrowth and post-growth scenarios have been suggested as valuable alternatives to be considered (Hickel et al. 2021; Keyßer and Lenzen 2021), though substantial challenges remain regarding political feasibility (Keyßer and Lenzen 2021).

The type of policy instrument assumed to drive the decarbonisation process also plays a vital role for determining feasibility. The majority of scenarios exploring climate stabilisation pathways in the past have focused on uniform carbon pricing as the most efficient instrument to regulate emissions. However, carbon taxation raises political challenges (Beiser-McGrath and Bernauer 2019) (Chapters 13 and 14). Carbon pricing will transfer economic surplus from consumers and producers to the government. Losses for producers will be highly concentrated in those industries possessing fixed or durable assets with 'high asset specificity' (Murphy 2002; Dolphin et al. 2020). These sectors have opposed climate jurisdictions (Jenkins 2014). Citizens are sensitive to rising energy prices, though revenue recycling can be used to increase support (Carattini et al. 2019). A recent model comparison project confirms findings from the extant literature: using revenues to reduce pre-existing capital or, to a lesser extent, labour taxes, reduces policy costs and eases distributional concerns (Barron et al. 2018; Mcfarland et al. 2018).

Nonetheless, winning support will require a mix of policies which go beyond carbon pricing, and include subsidies, mandates and feebates (Jenkins 2014; Rozenberg et al. 2018). More recent scenarios take into account a more comprehensive range of policies and regional heterogeneity in the near to medium term (Roelfsema et al. 2020). Regulatory policies complementing carbon prices could reduce the implementation challenges by increasing short-term emission reduction, though they could eventually reduce economic efficiency (Bertram et al. 2015b; Kriegler et al. 2018a). Innovation policies such as subsidies to R&D have been shown to be desirable due to innovation market failures, and also address the dynamic nature of political feasibility (Bosetti et al. 2011).

3.9 Methods of Assessment and Gaps in Knowledge and Data

3.9.1 AR6 Mitigation Pathways

The analysis in this chapter relies on the available literature as well as an assessment of the scenarios contained in the AR6 scenarios database. Scenarios were submitted by research and other institutions following an open call (Annex III.II.3.1). The scenarios included in the AR6 scenarios database are an unstructured ensemble, as they are from multiple underlying studies and depend on which institutions chose to submit scenarios to the database. As noted in Section 3.2, they do not represent the full scenario literature or the complete set of possible scenarios. For example, scenarios that include climate change impacts or economic degrowth are not fully represented, as these scenarios, with a few exceptions, were not submitted to the database. Additionally, sensitivity studies, which could help elucidate model behaviour and drivers of change, are mostly absent from the database – though examples exist in the literature (Marangoni et al. 2017).

The AR6 scenarios database contains 3131 scenarios of which 2425 with global scope were considered by this chapter, generated by almost 100 different model versions, from more than 50 model families. Of the 1686 vetted scenarios, 1202 provided sufficient information for a climate categorisation. Around 46% of the pathways are consistent with an end-of-century temperature of at least *likely* limiting warming to below 2°C (>67%). There are many ways of constructing scenarios that limit warming to a particular level and the choice of scenario construction has implications for the timing of both net zero CO_2 and GHG emissions and the deployment of CDR (Emmerling et al. 2019; Rogelj et al. 2019b; Johansson et al. 2020). The AR6 scenarios database includes scenarios where temperature is temporarily exceeded (40% of all scenarios in the database have median temperature in 2100 that is 0.1°C lower than median peak temperature). Climate stabilisation scenarios are typically implemented by assuming a carbon price rising at a particular rate per year, though that rate varies across model, scenario, and time period. Standard scenarios assume a global single carbon price to minimise policy costs. Cost-minimising pathways can be reconciled with equity considerations through posterior international transfers. Many scenarios extrapolate current policies and include non-market, regulatory instruments such as technology mandates.

Scenarios are not independent of each other and not representative of all possible outcomes, nor of the underlying scenario generation process; thus, the statistical power of the database is limited. Dependencies in the data-generation process originate from various sources. Certain model groups, and types, are over-represented. For example, eight model teams contributed 90% of scenarios. Second, not all models can generate all scenarios, and these differences are not random, thereby creating selection bias (Tavoni and Tol 2010).

Third, there are strong model dependencies: the modelling scientific community shares code and data, and several IAMs are open-source.

3.9.2 Models Assessed in This Chapter

The models assessed in this chapter differ in their sectoral coverage and the level of complexity in each sector. Models tend to have more detail in their representation of energy supply and transportation, than they do for industry (Section 3.4 and Annex III.I). Some models include detailed land-use models, while others exclude land models entirely and use supply curves to represent bioenergy potential (Bauer et al. 2018a). IAMs do not include all mitigation options available in the literature (Rogelj et al. 2018b; Smith et al. 2019). For example, most IAM pathways exclude many granular demand-side mitigation options and land-based mitigation options found in more detailed sectoral models; additionally, only a few pathways include CDR options beyond afforestation/reforestation and BECCS. Section 3.4 and Chapter 12 include some results and comparisons to non-IAM models (e.g., bottom-up studies and detailed sectoral models). These sectoral studies often include a more complete set of mitigation options but exclude feedbacks and linkages across sectors which may alter the mitigation potential of a given sector. There is an increasing focus in IAM studies on SDGs (Section 3.7), with some studies reporting the implications of mitigation pathways on SDGs (e.g., Bennich et al. 2020) and others using achieving SDGs as a constraint on the scenario itself (van Vuuren et al. 2015; Soergel et al. 2021a). However, IAMs are still limited in the SDGs they represent, often focusing on energy, water, air pollution and land. On the economic side, the majority of the models report information on marginal costs (i.e., carbon price). Only a subset provides full economic implications measured by either economic activity or welfare. Also often missing, is detail about economic inequality within countries or large aggregate regions.

For further details about the models and scenarios, see Annex III.

Frequently Asked Questions (FAQs)

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

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

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

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

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

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

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

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

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

References

Abel, G.J., B. Barakat, K.C. Samir, and W. Lutz, 2016: Meeting the Sustainable Development Goals leads to lower world population growth. *Proc. Natl. Acad. Sci.*, **113(50)**, 14294 LP – 14299, doi:10.1073/pnas.1611386113.

Aboumahboub, T. et al., 2014: On the regional distribution of climate mitigation costs: the impact of delayed cooperative action. *Clim. Change Econ.*, **5(1)**, 1–27, doi:10.1142/S2010007814400028.

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous, 2012: The Environment and Directed Technical Change. *Am Econ Rev*, **102(1)**, 131–166, doi:10.1257/aer.102.1.131.

Acemoglu, D., U. Akcigit, D. Hanley, and W. Kerr, 2016: Transition to clean technology. *J. Polit. Econ.*, **124(1)**, 52–104, doi:10.1086/684511.

Adler, M. et al., 2017: Priority for the worse-off and the social cost of carbon. *Nat. Clim. Change*, **7(6)**, 443–449, doi:10.1038/nclimate3298.

Aghion, P., C. Hepburn, A. Teytelboym, and D. Zenghelis, 2019: Path dependence, innovation and the economics of climate change. In: *Handbook on Green Growth* [R. Fouquet (ed.)]. Edward Elgar Publishing, Cheltenham, UK, pp. 67–83.

Akimoto, K., F. Sano, J. Oda, H. Kanaboshi, and Y. Nakano, 2021: Climate change mitigation measures for global net-zero emissions and the roles of CO_2 capture and utilization and direct air capture. *Energy Clim. Change*, **2**, 100057, doi:https://doi.org/10.1016/j.egycc.2021.100057.

Aldy, J. et al., 2016: Economic tools to promote transparency and comparability in the Paris Agreement. *Nat. Clim. Change*, **6(11)**, 1000–1004, doi:10.1038/nclimate3106.

Aleksandrowicz, L., R. Green, E.J.M. Joy, P. Smith, and A. Haines, 2016: The Impacts of Dietary Change on Greenhouse Gas Emissions, Land Use, Water Use, and Health: A Systematic Review. *PLoS One*, **11(11)**, e0165797.

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. *Nat. Clim. Change*, **6(8)**, 773–776, doi:10.1038/nclimate2998.

Allen, M.R., O.P. Dube, W. Solecki, F. Aragón-Durand, W. Cramer, S. Humphreys, M. Kainuma, J. Kala, N. Mahowald, Y. Mulugetta, R. Perez, M. Wairiu, and K. Zickfeld, 2018: Framing and Context. In: *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* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 49–91.

Anderegg, W.R.L. et al., 2020: Climate-driven risks to the climate mitigation potential of forests. *Science*, **368(6497)**, eaaz7005, doi:10.1126/science.aaz7005.

Anderson, K. and A. Larkin, 2013: *Avoiding dangerous climate change demands de-growth strategies from wealthier nations*. https://kevinanderson.info/blog/avoiding-dangerous-climate-change-demands-de-growth-strategies-from-wealthier-nations/.

Anderson, K. and G. Peters, 2016: The trouble with negative emissions. *Science*, **354(6309)**, 182–183, doi:10.1126/science.aah4567.

Andrijevic, M., J. Crespo Cuaresma, R. Muttarak, and C.-F. Schleussner, 2020a: Governance in socioeconomic pathways and its role for future adaptive capacity. *Nat. Sustain.*, **3**(1), 35–41, doi:10.1038/s41893-019-0405-0.

Andrijevic, M., C.-F. Schleussner, M.J. Gidden, D.L. McCollum, and J. Rogelj, 2020b: COVID-19 recovery funds dwarf clean energy investment needs. *Science*, **370(6514)**, 298–300, doi:10.1126/science.abc9697.

Arinoa, Y. et al., 2016: Estimating option values of solar radiation management assuming that climate sensitivity is uncertain. *Proc. Natl. Acad. Sci.*, **113(21)**, 5886–5891, doi:10.1073/pnas.1520795113.

Arnell, N.W. and B. Lloyd-Hughes, 2014: The global-scale impacts of climate change on water resources and flooding under new climate and socio-economic scenarios. *Clim. Change*, **122(1–2)**, 127–140, doi:10.1007/s10584-013-0948-4.

Arvesen, A., G. Luderer, M. Pehl, B.L. Bodirsky, and E.G. Hertwich, 2018: Deriving life cycle assessment coefficients for application in integrated assessment modelling. *Environ. Model. Softw.*, **99**, 111–125, doi:https://doi.org/10.1016/j.envsoft.2017.09.010.

Asadieh, B., and N.Y. Krakauer, 2017: Global change in streamflow extremes under climate change over the 21st century. *Hydrol. Earth Syst. Sci.*, **21(11)**, 5863–5874, doi:10.5194/hess-21-5863-2017.

Auffhammer, M., P. Baylis, and C.H. Hausman, 2017: Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States. *Proc. Natl. Acad. Sci.*, **114(8)**, 1886–1891, doi:10.1073/pnas.1613193114.

Azevedo, I., C. Bataille, J. Bistline, L. Clarke, and S. Davis, 2021: Net-Zero Emissions Energy Systems: What We Know and Do Not Know. *Energy Clim. Change*, **2,** 100049, doi: 10.1016/j.egycc.2021.100049.

Babacan, O. et al., 2020: Assessing the feasibility of carbon dioxide mitigation options in terms of energy usage. *Nat. Energy*, **5**(9), 720–728, doi:10.1038/s41560-020-0646-1.

Bajželj, B. and K.S. Richards, 2014: The positive feedback loop between the impacts of climate change and agricultural expansion and relocation. *Land*, **3(3)**, 898–916, doi:10.3390/land3030898.

Bajželj, B. et al., 2014: Importance of food-demand management for climate mitigation. *Nat. Clim. Change*, **4(10)**, 924–929, doi:10.1038/nclimate2353.

Baker, J.S., C.M. Wade, B.L. Sohngen, S. Ohrel, and A.A. Fawcett, 2019: Potential complementarity between forest carbon sequestration incentives and biomass energy expansion. *Energy Policy*, **126** (August 2018), 391–401, doi:10.1016/j.enpol.2018.10.009.

Baležentis, T., G. Liobikienė, D. Štreimikienė, and K. Sun, 2020: The impact of income inequality on consumption-based greenhouse gas emissions at the global level: {A} partially linear approach. *J. Environ. Manage.*, **267**, 110635, doi:10.1016/j.jenvman.2020.110635.

Ballard, T.C., E. Sinha, and A.M. Michalak, 2019: Long-Term Changes in Precipitation and Temperature Have Already Impacted Nitrogen Loading. *Environ. Sci. Technol.*, **53(9)**, 5080–5090, doi:10.1021/acs.est.8b06898.

Barker, T., E. Alexandri, J.F. Mercure, Y. Ogawa, and H. Pollitt, 2016: GDP and employment effects of policies to close the 2020 emissions gap. *Clim. Policy*, **16(4)**, 393–414, doi:10.1080/14693062.2014.1003774.

Barron, A.R., A.A. Fawcett, M.A.C. Hafstead, J.R. Mcfarland, and A.C. Morris, 2018: Policy Insights From the EMF 32 Study on U.S. Carbon Tax Scenarios. *Clim. Change Econ.*, **09(01)**, 1840003, doi:10.1142/S2010007818400031.

Bartos, M.D. and M.V. Chester, 2015: Impacts of climate change on electric power supply in the Western United States. *Nat. Clim. Change*, **5(8)**, 748–752, doi:10.1038/nclimate2648.

Bastien-Olvera, B.A. and F.C. Moore, 2020: Use and non-use value of nature and the social cost of carbon. *Nat. Sustain.*, **4**, 101–108, doi:10.1038/s41893-020-00615-0.

Battiston, S., A. Mandel, I. Monasterolo, F. Schütze, and G. Visentin, 2017: A climate stress-test of the financial system. *Nat. Clim. Change*, **7(4)**, 283–288, doi:10.1038/nclimate3255.

Battiston, S., I. Monasterolo, K. Riahi, and B.J. van Ruijven, 2021: Accounting for finance is key for climate mitigation pathways. *Science*, **372(6545)**, 918–920, doi:10.1126/science.abf3877.

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

Bauer, N. et al., 2018a: Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. *Clim. Change*, **163**, 1553–1568, doi:10.1007/s10584-018-2226-y.

Bauer, N., C. McGlade, J. Hilaire, and P. Ekins, 2018b: Divestment prevails over the green paradox when anticipating strong future climate policies. *Nat. Clim. Change*, **8(2)**, 130–134, doi:10.1038/s41558-017-0053-1.

Bauer, N. et al., 2020: Quantification of an efficiency–sovereignty trade-off in climate policy. *Nature*, **588(7837)**, 261–266, doi:10.1038/s41586-020-2982-5.

Beach, R.H. et al., 2015: Climate change impacts on US agriculture and forestry: Benefits of global climate stabilization. *Environ. Res. Lett.*, **10(9)**, doi:10.1088/1748-9326/10/9/095004.

Beck, S. and M. Mahony, 2017: The IPCC and the politics of anticipation. *Nat. Clim. Change*, **7(5)**, 311–313, doi:10.1038/nclimate3264.

Beck, S. and M. Mahony, 2018: The politics of anticipation: The IPCC and the negative emissions technologies experience. *Glob. Sustain.*, **1**, 1–8, doi:10.1017/sus.2018.7.

Bednar, J. et al., 2021: Operationalizing the net-negative carbon economy. *Nature*, **596**, 377–383, doi:10.1038/s41586-021-03723-9.

Beiser-McGrath, L.F. and T. Bernauer, 2019: Could revenue recycling make effective carbon taxation politically feasible? *Sci. Adv.*, **5(9)**, eaax3323, doi:10.1126/sciadv.aax3323.

Belaia, M., J.B. Moreno-Cruz, and D.W. Keith, 2021: Optimal Climate Policy in 3D: Mitigation, Carbon Removal and Solar Geoengineering. *Clim. Change Econ.*, **12(3)** , 2150008, doi:10.1142/S2010007821500081.

Béland, D. and M. Howlett, 2016: How Solutions Chase Problems: Instrument Constituencies in the Policy Process. *Governance*, **29(3)**, 393–409, doi:https://doi.org/10.1111/gove.12179.

Bennich, T., N. Weitz, and H. Carlsen, 2020: Deciphering the scientific literature on SDG interactions: A review and reading guide. *Sci. Total Environ.*, **728**, 138405, doi:10.1016/j.scitotenv.2020.138405.

Benveniste, H., O. Boucher, C. Guivarch, H. Le Treut, and P. Criqui, 2018: Impacts of nationally determined contributions on 2030 global greenhouse gas emissions: uncertainty analysis and distribution of emissions. *Environ. Res. Lett.*, **13(1)**, 14022, doi:10.1088/1748-9326/aaa0b9.

Benveniste, H., J. C. Cuaresma, M. Gidden, and R. Muttarak, 2021: Tracing international migration in projections of income and inequality across the Shared Socioeconomic Pathways. *Clim. Change*, **166(3)**, 39, doi:10.1007/s10584-021-03133-w.

Bergek, A., S. Jacobsson, and B.A. Sandén, 2008: 'Legitimation' and 'development of positive externalities': two key processes in the formation phase of technological innovation systems. *Technol. Anal. Strateg. Manag.*, **20(5)**, 575–592, doi:10.1080/09537320802292768.

Berger, A. et al., 2017: How much can nuclear energy do about global warming? *Int. J. Glob. Energy Issues*, **40(1/2)**, doi:10.1504/IJGEI.2017.080766.

Berthe, A. and L. Elie, 2015: Mechanisms explaining the impact of economic inequality on environmental deterioration. *Ecol. Econ.*, **116**, 191–200, doi:10.1016/j.ecolecon.2015.04.026.

Bertram, C. et al., 2015a: Carbon lock-in through capital stock inertia associated with weak near-term climate policies. *Technol. Forecast. Soc. 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. *Nat. Clim. Change*, **5(3)**, 235–239, doi:10.1038/nclimate2514.

Bertram, C. et al., 2018: Targeted policies can compensate most of the increased sustainability risks in 1.5°C mitigation scenarios. *Environ. Res. Lett.*, **13(6)**, doi:10.1088/1748-9326/aac3ec.

Bertram, C. et al., 2021: Energy system developments and investments in the decisive decade for the Paris Agreement goals. *Environ. Res. Lett.*, **16(7)**, 74020, doi:10.1088/1748-9326/ac09ae.

Bezerra, P. et al., 2021: Impacts of a warmer world on space cooling demand in Brazilian households. *Energy Build.*, **234**, 110696, doi:https://doi.org/10.1016/j.enbuild.2020.110696.

Bibas, R., A. Méjean, and M. Hamdi-Cherif, 2015: Energy efficiency policies and the timing of action: An assessment of climate mitigation costs. *Technol. Forecast. Soc. Change*, **90(PA)**, 137–152, doi:10.1016/j.techfore.2014.05.003.

Bijl, D.L. et al., 2018: A Global Analysis of Future Water Deficit Based On Different Allocation Mechanisms. *Water Resour. Res.*, **54(8)**, 5803–5824, doi:10.1029/2017WR021688.

Bindoff, N.L., W.W.L. Cheung, J.G. Kairo, J. Arístegui, V.A. Guinder, R. Hallberg, N. Hilmi, N. Jiao, M.S. Karim, L. Levin, S. O'Donoghue, S.R. Purca Cuicapusa, B. Rinkevich, T. Suga, A. Tagliabue, and P. Williamson, 2019: Changing Ocean, Marine Ecosystems, and Dependent Communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 447–587. https://doi.org/10.1017/9781009157964.007.

Bistline, J., M. Budolfson, and B. Francis, 2020: Deepening transparency about value-laden assumptions in energy and environmental modelling: improving best practices for both modellers and non-modellers. *Clim. Policy*, **21(1)** , 1–15, doi:10.1080/14693062.2020.1781048.

Bistline, J.E.T. and G.J. Blanford, 2021: Impact of carbon dioxide removal technologies on deep decarbonization of the electric power sector. *Nat. Commun.*, **12(1)**, 3732, doi:10.1038/s41467-021-23554-6.

Blanford, G.J., E. Kriegler, and M. Tavoni, 2014: Harmonization vs. fragmentation: Overview of climate policy scenarios in EMF27. *Clim. Change*, **123(3–4)**, 383–396, doi:10.1007/s10584-013-0951-9.

Böhringer, C., E.J. Balistreri, and T.F. Rutherford, 2012: The role of border carbon adjustment in unilateral climate policy: Overview of an Energy Modeling Forum study (EMF 29). *Energy Econ.*, **34**, S97–S110, doi: 10.1016/j.eneco.2012.10.003.

Böhringer, C., K.E. Rosendahl, and H.B. Storrøsten, 2017: Robust policies to mitigate carbon leakage. *J. Public Econ.*, **149**, 35–46, doi.org/10.1016/j.jpubeco.2017.03.006.

Böhringer, C., S. Peterson, T.F. Rutherford, J. Schneider, and M. Winkler, 2021: Climate policies after Paris: Pledge, Trade and Recycle: Insights from the 36th Energy Modeling Forum Study (EMF36). *Energy Econ.*, **103**, 105471, doi.org/10.1016/j.eneco.2021.105471.

Bonsch, M. et al., 2016: 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., C. Carraro, and M. Tavoni, 2009: Climate change mitigation strategies in fast-growing countries: The benefits of early action. *Energy Econ.*, **31(sup2)**, S144–S151, doi:10.1016/j.eneco.2009.06.011.

Bosetti, V., C. Carraro, R. Duval, and M. Tavoni, 2011: What should we expect from innovation? A model-based assessment of the environmental and mitigation cost implications of climate-related R&D. *Energy Econ.*, **33(6)**, 1313–1320, doi:10.1016/j.eneco.2011.02.010.

Bosetti, V. et al., 2015: Sensitivity to energy technology costs: A multi-model comparison analysis. *Energy Policy*, **80**, 244–263, doi.org/10.1016/j.enpol.2014.12.012.

Boucher, O., J.A. Lowe, and C.D. Jones, 2009: Implications of delayed actions in addressing carbon dioxide emission reduction in the context of geo-engineering. *Clim. Change*, **92(3–4)**, 261–273, doi:10.1007/s10584-008-9489-7.

Bowen, A., K. Kuralbayeva, and E.L. Tipoe, 2018: Characterising green employment: {The} impacts of 'greening' on workforce composition. *Energy Econ.*, **72**, 263–275, doi:10.1016/j.eneco.2018.03.015.

Bowles, N., S. Alexander, and M. Hadjikakou, 2019: The livestock sector and planetary boundaries: A 'limits to growth' perspective with dietary implications. *Ecol. Econ.*, **160** (January), 128–136, doi:10.1016/j.ecolecon.2019.01.033.

Boysen, L.R., W. Lucht, D. Gerten, and V. Heck, 2016: Impacts devalue the potential of large-scale terrestrial CO2 removal through biomass plantations. *Environ. Res. Lett.*, **11(9)**, 1–10, doi:10.1088/1748-9326/11/9/095010.

Boysen, L.R. et al., 2017: The limits to global-warming mitigation by terrestrial carbon removal. *Earth's Future*, **5(5)**, 463–474, doi:10.1002/2016EF000469.

BP, 2021: *Statistical Review of World Energy 2021.* Statistical Review of World Energy, London, UK, 70pp. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf.

Brandi, C., 2015: Safeguarding the earth system as a priority for sustainable development and global ethics: The need for an earth system SDG. *J. Glob. Ethics*, **11(1)**, 32–36, doi:10.1080/17449626.2015.1006791.

Breyer, C. and M. Jefferson, 2020: Use and Abuse of Energy and Climate Scenarios—A Week of Controversy on Scenarios. *Econ. Energy Environ. Policy*, **9**, doi:10.5547/2160-5890.9.1.mjef.

Brockway, P.E., S. Sorrell, G. Semieniuk, M.K. Heun, and V. Court, 2021: Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications. *Renew. Sustain. Energy Rev.*, **141** (December 2020), 110781, doi:10.1016/j.rser.2021.110781.

Brook, B.W., T. Blees, T.M.L. Wigley, and S. Hong, 2018: Silver Buckshot or Bullet: Is a Future 'Energy Mix' Necessary? *Sustainability*, **10(2)**, doi:10.3390/su10020302.

Brown, C., P. Alexander, A. Arneth, I. Holman, and M. Rounsevell, 2019: Achievement of Paris climate goals unlikely due to time lags in the land system. *Nat. Clim. Change*, **9(3)**, 203–208, doi:10.1038/s41558-019-0400-5.

Brown, P.T. and H. Saunders, 2020: Approximate calculations of the net economic impact of global warming mitigation targets under heightened damage estimates. *PLoS One*, **15(10)**, e0239520, doi:10.1371/journal.pone.0239520.

Brown, P.T., J. Moreno-Cruz, and K. Caldeira, 2020: Break-even year: a concept for understanding intergenerational trade-offs in climate change mitigation policy. *Environ. Res. Commun.*, **2(9)**, 95002, doi:10.1088/2515-7620/abb413.

Brown, S., S. Hanson, and R. Nicholls, 2014: Implications of sea-level rise and extreme events around Europe: A review of coastal energy infrastructure. *Clim. Change*, **122**, doi:10.1007/s10584-013-0996-9.

Brutschin, E. et al., 2021: A multidimensional feasibility evaluation of low-carbon scenarios. *Environ. Res. Lett.*, **16(6)**, 64069, doi:10.1088/1748-9326/abf0ce.

Budolfson, M., F. Dennig, M. Fleurbaey, A. Siebert, and R.H. Socolow, 2017: The comparative importance for optimal climate policy of discounting, inequalities and catastrophes. *Clim. Change*, **145(3–4)**, 481–494, doi:10.1007/s10584-017-2094-x.

Budolfson, M.B. et al., 2021: Utilitarian benchmarks for emissions and pledges promote equity, climate and development. *Nat. Clim. Change*, **11(10)**, 827–833, doi:10.1038/s41558-021-01130-6.

Burgess, M.G., J. Ritchie, J. Shapland, and R. Pielke, 2020: IPCC baseline scenarios have over-projected CO_2 emissions and economic growth. *Environ. Res. Lett.*, **16(1)**, doi:10.1088/1748-9326/abcdd2.

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.

Burrows, M.T. et al., 2019: Ocean community warming responses explained by thermal affinities and temperature gradients. *Nat. Clim. Change*, **9(12)**, 959–963, doi:10.1038/s41558-019-0631-5.

Butnar, I. et al., 2020: A deep dive into the modelling assumptions for biomass with carbon capture and storage (BECCS): A transparency exercise. *Environ. Res. Lett.*, **15(8)**, doi:10.1088/1748-9326/ab5c3e.

Byers, E. et al., 2018: Global exposure and vulnerability to multi-sector development and climate change hotspots. *Environ. Res. Lett.*, **13(5)**, 055012, doi:10.1088/1748-9326/aabf45.

Cai, Y. and T.S. Lontzek, 2019: The Social Cost of Carbon with Economic and Climate Risks. *J. Polit. Econ.*, **127(6)**, 2684–2734, doi:10.1086/701890.

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. *Proc. Natl. Acad. Sci.*, **112(15)**, 4606–4611, doi:10.1073/pnas.1503890112.

Cai, Y., T.M. Lenton, and T.S. Lontzek, 2016: Risk of multiple interacting tipping points should encourage rapid CO_2 emission reduction. *Nat. Clim. Change*, **6(5)**, 520–525, doi:10.1038/nclimate2964.

Cain, M. et al., 2019: Improved calculation of warming-equivalent emissions for short-lived climate pollutants. *npj Clim. Atmos. Sci.*, **2(1)**, doi:10.1038/s41612-019-0086-4.

Caldecott, B., 2017: Introduction to special issue: stranded assets and the environment. *J. Sustain. Financ. Invest.*, **7(1)**, 1–13, doi:10.1080/20430795.2016.1266748.

Calvin, K. et al., 2013: Implications of simultaneously mitigating and adapting to climate change: Initial experiments using GCAM. *Clim. Change*, **117(3)**, 545–560, doi:10.1007/s10584-012-0650-y.

Calvin, K. et al., 2014a: EU 20-20-20 energy policy as a model for global climate mitigation. *Clim. Policy*, **14(5)**, 581–598, doi:10.1080/14693062.2013.879794.

Calvin, K. et al., 2014b: Trade-offs of different land and bioenergy policies on the path to achieving climate targets. *Clim. Change*, **123(3–4)**, 691–704, doi:10.1007/s10584-013-0897-y.

Calvin, K. et al., 2021: Bioenergy for climate change mitigation: Scale and sustainability. *GCB Bioenergy*, **13(9)**, 1346–1371, doi.org/10.1111/gcbb.12863.

Calvin, K.V., R. Beach, A. Gurgel, M. Labriet, and A.M. Loboguerrero Rodriguez, 2014c: Agriculture, forestry, and other land-use emissions in Latin America. *Energy Econ.*, **56**, 615–624, doi:10.1016/j.eneco.2015.03.020.

Cameron, C. et al., 2016: Policy trade-offs between climate mitigation and clean cook-stove access in South Asia. *Nat. Energy*, **1(1)**, 1–5, doi:10.1038/nenergy.2015.10.

Canadell, J.G. and P.M.S. Monteiro, 2019: Global Carbon and other Biogeochemical Cycles and Feedbacks. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (in press).

Carattini, S., S. Kallbekken, and A. Orlov, 2019: How to win public support for a global carbon tax. *Nature*, **565**, 289–291, doi: 10.1038/d41586-019-00124-x.

Carton, W., 2019: Carbon Unicorns and Fossil Futures: Whose Emissions Reduction Pathways Is the IPCC Performing? In: *Has It Come to This? The Promises and Perils of Geoengineering on the Brink?* [J.P. Sapinski, Buck, H.J., and Malm A. (eds.)]. Rutgers University Press, Ithaca, NY, pp. 34–49, doi: 10.36019/9781978809390-003.

Chakravarty, S. and M. Tavoni, 2013: Energy poverty alleviation and climate change mitigation: Is there a trade off? *Energy Econ.*, **40**, S67–S73, doi:10.1016/j.eneco.2013.09.022.

Chang, K.M. et al., 2017: Ancillary health effects of climate mitigation scenarios as drivers of policy uptake: a review of air quality, transportation and diet co-benefits modeling studies. *Environ. Res. Lett.*, **12(11)**, 113001, doi:10.1088/1748-9326/aa8f7b.

Chateau, J. and A. Saint-Martin, 2013: Economic and employment impacts of climate change mitigation policies in {OECD}: {A} general-

3

equilibrium perspective. *Int. Econ.*, **135–136**, 79–103, doi:10.1016/j.inteco.2013.08.001.

Chaturvedi, V. et al., 2013a: *Climate Policy Implications for Agricultural Water Demand*. Pacific Northwest National Laboratory (PNNL), 16 pp. Available at: http://www.globalchange.umd.edu/wp-content/uploads/projects/PNNL-22356.pdf.

Chaturvedi, V. et al., 2013b: Climate mitigation policy implications for global irrigation water demand. *Mitig. Adapt. Strateg. Glob. Change*, **20(3)**, 389–407, doi:10.1007/s11027-013-9497-4.

Chen, C. and M. Tavoni, 2013: Direct air capture of CO_2 and climate stabilization: A model based assessment. *Clim. Change*, **118(1)**, 59–72, doi:10.1007/s10584-013-0714-7.

Cherp, A., V. Vinichenko, J. Jewell, E. Brutschin, and B. Sovacool, 2018: Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework. *Energy Res. Soc. Sci.*, **37** (January 2017), 175–190, doi:10.1016/j.erss.2017.09.015.

Cherp, A., V. Vinichenko, J. Tosun, J.A. Gordon, and J. Jewell, 2021: National growth dynamics of wind and solar power compared to the growth required for global climate targets. *Nat. Energy*, **6(7)**, 742–754, doi:10.1038/s41560-021-00863-0.

Cherubini, F., R.M. Bright, and A.H. Strømman, 2013: Erratum: Global climate impacts of forest bioenergy: What, when and how to measure? *Environ. Res. Lett.*, **8(2)**, doi:10.1088/1748-9326/8/2/029503.

Christensen, P., K. Gillingham, and W. Nordhaus, 2018: Uncertainty in forecasts of long-run economic growth. *Proc. Natl. Acad. Sci.*, **115(21)**, 5409–5414, doi:10.1073/pnas.1713628115.

Clarke, L. et al., 2009: International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Econ.*, **31(Sup2),** S64–S81, doi:10.1016/j.eneco.2009.10.013.

Clarke, L. et al., 2018: Effects of long-term climate change on global building energy expenditures. *Energy Econ.*, **72**, 667–677, doi:10.1016/j.eneco.2018.01.003.

Clarke L., K. Jiang, K. Akimoto, M. Babiker, G. Blanford, K. Fisher-Vanden, J.-C. Hourcade, V. Krey, E. Kriegler, A. Löschel, D. McCollum, S. Paltsev, S. Rose, P.R. Shukla, M. Tavoni, B.C.C. van der Zwaan, and D.P. van Vuuren, 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, UK, and New York, NY, USA, pp. 413–510.

Cointe, B., C. Cassen, and A. Nadaï, 2019: Organising policy-relevant knowledge for climate action: Integrated assessment modelling, the IPCC, and the emergence of a collective expertise on socioeconomic emission scenarios. *Sci. Technol. Stud.*, **32(4)**, 36–57, doi:10.23987/sts.65031.

Colelli, F. Pietro, and E. De Cian, 2020: Cooling demand in integrated assessment models: a methodological review. *Environ. Res. Lett.*, **15(11)**, 113005, doi:10.1088/1748-9326/abb90a.

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner, 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, UK, 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. *Environ. Res. Lett.*, **13(5)**, 54003, doi:10.1088/1748-9326/aab89c.

Conijn, J.G., P.S. Bindraban, J.J. Schröder, and R.E.E. Jongschaap, 2018: Can our global food system meet food demand within planetary boundaries? *Agric. Ecosyst. Environ.*, **251** (December 2016), 244–256, doi:10.1016/j.agee.2017.06.001.

Conway, D., C. Dalin, W.A. Landman, and T.J. Osborn, 2017: Hydropower plans in eastern and southern Africa increase risk of concurrent climate-related electricity supply disruption. *Nat. Energy*, **2(12)**, 946–953, doi:10.1038/s41560-017-0037-4.

Cosbey, A., S. Droege, C. Fischer, and C. Munnings, 2019: Developing Guidance for Implementing Border Carbon Adjustments: Lessons, Cautions, and Research Needs from the Literature. *Rev. Environ. Econ. Policy*, **13(1)**, 3–22, doi:10.1093/reep/rey020.

Cowie, A.L. et al., 2021: Applying a science-based systems perspective to dispel misconceptions about climate effects of forest bioenergy. *GCB Bioenergy*, **13(8)**, 1210–1231, doi:10.1111/gcbb.12844.

Crippa, M., E. et al., 2021: *GHG emissions of all world countries - 2021 Report*, Publications Office of the European Union, Luxembourg, doi:10.2760/173513.

Creutzig, F. et al., 2016: Beyond Technology: Demand-Side Solutions for Climate Change Mitigation. *Annu. Rev. Environ. Resour.*, **41(1)**, 173–198, doi:10.1146/annurev-environ-110615-085428.

Creutzig, F. et al., 2017: The underestimated potential of solar energy to mitigate climate change. *Nature Energy*, **2**, 17140, doi: 10.1038/nenergy.2017.140.

Creutzig, F. et al., 2018: Towards demand-side solutions for mitigating climate change. *Nat. Clim. Change*, **8(4)**, 268–271, doi:10.1038/s41558-018-0121-1.

Creutzig, F. et al., 2019: The mutual dependence of negative emission technologies and energy systems. *Energy Environ. Sci.*, **12(6)**, 1805–1817, doi:10.1039/c8ee03682a.

Cronin, J., G. Anandarajah, and O. Dessens, 2018a: Climate change impacts on the energy system: a review of trends and gaps. *Clim. Change*, **151(2)**, 79–93, doi:10.1007/s10584-018-2265-4.

Cronin, J.A., D. Fullerton, and S. Sexton, 2018b: Vertical and Horizontal Redistributions from a Carbon Tax and Rebate. *J. Assoc. Environ. Resour. Econ.*, **6(Sup1)**, S169–S208, doi:10.1086/701191.

Cui, R.Y. et al., 2018: Regional responses to future, demand-driven water scarcity. *Environ. Res. Lett.*, **13(9)**, 94006, doi:10.1088/1748-9326/aad8f7.

Cui, R.Y. et al., 2019: Quantifying operational lifetimes for coal power plants under the Paris goals. *Nat. Commun.*, **10(1)**, doi:10.1038/s41467-019-12618-3.

D'Alessandro, S., A. Cieplinski, T. Distefano, and K. Dittmer, 2020: Feasible alternatives to green growth. *Nat. Sustain.*, **3** , 329–335, doi:10.1038/s41893-020-0484-y.

D'Amour, C.B. et al., 2017: Future urban land expansion and implications for global croplands. *Proc. Natl. Acad. Sci.*, **114(34)**, 8939–8944, doi:10.1073/pnas.1606036114.

Dagnachew, A.G. et al., 2020: Integrating energy access, efficiency and renewable energy policies in Sub-Saharan Africa: a model-based analysis. *Environ. Res. Lett.*, **15(12)** , doi:10.1088/1748-9326/abcbb9.

Daioglou, V., B.J. van Ruijven, and D.P. van Vuuren, 2012: Model projections for household energy use in developing countries. *Energy*, **37(1)**, 601–615, doi:10.1016/j.energy.2011.10.044.

Daioglou, V. et al., 2014: Energy demand and emissions of the non-energy sector. *Energy Environ. Sci.*, **7(2)**, 482–498, doi:10.1039/c3ee42667j.

Daioglou, V., J.C. Doelman, B. Wicke, A. Faaij, and D.P. van Vuuren, 2019: Integrated assessment of biomass supply and demand in climate change mitigation scenarios. *Glob. Environ. Change*, **54**, 88–101, doi:10.1016/j.gloenvcha.2018.11.012.

Daioglou, V. et al., 2020: Bioenergy technologies in long-run climate change mitigation: results from the EMF-33 study. *Clim. Change*, **163(3)**, 1603–1620, doi:10.1007/s10584-020-02799-y.

Davis, S.J. et al., 2018: Net-zero emissions energy systems. *Science*, **360(6396)**, doi:10.1126/science.aas9793.

Day, E., S. Fankhauser, N. Kingsmill, H. Costa, and A. Mavrogianni, 2019: Upholding labour productivity under climate change: an assessment of adaptation options. *Clim. Policy*, **19(3)**, 367–385, doi:10.1080/14693062.2018.1517640.

De Cian, E. et al., 2020: Actors, decision-making, and institutions in quantitative system modelling. *Technol. Forecast. Soc. Change*,), **151** 1–10, doi:10.1016/j.techfore.2018.10.004.

de Coninck, H. et al., 2018: Strengthening and Implementing the Global Response Supplementary Material. In: *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* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 313–443.

DeAngelo, J. et al., 2021: Energy systems in scenarios at net-zero CO_2 emissions. *Nat. Commun.*, **12(1)**, 6096, doi:10.1038/s41467-021-26356-y.

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. *Clim. Change*, **99(1)**, 313–320, doi:10.1007/s10584-010-9798-5.

den Elzen, M.G.J. et al., 2015: *Enhanced policy scenarios for major emitting countries. Analysis of current and planned policies, and selected enhanced mitigation measures*. PBL Netherlands Environmental Assessment Agency, NewClimate Institute, International Institute for Applied Systems Analysis and Ecofys, Bilthoven, the Netherlands.

Deng, H.-M., Q.-M. Liang, L.-J. Liu, and L.D. Anadon, 2017: Co-benefits of greenhouse gas mitigation: a review and classification by type, mitigation sector, and geography. *Environ. Res. Lett.*, **12(12)**, 123001, doi:10.1088/1748-9326/aa98d2.

Dennig, F., M.B. Budolfson, M. Fleurbaey, A. Siebert, and R.H. Socolow, 2015: Inequality, climate impacts on the future poor, and carbon prices. *Proc. Natl. Acad. Sci.*, **112 (52)**, 15827–32, doi:10.1073/pnas.1513967112.

Dessens, O., G. Anandarajah, and A. Gambhir, 2016: Limiting global warming to 2°C: What do the latest mitigation studies tell us about costs, technologies and other impacts? *Energy Strateg. Rev.*, **13–14**, 67–76, doi:https://doi.org/10.1016/j.esr.2016.08.004.

Diaz, D., and F. Moore, 2017: Quantifying the economic risks of climate change. *Nat. Clim. Change*, **7(11)**, 774–782, doi:10.1038/nclimate3411.

Dietz, S. and N. Stern, 2015: Endogenous Growth, Convexity of Damage and Climate Risk: How Nordhaus' Framework Supports Deep Cuts in Carbon Emissions. *Econ. J.*, **125(583)**, 574–620, doi:10.1111/ecoj.12188.

Dietz, T., E. Ostrom, and P.C. Stern, 2003: The Struggle to Govern the Commons. *Science*, **302(5652)**, 1907–1912, doi:10.1126/science.1091015.

Do, H.X. et al., 2020: Historical and future changes in global flood magnitude - evidence from a model-observation investigation. *Hydrol. Earth Syst. Sci.*, **24(3)**, 1543–1564, doi:10.5194/hess-24-1543-2020.

Doelman, J.C., E. Stehfest, A. Tabeau, and H. van Meijl, 2019: Making the Paris agreement climate targets consistent with food security objectives. *Glob. Food Sec.*, **23**, 93–103, doi:https://doi.org/10.1016/j.gfs.2019.04.003.

Dolphin, G., M.G. Pollitt, and D.M. Newbery, 2020: The political economy of carbon pricing: a panel analysis. *Oxf. Econ. Pap.*, **72(2)**, 472–500.

Dominish, E., C. Briggs, S. Teske, and F. Mey, 2019: Just transition: Employment projections for the 2.0°C and 1.5°C scenarios. In: *Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5°C and +2°C* [Sven T. Springer International Publishing, Cham, pp. 413–435, doi:10.1007/978-3-030-05843-2_10.

Dorband, I.I., M. Jakob, M. Kalkuhl, and J.C. Steckel, 2019: Poverty and distributional effects of carbon pricing in low- and middle-income countries – A global comparative analysis. *World Dev.*, **115**, 246–257, doi:10.1016/j.worlddev.2018.11.015.

Dottori, F. et al., 2018: Increased human and economic losses from river flooding with anthropogenic warming. *Nat. Clim. Change*, **8(9)**, 781–786, doi:10.1038/s41558-018-0257-z.

Douenne, T., 2020: The Vertical and Horizontal Distributive Effects of Energy Taxes: A Case Study of a French Policy. *Energy J.*, **41(3)**, 231–254, doi:10.5547/01956574.41.3.tdou.

Drouet, L., V. Bosetti, and M. Tavoni, 2015: Selection of climate policies under the uncertainties in the Fifth Assessment Report of the IPCC. *Nat. Clim. Change*, **5(10)**, 937–943, doi:10.1038/nclimate2721.

Drouet, L. et al., 2021: Net zero emission pathways reduce the physical and economic risks of climate change. *Nat. Clim. Change*, **11**, 1070–1076, doi:10.1038/s41558-021-01218-z.

Drupp, M.A. and M.C. Hänsel, 2021: Relative Prices and Climate Policy: How the Scarcity of Nonmarket Goods Drives Policy Evaluation. *Am. Econ. J. Econ. Policy*, **13(1)**, 168–201, doi:10.1257/pol.20180760.

Dwivedi, P., M. Khanna, R. Bailis, and A. Ghilardi, 2014: Potential greenhouse gas benefits of transatlantic wood pellet trade. *Environ. Res. Lett.*, **9(2)**, 24007, doi:10.1088/1748-9326/9/2/024007.

Edelenbosch, O., D. Rovelli, A. Levesque, and E. Al., 2021: Long term, cross country effects of buildings insulation policies. *Technological Forecasting and Social Change*, **170**, 120887, doi: 10.1016/j.techfore.2021.120887.

Edelenbosch, O.Y., D.P. van Vuuren, K. Blok, K. Calvin, and S. Fujimori, 2020: Mitigating energy demand sector emissions: The integrated modelling perspective. *Appl. Energy*, **261** (December 2019), 114347, doi:10.1016/j.apenergy.2019.114347.

Edelenbosch, O.Y. et al., 2017a: Decomposing passenger transport futures: Comparing results of global integrated assessment models. *Transp. Res. Part D Transp. Environ.*, **55**, 281–293, doi:10.1016/j.trd.2016.07.003.

Edelenbosch, O.Y. et al., 2017b: Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models. *Energy*, **122**, 701–710, doi.org/10.1016/j.energy.2017.01.017.

Edmonds, J. et al., 2013: Can radiative forcing be limited to 2.6 Wm^{-2} without negative emissions from bioenergy and CO_2 capture and storage? *Clim. Change*, **118(1)**, 29–43, doi:10.1007/s10584-012-0678-z.

Edmonds, J. et al., 2021: How Much Could Article 6 Enhance Nationally Determined Contribution Ambition Toward Paris Agreement Goals Through Economic Efficiency? *Clim. Change Econ.*, **12(02)**, 2150007, doi:10.1142/S201000782150007X.

Emmerling, J. and M. Tavoni, 2018a: Exploration of the interactions between mitigation and solar radiation management in cooperative and non-cooperative international governance settings. *Glob. Environ. Change*, **53**, 244–251, doi:10.1016/j.gloenvcha.2018.10.006.

Emmerling, J. and M. Tavoni, 2018b: Climate Engineering and Abatement: A 'flat' Relationship Under Uncertainty. *Environ. Resour. Econ.*, **69(2)**, 395–415, doi:10.1007/s10640-016-0104-5.

Emmerling, J. and M. Tavoni, 2021: Representing inequalities in integrated assessment modeling of climate change. *One Earth*, **4(2)**, 177–180, doi.org/10.1016/j.oneear.2021.01.013.

Emmerling, J. et al., 2019: The role of the discount rate for emission pathways and negative emissions. *Environ. Res. Lett.*, **14(10)**, 104008, doi:10.1088/1748-9326/ab3cc9.

Emodi, N.V., T. Chaiechi, and A.B.M. R. Alam Beg, 2019: A techno-economic and environmental assessment of long-term energy policies and climate variability impact on the energy system. *Energy Policy*, **128** (June 2018), 329–346, doi:10.1016/j.enpol.2019.01.011.

Erb, K.-H. et al., 2016: Exploring the biophysical option space for feeding the world without deforestation. *Nat. Commun.*, **7(1)**, 11382, doi:10.1038/ncomms11382.

Eyer, J. and C.J. Wichman, 2018: Does water scarcity shift the electricity generation mix toward fossil fuels? Empirical evidence from the United States. *J. Environ. Econ. Manage.*, **87**, 224–241, doi:10.1016/j.jeem.2017.07.002.

Fajardy, M. and N. Mac Dowell, 2020: Recognizing the Value of Collaboration in Delivering Carbon Dioxide Removal. *One Earth*, **3(2)**, 214–225, doi.org/10.1016/j.oneear.2020.07.014.

Falchetta, G. and M.N. Mistry, 2021: The role of residential air circulation and cooling demand for electrification planning: Implications of climate change in sub-Saharan Africa. *Energy Econ.*, **99**, 105307, doi.org/10.1016/j.eneco.2021.105307.

Fankhaeser, S., F. Sehlleier, and N. Stern, 2008: Climate change, innovation and jobs. *Clim. Policy*, **8(4)**, 421–429, doi: 10.3763/cpol.2008.0513.

FAO, 2018: *The future of food and agriculture – Alternative pathways to 2050*. Global Perspectives Studies. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 224 pp. http://www.fao.org/global-perspectives-studies/resources/detail/en/c/1157082/.

FAO, IFAD, UNICEF, WFP and WHO, 2017: *The State of Food Security and Nutrition in the World 2017 Builiding Resillience for Peace and Food Security*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 132 pp.

Farfan, J. and C. Breyer, 2017: Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator. *J. Clean. Prod.*, **141**, 370–384, doi:10.1016/j.jclepro.2016.09.068.

Farquharson, D., P. Jaramillo, and C. Samaras, 2018: Sustainability implications of electricity outages in sub-Saharan Africa. *Nat. Sustain.*, **1(10)**, 589–597, doi:10.1038/s41893-018-0151-8.

Fattouh, B., R. Poudineh, and R. West, 2019: The rise of renewables and energy transition: what adaptation strategy exists for oil companies and oil-exporting countries? *Energy Transitions*, **3(1)**, 45–58, doi:10.1007/s41825-019-00013-x.

Favero, A., A. Daigneault, and B. Sohngen, 2020: Forests: Carbon sequestration, biomass energy, or both? *Sci. Adv.*, **6(13)**, eaay6792, doi:10.1126/sciadv.aay6792.

Fawcett, A.A. et al., 2015: Can Paris pledges avert severe climate change? *Science*, **350(6265)**, 1168–1169, doi:10.1126/science.aad5761.

Fekete, H. et al., 2015: *Impacts of good practice policies on regional and global greenhouse gas emissions*. NewClimate Institute, PBL Netherlands Environmental Assessment Agency and International Institute for Applied Systems Analysis, Cologne, Germany, 81 pp. https://newclimate.org/wp-content/uploads/2015/07/task2c_goodpracticeanalysis_july_2015.pdf.

Fekete, H. et al., 2021: A review of successful climate change mitigation policies in major emitting economies and the potential of global replication. *Renew. Sustain. Energy Rev.*, **137**, 110602, doi.org/10.1016/j.rser.2020.110602.

Fisch-Romito, V. and C. Guivarch, 2019: Transportation infrastructures in a low carbon world: An evaluation of investment needs and their determinants. *Transp. Res. Part D Transp. Environ.*, **72** (May), 203–219, doi:10.1016/j.trd.2019.04.014.

Fisch-Romito, V., C. Guivarch, F. Creutzig, J.C. Minx, and M.W. Callaghan, 2021: Systematic map of the literature on carbon lock-in induced by long-lived capital. *Environ. Res. Lett.*, **16(5)** , doi:10.1088/1748-9326/aba660.

Fischer, C. and R.G. Newell, 2008: Environmental and technology policies for climate mitigation. *J. Environ. Econ. Manage.*, **55(2)**, 142–162, doi:10.1016/j.jeem.2007.11.001.

Fischetti, M., 2018: A Good Life for All. *Sci. Am.*, **318(6)**, 84, doi:10.1038/scientificamerican0618-84.

Fleurbaey, M. et al., 2019: The Social Cost of Carbon: Valuing Inequality, Risk, and Population for Climate Policy. *Monist*, **102(1)**, 84–109, doi:10.1093/monist/ony023.

Flörke, M., I. Bärlund, M.T. van Vliet, A.F. Bouwman, and Y. Wada, 2019: Analysing trade-offs between SDGs related to water quality using salinity as a marker. *Curr. Opin. Environ. Sustain.*, **36**, 96–104, doi:10.1016/j.cosust.2018.10.005.

Fofrich, R. et al., 2020: Early retirement of power plants in climate mitigation scenarios. *Environ. Res. Lett.*, **15(9)**, 94064, doi:10.1088/1748-9326/ab96d3.

Foley, J.A. et al., 2011: Solutions for a cultivated planet. *Nature*, **478(7369)**, 337–342, doi:10.1038/nature10452.

Forster, P.M. et al., 2020: Current and future global climate impacts resulting from COVID-19. *Nat. Clim. Change*, **10(10)**, 913–919, doi:10.1038/s41558-020-0883-0.

Foxon, T.J., G.P. Hammond, and P.J.G. Pearson, 2010: Developing transition pathways for a low carbon electricity system in the UK. *Technol. Forecast. Soc. Change*, **77(8)**, 1203–1213, doi:10.1016/j.techfore.2010.04.002.

Franks, M., K. Lessmann, M. Jakob, J.C. Steckel, and O. Edenhofer, 2018: Mobilizing domestic resources for the Agenda 2030 via carbon pricing. *Nat. Sustain.*, **1(7)**, 350–357, doi:10.1038/s41893-018-0083-3.

Freire-González, J., 2018: Environmental taxation and the double dividend hypothesis in CGE modelling literature: A critical review. *J. Policy Model.*, **40(1)**, 194–223, doi:10.1016/j.jpolmod.2017.11.002.

Fremstad, A. and M. Paul, 2019: The Impact of a Carbon Tax on Inequality. *Ecol. Econ.*, **163**, 88–97, doi:10.1016/j.ecolecon.2019.04.016.

Fricko, O. et al., 2016: Energy sector water use implications of a 2°C climate policy. *Environ. Res. Lett.*, **11(3)**, 34011, doi:10.1088/1748-9326/11/3/034011.

Friedlingstein, P. et al., 2020: Global Carbon Budget 2020. *Earth Syst. Sci. Data Discuss.*, **12(4)**, 1–3, doi:10.5194/essd-2020-286.

Fuglestvedt, J. et al., 2018: Implications of possible interpretations of 'greenhouse gas balance' in the Paris Agreement. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, **376(2119)**, 20160445, doi:10.1098/rsta.2016.0445.

Fuhrman, J., H. McJeon, S.C. Doney, W. Shobe, and A.F. Clarens, 2019: From Zero to Hero?: Why Integrated Assessment Modeling of Negative Emissions Technologies Is Hard and How We Can Do Better. *Front. Clim.*, **1** (December), doi:10.3389/fclim.2019.00011.

Fuhrman, J. et al., 2020: Food–energy–water implications of negative emissions technologies in a +1.5°C future. *Nat. Clim. Change*, **10(10)**, 920–927, doi:10.1038/s41558-020-0876-z.

Fuhrman, J. et al., 2021: The Role of Direct Air Capture and Negative Emissions Technologies in the Shared Socioeconomic Pathways towards +1.5°C and +2°C Futures. *Environ. Res. Lett*, **16(11)**.

Fujimori, S., M. Kainuma, T. Masui, T. Hasegawa, and H. Dai, 2014: The effectiveness of energy service demand reduction: A scenario analysis of global climate change mitigation. *Energy Policy*, **75**, 379–391, doi:10.1016/j.enpol.2014.09.015.

Fujimori, S., T. Masui, and Y. Matsuoka, 2015: Gains from emission trading under multiple stabilization targets and technological constraints. *Energy Econ.*, **48**, 306–315, doi:10.1016/j.eneco.2014.12.011.

Fujimori, S. et al., 2016a: Will international emissions trading help achieve the objectives of the Paris Agreement? *Environ. Res. Lett.*, **11(10)**, 104001, doi:10.1088/1748-9326/11/10/104001.

Fujimori, S. et al., 2016b: Implication of Paris Agreement in the context of long-term climate mitigation goals. *Springerplus*, **5(1)**, 1620, doi:10.1186/s40064-016-3235-9.

Fujimori, S., N. Hanasaki, and T. Masui, 2017: Projections of industrial water withdrawal under shared socioeconomic pathways and climate mitigation scenarios. *Sustain. Sci.*, **12(2)**, 275–292, doi:10.1007/s11625-016-0392-2.

Fujimori, S. et al., 2018: Inclusive climate change mitigation and food security policy under 1.5°C climate goal. *Environ. Res. Lett.*, **13(7)**, 74033, doi:10.1088/1748-9326/aad0f7.

Fujimori, S. et al., 2019: A multi-model assessment of food security implications of climate change mitigation. *Nat. Sustain.*, **2(5)**, 386–396, doi:10.1038/s41893-019-0286-2.

Fujimori, S. et al., 2020a: Measuring the sustainable development implications of climate change mitigation. *Environ. Res. Lett.*, **15(8)**, 85004, doi:10.1088/1748-9326/ab9966.

Fujimori, S., T. Hasegawa, and K. Oshiro, 2020b: An assessment of the potential of using carbon tax revenue to tackle poverty. *Environ. Res. Lett.*, **15(11)**, 114063, doi:10.1088/1748-9326/abb55d.

Fullerton, D. and E. Muehlegger, 2019: Who Bears the Economic Burdens of Environmental Regulations? *Rev. Environ. Econ. Policy*, **13(1)**, 62–82, doi:10.1093/reep/rey023.

Fuso Nerini, F. et al., 2018: Mapping synergies and trade-offs between energy and the Sustainable Development Goals. *Nat. Energy*, **3(1)**, 10–15, doi:10.1038/s41560-017-0036-5.

Fuss, S., W.H. Reuter, J. Szolgayová, and M. Obersteiner, 2013: Optimal mitigation strategies with negative emission technologies and carbon sinks under uncertainty. *Clim. Change*, **118(1)**, 73–87, doi:10.1007/s10584-012-0676-1.

Fuss, S. et al., 2014: Betting on negative emissions. *Nat. Clim. Change*, **4(10)**, 850–853, doi:10.1038/nclimate2392.

Fuss, S. et al., 2018: Negative emissions – Part 2: Costs, potentials and side effects. *Environ. Res. Lett.*, **13**, 2–4, doi.org/10.1088/1748-9326/aabf9f.

Fuss, S. et al., 2020: Moving toward Net-Zero Emissions Requires New Alliances for Carbon Dioxide Removal. *One Earth*, **3(2)**, 145–149, doi:10.1016/j.oneear.2020.08.002.

Fyson, C.L., S. Baur, M. Gidden, and C.F. Schleussner, 2020: Fair-share carbon dioxide removal increases major emitter responsibility. *Nat. Clim. Change*, **10(9)**, 836–841, doi:10.1038/s41558-020-0857-2.

Galik, C.S., 2020: A continuing need to revisit BECCS and its potential. *Nat. Clim. Change*, **10(1)**, 2–3, doi:10.1038/s41558-019-0650-2.

Gambhir, A. et al., 2017: Assessing the feasibility of global long-term mitigation scenarios. *Energies*, **10(1)**, doi:10.3390/en10010089.

Gambhir, A., I. Butnar, P.H. Li, P. Smith, and N. Strachan, 2019: A review of criticisms of integrated assessment models and proposed approaches to address these, through the lens of BECCs. *Energies*, **12(9)**, doi:10.3390/en12091747.

Garcia-Casals, X., R. Ferroukhi, and B. Parajuli, 2019: Measuring the socio-economic footprint of the energy transition. *Energy Transitions*, **3(1–2)**, 105–118, doi:10.1007/s41825-019-00018-6.

Garnett, T., 2016: Plating up solutions. *Science*, **353(6305)**, 1202–1204, doi:10.1126/science.aah4765.

Gaupp, F., J. Hall, and S. Dadson, 2015: The role of storage capacity in coping with intra- and inter-annual water variability in large river basins. *Environ. Res. Lett.*, **10(12)**, doi:10.1088/1748-9326/10/12/125001.

Gazzotti, P. et al., 2021: Persistent inequality in economically optimal climate policies. *Nat. Commun.*, **12(1)**, 3421, doi:10.1038/s41467-021-23613-y.

Geden, O., 2015: Policy: Climate advisers must maintain integrity. *Nature*, **521(7550)**, 27–28, doi:10.1038/521027a.

Geden, O., 2016: The Paris Agreement and the inherent inconsistency of climate policymaking. *WIREs Clim. Change*, **7(6)**, 790–797, doi.org/10.1002/wcc.427.

Geden, O. and A. Löschel, 2017: Define limits for temperature overshoot targets. *Nat. Geosciences*, **10(12)**, 881–882, doi:10.1038/s41561-017-0026-z.

Geels, D.I.F. W., and I.F.W. Geels, 2005: The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930). *Technol. Anal. Strateg. Manag.*, **17(4)**, 445–476, doi:10.1080/09537320500357319.

Geels, F.W., 2018: Disruption and low-carbon system transformation: Progress and new challenges in socio-technical transitions research and the Multi-Level Perspective. *Energy Res. Soc. Sci.*, **37** (October), 224–231, doi:10.1016/j.erss.2017.10.010.

Geels, F.W., F. Berkhout, and D.P. Van Vuuren, 2016a: Bridging analytical approaches for low-carbon transitions. *Nat. Clim. Change*, **6(6)**, 576–583, doi:10.1038/nclimate2980.

Geels, F.W. et al., 2016b: The enactment of socio-technical transition pathways: A reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990–2014). *Res. Policy*, **45(4)**, 896–913, doi:10.1016/j.respol.2016.01.015.

Geels, F.W., A. McMeekin, and B. Pfluger, 2020: Socio-technical scenarios as a methodological tool to explore social and political feasibility in low-carbon transitions: Bridging computer models and the multi-level perspective in UK electricity generation (2010–2050). *Technol. Forecast. Soc. Change*, **151**, doi:10.1016/j.techfore.2018.04.001.

Geiges, A. et al., 2020: Incremental improvements of 2030 targets insufficient to achieve the Paris Agreement goals. *Earth Syst. Dyn. Discuss.*, 1–18, doi:10.5194/esd-2019-54.

Gernaat, D.E.H. J. et al., 2021: Climate change impacts on renewable energy supply. *Nat. Clim. Change*, **11(2)**, 119–125, doi:10.1038/s41558-020-00949-9.

Giannaris, S., C. Bruce, B. Jacobs, W. Srisang, and D. Janowczyk, 2020: Implementing a second generation CCS facility on a coal fired power station – results of a feasibility study to retrofit SaskPower's Shand power station with CCS. *Greenh. Gases Sci. Technol.*, **10(3)**, 506–518, doi.org/10.1002/ghg.1989.

Giannousakis, A. et al., 2021: How uncertainty in technology costs and carbon dioxide removal availability affect climate mitigation pathways. *Energy*, **216**, 119253, doi.org/10.1016/j.energy.2020.119253.

Giarola, S. et al., 2021: Challenges in the harmonisation of global integrated assessment models: A comprehensive methodology to reduce model response heterogeneity. *Sci. Total Environ.*, **783**, 146861, doi.org/10.1016/j.scitotenv.2021.146861.

Gilabert, P., and H. Lawford-Smith, 2012: Political Feasibility: A Conceptual Exploration. *Polit. Stud.*, **60(4)**, 809–825, doi:10.1111/j.1467-9248.2011.00936.x.

Glanemann, N., S.N. Willner, and A. Levermann, 2020: Paris Climate Agreement passes the cost-benefit test. *Nat. Commun.*, **11(1)**, 110, doi:10.1038/s41467-019-13961-1.

González, M.F. and T. Ilyina, 2016: Impacts of artificial ocean alkalinization on the carbon cycle and climate in Earth system simulations. *Geophys. Res. Lett.*, **43(12)**, 6493–6502, doi:10.1002/2016GL068576.

Gosling, S.N., and N.W. Arnell, 2016: A global assessment of the impact of climate change on water scarcity. *Clim. Change*, **134(3)**, 371–385, doi:10.1007/s10584-013-0853-x.

Gota, S., C. Huizenga, K. Peet, N. Medimorec, and S. Bakker, 2019: Decarbonising transport to achieve Paris Agreement targets. *Energy Effic.*, **12(2)**, 363–386, doi:10.1007/s12053-018-9671-3.

Goulder, L.H., and I.W.H. Parry, 2008: Instrument choice in environmental policy. *Rev. Environ. Econ. Policy*, **2(2)**, 152–174, doi: 10.1093/reep/ren005.

Graham, N.T. et al., 2018: Water Sector Assumptions for the Shared Socioeconomic Pathways in an Integrated Modeling Framework. *Water Resour. Res.*, **54(9)**, 6423–6440, doi:10.1029/2018WR023452.

Graham, N.T. et al., 2020: Humans drive future water scarcity changes across all Shared Socioeconomic Pathways. *Environ. Res. Lett.*, **15(1)**, doi:10.1088/1748-9326/ab639b.

Graichen, J., S. Healy, A. Siemons, N. Höhne, and T. Kuramochi, 2017: International Climate Initiatives – A way forward to close the emissions gap? Dessau-Roßlau , ISSN 1862-4359, **28**. https://inis.iaea.org/collection/NCLCollectionStore/_Public/49/072/49072173.pdf.

Grant, N., A. Hawkes, T. Napp, and A. Gambhir, 2020: The appropriate use of reference scenarios in mitigation analysis. *Nat. Clim. Change*, **10(7)**, 605–610, doi:10.1038/s41558-020-0826-9.

Grant, N., A. Hawkes, S. Mittal, and A. Gambhir, 2021: The policy implications of an uncertain carbon dioxide removal potential. *Joule*, **5**, doi:10.1016/j.joule.2021.09.004.

Grassi, G. et al., 2018: Reconciling global-model estimates and country reporting of anthropogenic forest CO_2 sinks. *Nat. Clim. Change*, **8(10)**, 914–920, doi:10.1038/s41558-018-0283-x.

Grassi, G. et al., 2021: Critical adjustment of land mitigation pathways for assessing countries' climate progress. *Nat. Clim. Change*, **11(5)**, 425–434, doi:10.1038/s41558-021-01033-6.

Green, R.F. et al., 2018: Greenhouse gas emissions and water footprints of typical dietary patterns in India. *Sci. Total Environ.*, **643**, 1411–1418, doi.org/10.1016/j.scitotenv.2018.06.258.

Greve, P. et al., 2018: Global assessment of water challenges under uncertainty in water scarcity projections. *Nat. Sustain.*, **1(9)**, 486–494, doi:10.1038/s41893-018-0134-9.

Griscom, B.W. et al., 2017: Natural climate solutions. *Proc. Natl. Acad. Sci.*, **(6)**, 1–6, doi:10.1073/pnas.1710465114.

Grubb, M., C. Wieners, and P. Yang, 2021: Modeling myths: On DICE and dynamic realism in integrated assessment models of climate change mitigation. *WIREs Clim. Change*, **12(3)**, e698, doi.org/10.1002/wcc.698.

Grubler, A. et al., 2018: A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies. *Nat. Energy*, **3(6)**, 515–527, doi:10.1038/s41560-018-0172-6.

Grunewald, N., S. Klasen, I. Martínez-Zarzoso, and C. Muris, 2017: The Trade-off Between Income Inequality and Carbon Dioxide Emissions. *Ecol. Econ.*, **142**, 249–256, doi:10.1016/j.ecolecon.2017.06.034.

Guivarch, C. and A. Pottier, 2018: Climate Damage on Production or on Growth: What Impact on the Social Cost of Carbon? *Environ. Model. Assess.*, **23(2)**, 117–130, doi:10.1007/s10666-017-9572-4.

Guivarch, C., R. Crassous, O. Sassi, and S. Hallegatte, 2011: The costs of climate policies in a second-best world with labour market imperfections. *Clim. Policy*, **11(1)**, 768–788, doi:10.3763/cpol.2009.0012.

Güneralp, B. et al., 2017: Global scenarios of urban density and its impacts on building energy use through 2050. *Proc. Natl. Acad. Sci.*, **114(34)**, 8945 LP–8950, doi:10.1073/pnas.1606035114.

Gütschow, J., M.L. Jeffery, M. Schaeffer, and B. Hare, 2018: Extending Near-Term Emissions Scenarios to Assess Warming Implications of Paris Agreement NDCs. *Earth's Future*, **6(9)**, 1242–1259, doi.org/10.1002/2017EF000781.

Haberl, H. et al., 2020: A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. *Environ. Res. Lett.*, **15(6)**, 65003, doi:10.1088/1748-9326/ab842a.

Hall, C., T.P. Dawson, J.I. Macdiarmid, R.B. Matthews, and P. Smith, 2017: The impact of population growth and climate change on food security in Africa: looking ahead to 2050. *Int. J. Agric. Sustain.*, **15(2)**, 124–135, doi:10.1080/14735903.2017.1293929.

Hallegatte, S., A. Vogt-Schilb, J. Rozenberg, M. Bangalore, and C. Beaudet, 2020: From Poverty to Disaster and Back: a Review of the Literature. *Econ. Disasters Clim. Change*, **4**, 223–247, 1–25, doi: 10.1007/s41885-020-00060-5.

Hamilton, I. et al., 2021: The public health implications of the Paris Agreement: a modelling study. *Lancet Planet. Heal.*, **5(2)**, e74–e83, doi:10.1016/S2542-5196(20)30249-7.

Hanaoka, T. and T. Masui, 2020: Exploring effective short-lived climate pollutant mitigation scenarios by considering synergies and trade-offs of combinations of air pollutant measures and low carbon measures towards the level of the 2°C target in Asia. *Environ. Pollut.*, **261**, 113650, doi:10.1016/j.envpol.2019.113650.

Hanasaki, N. et al., 2013: A global water scarcity assessment under Shared Socio-economic Pathways – Part 2: Water availability and scarcity. *Hydrol. Earth Syst. Sci.*, **17(7)**, 2375–2391, doi:10.5194/hess-17-2393-2013.

Hänsel, M.C. et al., 2020: Climate economics support for the UN climate targets. *Nat. Clim. Change* **10**, , 781–789, doi:10.1038/s41558-020-0833-x.

Hansen, K., C. Breyer, and H. Lund, 2019: Status and perspectives on 100% renewable energy systems. *Energy*, **175**, 471–480, doi.org/10.1016/j.energy.2019.03.092.

Hanssen, S.V. et al., 2020: The climate change mitigation potential of bioenergy with carbon capture and storage. *Nat. Clim. Change*, **10(11)**, 1023–1029, doi:10.1038/s41558-020-0885-y.

Hardt, L. and D.W. O'Neill, 2017: Ecological Macroeconomic Models: Assessing Current Developments. *Ecol. Econ.*, **134**, 198–211, doi:10.1016/j.ecolecon.2016.12.027.

Harmsen, J.H.M. et al., 2019a: Long-term marginal abatement cost curves of non-CO_2 greenhouse gases. *Environ. Sci. Policy*, **99** (March), 136–149, doi:10.1016/j.envsci.2019.05.013.

Harmsen, M. et al., 2019b: The role of methane in future climate strategies: mitigation potentials and climate impacts. *Clim. Change*, **163**, 1409–1425, doi:10.1007/s10584-019-02437-2.

Harmsen, M. et al., 2020: Taking some heat off the NDCs? The limited potential of additional short-lived climate forcers' mitigation. *Clim. Change*, **163(3)**, 1443–1461, doi:10.1007/s10584-019-02436-3.

Harmsen, M. et al., 2021: Integrated assessment model diagnostics: key indicators and model evolution. *Environ. Res. Lett.*, **16(5)**, 54046, doi:10.1088/1748-9326/abf964.

Harmsen, M.J.H.M. et al., 2016: How climate metrics affect global mitigation strategies and costs: a multi-model study. *Clim. Change*, **136(2)**, 203–216, doi:10.1007/s10584-016-1603-7.

Hasegawa, T. et al., 2014: Climate change impact and adaptation assessment on food consumption utilizing a new scenario framework. *Environ. Sci. Technol.*, **48(1)**, 438–445, doi:10.1021/es4034149.

Hasegawa, T. et al., 2015: Consequence of Climate Mitigation on the Risk of Hunger. *Environ. Sci. Technol.*, **49(12)**, 7245–7253, doi:10.1021/es5051748.

Hasegawa, T. et al., 2018: Risk of increased food insecurity under stringent global climate change mitigation policy. *Nat. Clim. Change*, **8(8)**, 699–703, doi:10.1038/s41558-018-0230-x.

Hasegawa, T. et al., 2021a: Land-based implications of early climate actions without global net-negative emissions. *Nat. Sustain.*, 4, 1052–1059, doi:10.1038/s41893-021-00772-w.

Hasegawa, T. et al., 2021b: Extreme climate events increase risk of global food insecurity and adaptation needs. *Nat. Food*, **2(8)**, 587–595, doi:10.1038/s43016-021-00335-4.

Hatfield-Dodds, S. et al., 2017: Assessing global resource use and greenhouse emissions to 2050, with ambitious resource efficiency and climate mitigation policies. *J. Clean. Prod.*, **144**, 403–414, doi:10.1016/j.jclepro.2016.12.170.

Hausfather, Z. and G.P. Peters, 2020: Emissions – the 'business as usual' story is misleading. *Nature*, **577(7792)**, 618–620, doi:10.1038/d41586-020-00177-3.

Havlík, P. et al., 2014: Climate change mitigation through livestock system transitions. *Proc. Natl. Acad. Sci.*, **111(10)**, 3709–3714, doi:10.1073/pnas.1308044111.

Haxeltine, A. et al., 2008: A Conceptual Framework for transition modelling. *Int. J. Innov. Sustain. Dev.*, **3(1/2)**, 93, doi:10.1504/IJISD.2008.018195.

Hejazi, M. et al., 2014: Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. *Technol. Forecast. Soc. Change*, **81**, 205–226, doi: 10.1016/j.techfore.2013.05.006.

Helwegen, K.G., C.E. Wieners, J.E. Frank, and H.A. Dijkstra, 2019: Complementing CO_2 emission reduction by solar radiation management might strongly enhance future welfare. *Earth Syst. Dynam.*, **10(3)**, 453–472, doi:10.5194/esd-10-453-2019.

Henry, R.C. et al., 2018: Food supply and bioenergy production within the global cropland planetary boundary. *PLoS One*, **13(3)**, e0194695, doi: 10.1371/journal.pone.0194695.

Hepburn, C., B. O'Callaghan, N. Stern, J. Stiglitz, and D. Zenghelis, 2020: *Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change?* Oxford Review of Economic Policy, **36(1)**, S359–S381, doi: 10.1093/oxrep/graa015.

Hess, J.J. et al., 2020: Guidelines for Modeling and Reporting Health Effects of Climate Change Mitigation Actions. *Environ. Health Perspect.*, **128(11)**, 115001, doi:10.1289/EHP6745.

Heutel, G., J. Moreno-Cruz, and S. Shayegh, 2018: Solar geoengineering, uncertainty, and the price of carbon. *J. Environ. Econ. Manage.*, **87**, 24–41, doi.org/10.1016/j.jeem.2017.11.002.

Hickel, J. and G. Kallis, 2020: Is Green Growth Possible? *New Polit. Econ.*, **25(4)**, 469–486, doi:10.1080/13563467.2019.1598964.

Hickel, J. et al., 2021: Urgent need for post-growth climate mitigation scenarios. *Nat. Energy*, **6(8)**, 766–768, doi:10.1038/s41560-021-00884-9.

Hilaire, J. et al., 2019: Negative emissions and international climate goals—learning from and about mitigation scenarios. *Clim. Change*, **157(2)**, 189–219, doi:10.1007/s10584-019-02516-4.

Hirt, L.F., G. Schell, M. Sahakian, and E. Trutnevyte, 2020: A review of linking models and socio-technical transitions theories for energy and climate solutions. *Environ. Innov. Soc. Transitions*, **35**, 162–179, doi:10.1016/j.eist.2020.03.002.

Hock, R., G. Rasul, C. Adler, B. Cáceres, S. Gruber, Y. Hirabayashi, M. Jackson, A. Kääb, S. Kang, S. Kutuzov, Al. Milner, U. Molau, S. Morin, B. Orlove, and H. Steltzer, 2019: High Mountain Areas. In *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 131–202.

Hoekstra, A., M. Steinbuch, and G. Verbong, 2017: Creating Agent-Based Energy Transition Management Models That Can Uncover Profitable Pathways to Climate Change Mitigation. *Complexity*, **2017**, 1967645, doi:10.1155/2017/1967645.

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. *Environ. Sci. Policy*, **71**, 30–40, doi:10.1016/j.envsci.2017.02.008.

Hof, C. et al., 2018: Bioenergy cropland expansion may offset positive effects of climate change mitigation for global vertebrate diversity. *Proc. Natl. Acad. Sci.*, **115(52)**, 13294 LP–13299, doi:10.1073/pnas.1807745115.

Hofman, P., B. Elzen, and F.W. Geels, 2004: Sociotechnical scenarios as a new policy tool to explore system innovations: Co-evolution of technology and society in the Netherland's electricity domain. *Innov. Manag. Policy Pract.*, **6(2)**, 344–360, doi:10.5172/impp.2004.6.2.344.

Hofmann, M., S. Mathesius, E. Kriegler, D.P. va. van Vuuren, and H.J. Schellnhuber, 2019: Strong time dependence of ocean acidification mitigation by atmospheric carbon dioxide removal. *Nat. Commun.*, **10(1)**, 5592, doi:10.1038/s41467-019-13586-4.

Höglund-Isaksson, L., A. Gómez-Sanabria, Z. Klimont, P. Rafaj, and W. Schöpp, 2020: Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe –results from the GAINS model. *Environ. Res. Commun.*, **2(2)**, 25004, doi:10.1088/2515-7620/ab7457.

Höhne, N. et al., 2021: Wave of net zero emission targets opens window to meeting the Paris Agreement. *Nat. Clim. Change*, **11(10)**, 820–822, doi:10.1038/s41558-021-01142-2.

Holz, C., L.S. 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. *Environ. Res. Lett.*, **13(6)**, doi:10.1088/1748-9326/aac0c1.

Honegger, M. and D. Reiner, 2018: The political economy of negative emissions technologies: consequences for international policy design. *Clim. Policy*, **18(3)**, 306–321, doi:10.1080/14693062.2017.1413322.

Honegger, M., A. Michaelowa, and J. Roy, 2021: Potential implications of carbon dioxide removal for the sustainable development goals. *Clim. Policy*, **21(5)**, 678–698, doi:10.1080/14693062.2020.1843388.

Hong, S., C.J.A. Bradshaw, and B.W. Brook, 2014a: South Korean energy scenarios show how nuclear power can reduce future energy and environmental costs. *Energy Policy*, **74**, 569–578, doi.org/10.1016/j.enpol.2014.05.054.

Hong, S., C.J.A. Bradshaw, and B.W. Brook, 2014b: Nuclear power can reduce emissions and maintain a strong economy: Rating Australia's optimal future electricity-generation mix by technologies and policies. *Appl. Energy*, **136**, 712–725, doi.org/10.1016/j.apenergy.2014.09.062.

Houghton, R.A. and A.A. Nassikas, 2017: Global and regional fluxes of carbon from land use and land cover change 1850–2015. *Global Biogeochem. Cycles*, **31**, 456–472, doi: 10.1002/2016GB005546.

Howard, D.B., R. Soria, J. Thé, R. Schaeffer, and J.-D. Saphores, 2020: The energy-climate-health nexus in energy planning: A case study in Brazil. *Renew. Sustain. Energy Rev.*, **132**, 110016, doi.org/10.1016/j.rser.2020.110016.

Howard, P.H. and T. Sterner, 2017: Few and Not So Far Between: A Meta-analysis of Climate Damage Estimates. *Environ. Resour. Econ.*, **68**, 197–225, doi:10.1007/s10640-017-0166-z.

Hubacek, K. et al., 2017a: Global carbon inequality. *Energy, Ecol. Environ.*, **2(6)**, 361–369, doi:10.1007/s40974-017-0072-9.

Hubacek, K., G. Baiocchi, K. Feng, and A. Patwardhan, 2017b: Poverty eradication in a carbon constrained world. *Nat. Commun.*, **8(1)**, 1–8, doi:10.1038/s41467-017-00919-4.

Hughes, N., 2013: Towards improving the relevance of scenarios for public policy questions: A proposed methodological framework for policy relevant low carbon scenarios. *Technol. Forecast. Soc. Change*, **80(4)**, 687–698, doi:10.1016/j.techfore.2012.07.009.

Humpenöder, F. et al., 2018: Large-scale bioenergy production: How to resolve sustainability trade-offs? *Environ. Res. Lett.*, **13(2)**, doi:10.1088/1748-9326/aa9e3b.

Huppmann, D., J. Rogelj, E. Kriegler, V. Krey, and K. Riahi, 2018: A new scenario resource for integrated 1.5 °C research. *Nat. Clim. Change*, **8(12)**, 1027–1030, doi:10.1038/s41558-018-0317-4.

Hurlbert, M., J. Krishnaswamy, E. Davin, F.X. Johnson, C.F. Mena, J. Morton, S. Myeong, D. Viner, K. Warner, A. Wreford, S. Zakieldeen, Z. Zommers, 2019: Risk Management and Decision making in Relation to Sustainable Development. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Iacobucci, G., 2016: NHS is unprepared for risks posed by climate change, warn leading UK health bodies. *BMJ*, **352**, i1781, doi:10.1136/bmj.i1781.

IEA, 2011: *Climate change*. International Energy Agency (IEA), Paris, France, 267–268 pp.

IEA, 2019: *World Energy Outlook 2019*. International Energy Agency (IEA), Paris, France, 810 pp. https://www.iea.org/reports/world-energy-outlook-2019.

IEA, 2020a: *World Energy Outlook 2020*. International Energy Agency (IEA), Paris, France 464 pp. https://www.iea.org/reports/world-energy-outlook-2020.

IEA, 2020b: *Global Energy Review 2020*. International Energy Agency (IEA), Paris, France, 55pp. https://www.iea.org/reports/global-energy-review-2020.

IEA, 2021a: *Net Zero by 2050. A Roadmap for the Global Energy Sector*. International Energy Agency (IEA), Paris, France, 224 pp. https://www.iea.org/reports/net-zero-by-2050.

IEA, 2021b: *Conditions and requirements for the technical feasibility of a power system with a high share of renewables in France towards 2050*. International Energy Agency (IEA), Paris, France, 186 pp. https://www.iea.org/reports/conditions-and-requirements-for-the-technical-feasibility-of-a-power-system-with-a-high-share-of-renewables-in-france-towards-2050.

IEA, 2021: *CO_2 Emissions from Fossil Fuel Combustion 2021.* International Energy Agency (IEA), Paris, France. https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2.

IMF, 2020: *World Economic Outlook, October 2020: a long and difficult ascent*. https://www.imf.org/en/Publications/WEO/Issues/2020/09/30/world-economic-outlook-october-2020#Full Report and Executive Summary.

IMF, 2021: *World Economic Outlook, October 2021: Recovery during a Pandemic—Health Concerns, Supply Disruptions, Price Pressures.* https://www.imf.org/en/Publications/WEO/Issues/2021/10/12/world-economic-outlook-october-2021.

IPBES, 2019: Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [S. Díaz, J. Settele, E. S. Brondízio, H. T. Ngo, M. Guèze et al.(eds.)]. IPBES secretariat, Bonn, Germany. 56 pp.

IPCC, 2018: Summary for Policymakers. In: *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* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2019a: Summary for Policymakers. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2019b: IPCC *Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Isaac, M. and D.P. van Vuuren, 2009: Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy*, **37(2)**, 507–521, doi:10.1016/j.enpol.2008.09.051.

Ivanova, D. et al., 2020: Quantifying the potential for climate change mitigation of consumption options. *Environ. Res. Lett.*, **15(9)**, 93001, doi:10.1088/1748-9326/ab8589.

Iyer, G. et al., 2015a: Diffusion of low-carbon technologies and the feasibility of long-term climate targets. *Technol. Forecast. Soc. Change*, **90(PA)**, 103–118, doi:10.1016/j.techfore.2013.08.025.

Iyer, G.C. et al., 2015b: The contribution of Paris to limit global warming to 2°C. *Environ. Res. Lett.*, **10(12)**, doi:10.1088/1748-9326/10/12/125002.

Iyer, G.C. et al., 2015c: Improved representation of investment decisions in assessments of CO_2 mitigation. *Nat. Clim. Change*, **5(5)**, 436–440, doi:10.1038/nclimate2553.

Jackson, R.B., E.I. Solomon, J.G. Canadell, M. Cargnello, and C.B. Field, 2019: Methane removal and atmospheric restoration. *Nat. Sustain.*, **2(6)**, 436–438, doi:10.1038/s41893-019-0299-x.

Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, and B. V Mathiesen, 2018: Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes. *Renew. Energy*, **123**, 236–248, doi.org/10.1016/j.renene.2018.02.009.

Jafino, B.A., J.H. Kwakkel, and B. Taebi, 2021: Enabling assessment of distributive justice through models for climate change planning: A review of recent advances and a research agenda. *WIREs Clim. Change*, **12(4)**, e721, doi.org/10.1002/wcc.721.

Jakob, M. and J.C. Steckel, 2016: Implications of climate change mitigation for sustainable development. *Environ. Res. Lett.*, **11(10)**, doi:10.1088/1748-9326/11/10/104010.

Jakob, M., G. Luderer, J. Steckel, M. Tavoni, and S. Monjon, 2012: Time to act now? Assessing the costs of delaying climate measures and benefits of early action. *Clim. Change*, **114**, 79–99, doi: 10.1007/s10584-011-0128-3.

Jakob, M. et al., 2016: Carbon Pricing Revenues Could Close Infrastructure Access Gaps. *World Dev.*, **84**, 254–265, doi:10.1016/j.worlddev.2016.03.001.

Jakob, M. et al., 2020: The future of coal in a carbon-constrained climate. *Nat. Clim. Change*, **10**, 704–707, doi:10.1038/s41558-020-0866-1.

Jeffery, M.L., J. Gütschow, M.R. Rocha, and R. Gieseke, 2018: Measuring Success: Improving Assessments of Aggregate Greenhouse Gas Emissions Reduction Goals. *Earth's Future*, **6(9)**, 1260–1274, doi:10.1029/2018EF000865.

Jenkins, J.D., 2014: Political economy constraints on carbon pricing policies: What are the implications for economic efficiency, environmental efficacy, and climate policy design? *Energy Policy*, **69**, 467–477, doi:10.1016/j.enpol.2014.02.003.

Jewell, J. and A. Cherp, 2020: On the political feasibility of climate change mitigation pathways: Is it too late to keep warming below 1.5°C? *Wiley Interdiscip. Rev. Clim. Change*, **11(1)**, 1–12, doi:10.1002/wcc.621.

Jewell, J., V. Vinichenko, L. Nacke, and A. Cherp, 2019: Prospects for powering past coal. *Nat. Clim. Change*, **9(8)**, 592–597, doi:10.1038/s41558-019-0509-6.

Jia, G., E. Shevliakova, P. Artaxo, N. De Noblet-Ducoudré, R. Houghton, J. House, K. Kitajima, C. Lennard, A. Popp, A. Sirin, R. Sukumar, L. Verchot, 2019: Land–climate interactions. In: *Climate Change and Land: an IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 131–247.

Jiang, K.J., K. Tamura, and T. Hanaoka, 2017: Can we go beyond INDCs: Analysis of a future mitigation possibility in China, Japan, EU and the U.S. *Adv. Clim. Change Res.*, **8(2)**, 117–122, doi:10.1016/j.accre.2017.05.005.

Jiang, L. and B.C. O'Neill, 2017: Global urbanization projections for the Shared Socioeconomic Pathways. *Glob. Environ. Change*, **42**, 193–199, doi.org/10.1016/j.gloenvcha.2015.03.008.

Johansson, Å. et al., 2013: *Long-term growth scenarios*. OECD Economics Department Working Papers No. 1000, 90 pp. https://www.oecd-ilibrary.org/economics/long-term-growth-scenarios_5k4ddxpr2fmr-en.

Johansson, D.J.A., C. Azar, M. Lehtveer, and G.P. Peters, 2020: The role of negative carbon emissions in reaching the Paris climate targets: The impact of target formulation in integrated assessment models. *Environ. Res. Lett*, (in press), doi:10.1088/1748-9326/abc3f0.

Johnson, V.C.A., F. Sherry-Brennan, and P.J.G. Pearson, 2016: Alternative liquid fuels in the UK in the inter-war period (1918–1938): Insights from a failed energy transition. *Environ. Innov. Soc. Transitions*, **20**, 33–47, doi:10.1016/j.eist.2015.12.001.

Jones, C.D. et al., 2021: The Climate Response to Emissions Reductions Due to COVID-19: Initial Results From CovidMIP. *Geophys. Res. Lett.*, **48(8)**, e2020GL091883, doi.org/10.1029/2020GL091883.

Jorgenson, A., J. Schor, and X. Huang, 2017: Income Inequality and Carbon Emissions in the United States: A State-level Analysis, 1997–2012. *Ecol. Econ.*, **134**, 40–48, doi:10.1016/j.ecolecon.2016.12.016.

Kahn, M.E. et al., 2019: *Long-Term Macroeconomic Effects of Climate Change: A Cross-Country Analysis*. IMF Working Papers, Working Paper No. 19/215, 59 pp. https://www.imf.org/en/Publications/WP/Issues/2019/10/11/Long-Term-Macroeconomic-Effects-of-Climate-Change-A-Cross-Country-Analysis-48691.

Kallis, G., C. Kerschner, and J. Martinez-Alier, 2012: The economics of degrowth. *Ecol. Econ.*, **84**, 172–180, doi:10.1016/j.ecolecon.2012.08.017.

3

Kallis, G., S. Paulson, G. D'Alisa, and F. Demaria, 2020: *The case for degrowth*. John Wiley & Sons, Hoboken, NJ, USA, 140 pp.

Karlsson, M. and M. Gilek, 2020: Mind the gap: Coping with delay in environmental governance. *Ambio*, **49(5)**, 1067–1075, doi:10.1007/s13280-019-01265-z.

Karlsson, M., E. Alfredsson, and N. Westling, 2020: Climate policy co-benefits: a review. *Clim. Policy*, **20(3)**, 292–316, doi:10.1080/14693062.2020.1724070.

Kaufman, N., A.R. Barron, W. Krawczyk, P. Marsters, and H. McJeon, 2020: A near-term to net zero alternative to the social cost of carbon for setting carbon prices. *Nat. Clim. Change*, **10(11)**, 1010–1014, doi:10.1038/s41558-020-0880-3.

Kayal, M., H. Lewis, J. Ballard, and E. Kayal, 2019: Humanity and the 21st century's resource gauntlet: a commentary on Ripple et al.'s article "World scientists' warning to humanity: a second notice". *Rethink. Ecol.*, **4**, 21–30, doi: 10.3897/rethinkingecology.4.32116.

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. *Glob. Environ. Change*, **42**, 181–192, doi:10.1016/j.gloenvcha.2014.06.004.

Kefford, B.M., B. Ballinger, D.R. Schmeda-Lopez, C. Greig, and S. Smart, 2018: The early retirement challenge for fossil fuel power plants in deep decarbonisation scenarios. *Energy Policy*, **119**, 294–306, doi:10.1016/j.enpol.2018.04.018.

Keller, D.P. et al., 2018a: The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP): Rationale and experimental protocol for CMIP6. *Geosci. Model Dev.*, **11(3)**, 1133–1160, doi:10.5194/gmd-11-1133-2018.

Keller, D.P. et al., 2018b: The Effects of Carbon Dioxide Removal on the Carbon Cycle. *Curr. Clim. Change Reports*, **4(3)**, 250–265, doi:10.1007/s40641-018-0104-3.

Kemp-Benedict, E., 2018: Dematerialization, Decoupling, and Productivity Change. *Ecol. Econ.*, **150** (April), 204–216, doi:10.1016/j.ecolecon.2018.04.020.

Keohane, N., A. Petsonk, and A. Hanafi, 2017: Toward a club of carbon markets. *Clim. Change*, **144(1)**, 81–95, doi:10.1007/s10584-015-1506-z.

Keppo, I. and S. Rao, 2007: International climate regimes: Effects of delayed participation. *Technol. Forecast. Soc. Change*, **74(7)**, 962–979, doi:10.1016/j.techfore.2006.05.025.

Keppo, I. et al., 2021: Exploring the possibility space: Taking stock of the diverse capabilities and gaps in integrated assessment models. *Environ. Res. Lett.*, **16**, 053006, doi: 10.1088/1748-9326/abe5d8.

Kermeli, K. et al., 2019: The scope for better industry representation in long-term energy models: Modeling the cement industry. *Appl. Energy*, **240** (February), 964–985, doi:10.1016/j.apenergy.2019.01.252.

Keyßer, L.T. and M. Lenzen, 2021: 1.5°C degrowth scenarios suggest the need for new mitigation pathways. *Nat. Commun.*, **12(1)**, 2676, doi:10.1038/s41467-021-22884-9.

Kii, M., 2021: Projecting future populations of urban agglomerations around the world and through the 21st century. *npj Urban Sustain.*, **1(1)**, 10, doi:10.1038/s42949-020-00007-5.

Kikstra, J.S. et al., 2021a: Climate mitigation scenarios with persistent COVID-19-related energy demand changes. *Nat. Energy*, **6**, 1114–1123 doi:10.1038/s41560-021-00904-8.

Kikstra, J.S., A. Mastrucci, J. Min, K. Riahi, and N.D. Rao, 2021b: Decent living gaps and energy needs around the world. *Environ. Res. Lett.*, **16(9)**, 95006, doi:10.1088/1748-9326/ac1c27.

Kim, J.B. et al., 2017: Assessing climate change impacts, benefits of mitigation, and uncertainties on major global forest regions under multiple socioeconomic and emissions scenarios. *Environ. Res. Lett.*, **12(4)**, doi:10.1088/1748-9326/aa63fc.

Kim, S.E. et al., 2020: Air quality co-benefits from climate mitigation for human health in South Korea. *Environ. Int.*, **136**, 105507, doi.org/10.1016/j.envint.2020.105507.

Kim, S. J., J.S. Baker, B.L. Sohngen, and M. Shell, 2018: Cumulative global forest carbon implications of regional bioenergy expansion policies. *Resour. Energy Econ.*, **53**, 198–219, doi.org/10.1016/j.reseneeco.2018.04.003.

Kinney, P.L., 2018: Interactions of Climate Change, Air Pollution, and Human Health. *Curr. Environ. Heal. Reports*, **5(1)**, 179–186, doi:10.1007/s40572-018-0188-x.

Kjellstrom, T. et al., 2016: Heat, Human Performance, and Occupational Health: A Key Issue for the Assessment of Global Climate Change Impacts. *Annu. Rev. Public Health*, **37(1)**, 97–112, doi:10.1146/annurev-publhealth-032315-021740.

Kjellstrom, T., C. Freyberg, B. Lemke, M. Otto, and D. Briggs, 2018: Estimating population heat exposure and impacts on working people in conjunction with climate change. *Int. J. Biometeorol.*, **62(3)**, 291–306, doi:10.1007/s00484-017-1407-0.

Klenert, D. et al., 2018: Making carbon pricing work for citizens. *Nat. Clim. Change*, **8(8)**, 669–677, doi:10.1038/s41558-018-0201-2.

Knight, K.W., J.B. Schor, and A.K. Jorgenson, 2017: Wealth Inequality and Carbon Emissions in High-income Countries: *Soc. Curr.*, **4(5)**, 403–412, doi:10.1177/2329496517704872.

Knobloch, F., H. Pollitt, U. Chewpreecha, V. Daioglou, and J.F. Mercure, 2017: Simulating the deep decarbonisation of residential heating for limiting global warming to 1.5°C. *arXiv*, **12**, 521–550, doi: 10.1007/s12053-018-9710-0.

Knopf, B., G. Luderer, and O. Edenhofer, 2011: Exploring the feasibility of low stabilization targets. *Wiley Interdiscip. Rev. Clim. Change*, **2(4)**, 617–626, doi:10.1002/wcc.124.

Köberle, A.C., 2019: The Value of BECCS in IAMs: a Review. *Curr. Sustain. Energy Reports*, **6**(4), 107–115, doi:10.1007/s40518-019-00142-3.

Köberle, A. et al., 2021: The Cost of Mitigation Revisited. *Nat. Clim. Change* (in press).

Koch, H., S. Vögele, F. Hattermann, and S. Huang, 2014: Hydro-climatic conditions and thermoelectric electricity generation – Part II: Model application to 17 nuclear power plants in Germany. *Energy*, **69**, 700–707, doi:10.1016/j.energy.2014.03.071.

Köhler, J. et al., 2019: An agenda for sustainability transitions research: State of the art and future directions. *Environ. Innov. Soc. Transitions*, **31**, 1–32, doi.org/10.1016/j.eist.2019.01.004.

Köhler, J., B. Turnheim, and M. Hodson, 2020: Low carbon transitions pathways in mobility: Applying the MLP in a combined case study and simulation bridging analysis of passenger transport in the Netherlands. *Technol. Forecast. Soc. Change*, **151**, doi:10.1016/j.techfore.2018.06.003.

Koomey, J., 2013: Moving beyond benefit–cost analysis of climate change. *Environ. Res. Lett.*, **8(4)**, 41005, doi:10.1088/1748-9326/8/4/041005.

Kornek, U., D. Klenert, O. Edenhofer, and M. Fleurbaey, 2021: The social cost of carbon and inequality: When local redistribution shapes global carbon prices. *J. Environ. Econ. Manage.*, **107**, 102450, doi.org/10.1016/j.jeem.2021.102450.

Koutroulis, A.G. et al., 2019: Global water availability under high-end climate change: A vulnerability based assessment. *Glob. Planet. Change*, **175** (August 2018), 52–63, doi:10.1016/j.gloplacha.2019.01.013.

Krey, V. and K. Riahi, 2009: Implications of delayed participation and technology failure for the feasibility, costs, and likelihood of staying below temperature targets—Greenhouse gas mitigation scenarios for the 21st century. *Energy Econ.*, **31**, S94–S106, doi: 10.1016/j.eneco.2009.07.001.

Krey, V. et al., 2012: Urban and rural energy use and carbon dioxide emissions in Asia. *Energy Econ.*, **34(sup3)**, S272–S283, doi:10.1016/j.eneco.2012.04.013.

Krey, V. et al., 2019: Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models. *Energy*, **172**, 1254–1267, doi:10.1016/j.energy.2018.12.131.

Kriegler, E. et al., 2013a: What does the 2°C target imply for a global climate agreement in 2020? The LIMITS study on Durban Platform scenarios. *Clim. Change Econ.*, **4(4)**, 1340008, doi:10.1142/S2010007813400083.

Kriegler, E., O. Edenhofer, L. Reuster, G. Luderer, and D. Klein, 2013b: Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Clim. Change*, **118(1)**, 45–57, doi:10.1007/s10584-012-0681-4.

Kriegler, E. et al., 2014a: The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. *Clim. Change*, **123(3–4)**, 353–367, doi:10.1007/s10584-013-0953-7.

Kriegler, E. et al., 2014b: A new scenario framework for climate change research: The concept of shared climate policy assumptions. *Clim. Change*, **122(3)**, 401–414, doi:10.1007/s10584-013-0971-5.

Kriegler, E. et al., 2015: Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technol. Forecast. Soc. 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. *Clim. Change*, **136(1)**, 7–22, doi:10.1007/s10584-016-1668-3.

Kriegler, E. et al., 2018a: Short term policies to keep the door open for Paris climate goals. *Environ. Res. Lett.*, **13(7)**, 74022, doi:10.1088/1748-9326/aac4f1.

Kriegler, E. et al., 2018b: Pathways limiting warming to 1.5°C: A tale of turning around in no time? *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, **376(2119)**, 20160457, doi:10.1098/rsta.2016.0457.

Kuramochi, T. et al., 2018: Ten key short-term sectoral benchmarks to limit warming to 1.5°C. *Clim. Policy*, **18(3)**, 287–305, doi:10.1080/14693062.2017.1397495.

Kyle, P. et al., 2013: Influence of climate change mitigation technology on global demands of water for electricity generation. *Int. J. Greenh. Gas Control*, **13**, 112–123, doi:10.1016/j.ijggc.2012.12.006.

Kyle, P., C. Müller, K. Calvin, and A. Thomson, 2014: Meeting the radiative forcing targets of the representative concentration pathways in a world with agricultural climate impacts. *Earth's Future*, **2(2)**, 83–98, doi:10.1002/2013ef000199.

La Viña, A.G., J.M. Tan, T.I.M. Guanzon, M.J. Caleda, and L. Ang, 2018: Navigating a trilemma: Energy security, equity, and sustainability in the Philippines' low-carbon transition. *Energy Res. Soc. Sci.*, **35** (October), 37–47, doi:10.1016/j.erss.2017.10.039.

Labriet, M. et al., 2015: Worldwide impacts of climate change on energy for heating and cooling. *Mitig. Adapt. Strateg. Glob. Change*, **20(7)**, 1111–1136, doi:10.1007/s11027-013-9522-7.

Laganière, J., D. Paré, E. Thiffault, and P.Y. Bernier, 2017: Range and uncertainties in estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced from Canadian forests. *GCB Bioenergy*, **9(2)**, 358–369, doi.org/10.1111/gcbb.12327.

Lamb, W.F. and N.D. Rao, 2015: Human development in a climate-constrained world: What the past says about the future. *Glob. Environ. Change*, **33**, 14–22, doi:10.1016/j.gloenvcha.2015.03.010.

Lamb, W.F. et al., 2020: What are the social outcomes of climate policies? A systematic map and review of the ex-post literature. *Environ. Res. Lett.*, **15(11)**, doi:10.1088/1748-9326/abc11f.

Lamers, P. and M. Junginger, 2013: The 'debt' is in the detail: a synthesis of recent temporal forest carbon analyses on woody biomass forenergy. *Biofuels, Bioprod. Biorefining*, **7(4),** 373–384, doi:10.1002/bbb.1407.

Lane, J.L. et al., 2016: Understanding constraints to the transformation rate of global energy infrastructure. *Wiley Interdiscip. Rev. Energy Environ.*, **5(1)**, 33–48, doi:10.1002/wene.177.

Le Quéré, C. et al., 2021: Fossil CO_2 emissions in the post-COVID-19 era. *Nat. Clim. Change*, **11(3)**, 197–199, doi:10.1038/s41558-021-01001-0.

Leach, M. et al., 2007: *Understanding governance: Pathways to sustainability*. STEPS Working Paper 2, Brighton: STEPS Centre.

Leal Filho, W. et al., 2018: Reinvigorating the sustainable development research agenda: the role of the sustainable development goals (SDG). *Int. J. Sustain. Dev. World Ecol.*, **25(2)**, 131–142, doi:10.1080/13504509.2017.1342103.

Leclère, D. et al., 2020: Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature*, **585(7826)**, 551–556, doi:10.1038/s41586-020-2705-y.

Lefèvre, J. et al., 2021: A pathway design framework for sectoral deep decarbonization: the case of passenger transportation. *Clim. Policy*, **21(1)**, 93–106, doi:10.1080/14693062.2020.1804817.

Lehtveer, M. and F. Hedenus, 2015a: Nuclear power as a climate mitigation strategy – technology and proliferation risk. *J. Risk Res.*, **18(3)**, 273–290, doi:10.1080/13669877.2014.889194.

Lehtveer, M. and F. Hedenus, 2015b: How much can nuclear power reduce climate mitigation cost? – Critical parameters and sensitivity. *Energy Strateg. Rev.*, **6**, 12–19, doi.org/10.1016/j.esr.2014.11.003.

Leimbach, M. and A. Giannousakis, 2019: Burden sharing of climate change mitigation: global and regional challenges under shared socio-economic pathways. *Clim. Change*, **155(2)**, 273–291, doi:10.1007/s10584-019-02469-8.

Lemoine, D. and C.P. Traeger, 2016: Economics of tipping the climate dominoes. *Nat. Clim. Change*, **6**(5), 514–519, doi:10.1038/nclimate2902.

Lenton, T.M. et al., 2019: Climate tipping points – too risky to bet against. *Nature*, **575**, 592–595, doi: 10.1038/d41586-019-03595-0.

Levesque, A. et al., 2018: How much energy will buildings consume in 2100? A global perspective within a scenario framework. *Energy*, **148**, 514–527, doi:10.1016/j.energy.2018.01.139.

Levi, M., T. Kjellstrom, and A. Baldasseroni, 2018: Impact of climate change on occupational health and productivity: a systematic literature review focusing on workplace heat. *Med. Lav.*, **109(3)**, 163–179, doi:10.23749/mdl.v109i3.6851.

Li, F.G.N. and N. Strachan, 2019: Take me to your leader: Using socio-technical energy transitions (STET) modelling to explore the role of actors in decarbonisation pathways. *Energy Res. Soc. Sci.*, **51**, 67–81, doi:10.1016/j.erss.2018.12.010.

Li, F.G.N., E. Trutnevyte, and N. Strachan, 2015: A review of socio-technical energy transition (STET) models. *Technol. Forecast. Soc. Change*, **100(C)**, 290–305, doi: 10.1016/j.techfore.2015.07.017.

Li, M. et al., 2018: Air quality co-benefits of carbon pricing in China. *Nat. Clim. Change*, **8(5)**, 398–403, doi:10.1038/s41558-018-0139-4.

Li, N. et al., 2019: Air Quality Improvement Co-benefits of Low-Carbon Pathways toward Well Below the 2°C Climate Target in China. *Environ. Sci. Technol.*, **53(10)**, 5576–5584, doi:10.1021/acs.est.8b06948.

Limaye, V.S., W. Max, J. Constible, and K. Knowlton, 2019: Estimating the Health-Related Costs of 10 Climate-Sensitive U.S. Events During 2012. *GeoHealth*, **3(9)**, 245–265, doi.org/10.1029/2019GH000202.

Limaye, V.S., W. Max, J. Constible, and K. Knowlton, 2020: Estimating The Costs Of Inaction And The Economic Benefits Of Addressing The Health Harms Of Climate Change. *Health Aff.*, **39(12)**, 2098–2104, doi:10.1377/hlthaff.2020.01109.

Liobikienė, G., 2020: The revised approaches to income inequality impact on production-based and consumption-based carbon dioxide emissions: literature review. *Environ. Sci. Pollut. Res.*, **27(9)**, 8980–8990, doi:10.1007/s11356-020-08005-x.

Liobikienė, G., and D. Rimkuvienė, 2020: The role of income inequality on consumption-based greenhouse gas emissions under different stages of economic development. *Environ. Sci. Pollut. Res.*, **27**, 43067–43076, doi:10.1007/s11356-020-10244-x.

Liu, C., Y. Jiang, and R. Xie, 2019: Does income inequality facilitate carbon emission reduction in the US? *J. Clean. Prod.*, **217**, 380–387, doi:10.1016/j.jclepro.2019.01.242.

Liu, J.-Y. et al., 2020a: The importance of socioeconomic conditions in mitigating climate change impacts and achieving Sustainable Development Goals. *Environ. Res. Lett.*, **16(1)**, 14010, doi:10.1088/1748-9326/abcac4.

Liu, J. et al., 2017: Water scarcity assessments in the past, present, and future. *Earth's Future*, **5(6)**, 545–559, doi:10.1002/2016EF000518.

Liu, J.Y., S. Fujimori, and T. Masui, 2016: Temporal and spatial distribution of global mitigation cost: INDCs and equity. *Environ. Res. Lett.*, **11(11)**, doi:10.1088/1748-9326/11/11/114004.

Liu, J.Y. et al., 2018: Socioeconomic factors and future challenges of the goal of limiting the increase in global average temperature to 1.5°C. *Carbon Manag.*, **9(5)**, 447–457, doi:10.1080/17583004.2018.1477374.

Liu, S. et al., 2021: Health Benefits of Emission Reduction under 1.5°C Pathways Far Outweigh Climate-Related Variations in China. *Environ. Sci. Technol.*, **55(16)**, 10957–10966, doi:10.1021/acs.est.1c01583.

Liu, Y., M. Zhang, and R. Liu, 2020b: The Impact of Income Inequality on Carbon Emissions in China: A Household-Level Analysis. *Sustainability*, **12(7)**, 2715, doi:10.3390/su12072715.

Liu, Z. et al., 2020c: Near-real-time monitoring of global CO_2 emissions reveals the effects of the COVID-19 pandemic. *Nat. Commun.*, **11(1)**, 5172, doi:10.1038/s41467-020-18922-7.

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 Interdiscip. Rev. Clim. Change*, **6(1)**, 93–112, doi: 10.1002/wcc.324.

Longden, T., 2014: Travel intensity and climate policy: The influence of different mobility futures on the diffusion of battery integrated vehicles. *Energy Policy*, **72(2014)**, 219–234, doi:10.1016/j.enpol.2014.04.034.

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. *Nat. Clim. Change*, **5(5)**, 441–444, doi:10.1038/nclimate2570.

Lovins, A.B., D. Ürge-Vorsatz, L. Mundaca, D.M. Kammen, and J.W. Glassman, 2019: Recalibrating climate prospects. *Environ. Res. Lett.*, **14(12)**, 120201, doi:10.1088/1748-9326/ab55ab.

Lucena, A.F.P. et al., 2018: Interactions between climate change mitigation and adaptation: The case of hydropower in Brazil. *Energy*, **164**, 1161–1177, doi:10.1016/j.energy.2018.09.005.

Luderer, G. et al., 2013: Economic mitigation challenges: How further delay closes the door for achieving climate targets. *Environ. Res. Lett.*, **8(3)**, 034033, doi:10.1088/1748-9326/8/3/034033.

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. *Clim. Change*, **136(1)**, 127–140, doi:10.1007/s10584-013-0899-9.

Luderer, G. et al., 2018: Residual fossil CO_2 emissions in 1.5–2°C pathways. *Nat. Clim. Change*, **8(7)**, 626–633, doi:10.1038/s41558-018-0198-6.

Luderer, G. et al., 2022: Impact of declining renewable energy costs on electrification in low-emission scenarios. *Nat. Energy*, **7**, 32–42, doi:10.1038/s41560-021-00937-z.

Lund, M.T. et al., 2020: A continued role of short-lived climate forcers under the Shared Socioeconomic Pathways. *Earth Syst. Dyn.*, **11(4)**, 977–993, doi:10.5194/esd-11-977-2020.

Lynch, J., M. Cain, R. Pierrehumbert, and M. Allen, 2020: Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. *Environ. Res. Lett.*, **15(4)**, 44023, doi:10.1088/1748-9326/ab6d7e.

MacDougall, A.H. and P. Friedlingstein, 2015: The Origin and Limits of the Near Proportionality between Climate Warming and Cumulative CO_2 Emissions. *J. Clim.*, **28(10)**, 4217–4230, doi:10.1175/jcli-d-14-00036.1.

Mader, S., 2018: The nexus between social inequality and CO_2 emissions revisited: Challenging its empirical validity. *Environ. Sci. Policy*, **89**, 322–329, doi:10.1016/j.envsci.2018.08.009.

Magneschi, G., T. Zhang, and R. Munson, 2017: The Impact of CO_2 Capture on Water Requirements of Power Plants. *Energy Procedia*, **114** (November 2016), 6337–6347, doi:10.1016/j.egypro.2017.03.1770.

Maïzi, N., S. Bouckaert, and E. Assoumou, 2017: Long-Term Water and Energy Issues in European Power Systems. *Compet. Water Resour. Exp. Manag. Approaches US Eur.*, 233–251, doi:10.1016/B978-0-12-803237-4.00013-6.

Majone, G., 1975a: The feasibility of social policies. *Policy Sci.*, **6(1)**, 49–69, doi:10.1007/BF00186755.

Majone, G., 1975b: On the Notion of Political Feasibility*. *Eur. J. Polit. Res.*, **3(3)**, 259–274, doi:10.1111/j.1475-6765.1975.tb00780.x.

Malerba, D. and K.S. Wiebe, 2021: Analysing the effect of climate policies on poverty through employment channels. *Environ. Res. Lett.*, **16(3)**, 35013, doi:10.1088/1748-9326/abd3d3.

Marangoni, G. et al., 2017: Sensitivity of projected long-term CO_2 emissions across the Shared Socioeconomic Pathways. *Nat. Clim. Change*, **7(2)**, 113–117, 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. *Clim. Change*, **144(2)**, 181–193, doi:10.1007/s10584-017-2051-8.

Marinova, S., S. Deetman, E. van der Voet, and V. Daioglou, 2020: Global construction materials database and stock analysis of residential buildings between 1970–2050. *J. Clean. Prod.*, **247**, 119146, doi.org/10.1016/j.jclepro.2019.119146.

Markandya, A. et al., 2018: Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study. *Lancet Planet. Heal.*, **2(3)**, e126–e133, doi:10.1016/S2542-5196(18)30029-9.

Markhvida, M., B. Walsh, S. Hallegatte, and J. Baker, 2020: Quantification of disaster impacts through household well-being losses. *Nat. Sustain.*, **3**, 538–547, doi:10.1038/s41893-020-0508-7.

Markkanen, S. and A. Anger-Kraavi, 2019: Social impacts of climate change mitigation policies and their implications for inequality. *Clim. Policy*, **19(7)**, 827–844, doi:10.1080/14693062.2019.1596873.

Maruyama Rentschler, J.E., M.G.M. Kornejew, S. Hallegatte, J.M. Braese, and M.A.B. Obolensky, 2019: Underutilized potential: The business costs of unreliable infrastructure in developing countries. World Bank Group, Climate Change Group, Global Facility for Disaster Reduction and Recovery, World Bank policy research working paper 8899.

Mastrucci, A., E. Byers, S. Pachauri, and N.D. Rao, 2019: Improving the SDG energy poverty targets: Residential cooling needs in the Global South. *Energy Build.*, **186**, 405–415, doi:10.1016/j.enbuild.2019.01.015.

Mastrucci, A., B. van Ruijven, E. Byers, M. Poblete-Cazenave, and S. Pachauri, 2021: Global scenarios of residential heating and cooling energy demand and CO_2 emissions. *Clim. Change*, **168(3)**, 14, doi:10.1007/s10584-021-03229-3.

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.

McCollum, D.L. et al., 2017: Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. *Transp. Res. Part D Transp. Environ.*, **55**, 322–342, doi:10.1016/j.trd.2016.04.003.

McCollum, D.L. et al., 2018a: Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nat. Energy*, **3(7)**, 589, doi:10.1038/s41560-018-0179-z.

McCollum, D.L. et al., 2018b: Connecting the sustainable development goals by their energy inter-linkages. *Environ. Res. Lett.*, **13(3)**, doi:10.1088/1748-9326/aaafe3.

McElwee, P. et al., 2020: The impact of interventions in the global land and agri-food sectors on Nature's Contributions to People and the UN Sustainable Development Goals. *Glob. Chang. Biol.*, **26(9)**, 4691–4721, doi:10.1111/gcb.15219.

McFarland, J. et al., 2015: Impacts of rising air temperatures and emissions mitigation on electricity demand and supply in the United States: a multi-model comparison. *Clim. Change*, **131(1)**, 111–125, doi:10.1007/s10584-015-1380-8.

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. *Clim. Change Econ.*, **09(01)**, 1840002, doi:10.1142/S201000781840002X.

Mcjeon, H. et al., 2021: Fossil energy deployment through midcentury consistent with 2°C climate stabilization. *Energy Clim. Change*, **2** (April), 100034, doi:10.1016/j.egycc.2021.100034.

3

Meckling, J., T. Sterner, and G. Wagner, 2017: Policy sequencing toward decarbonization. *Nat. Energy*, **2(12)**, 918–922, doi:10.1038/s41560-017-0025-8.

Meijl, H. Van et al., 2018: Comparing impacts of climate change and mitigation on global agriculture by 2050. *Environ. Res. Lett.*, **13 (6),** doi: 10.1088/1748-9326/aabdc4.

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., 2020: The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geosci. Model Dev.*, **13(8)**, 3571–3605, doi:10.5194/gmd-13-3571-2020.

Méjean, A., C. Guivarch, J. Lefèvre, and M. Hamdi-Cherif, 2019: The transition in energy demand sectors to limit global warming to 1.5 °C. *Energy Effic.*, **12(2)**, 441–462, doi:10.1007/s12053-018-9682-0.

Méjean, A., A. Pottier, M. Fleurbaey, and S. Zuber, 2020: Catastrophic climate change, population ethics and intergenerational equity. *Clim. Change*, **163(2)**, 873–890, doi:10.1007/s10584-020-02899-9.

Meng, J., R. Way, E. Verdolini, and L. Diaz Anadon, 2021: Comparing expert elicitation and model-based probabilistic technology cost forecasts for the energy transition. *Proc. Natl. Acad. Sci.*, **118(27)**, e1917165118, doi:10.1073/pnas.1917165118.

Mengel, M., A. Nauels, J. Rogelj, and C.F. Schleussner, 2018: Committed sea-level rise under the Paris Agreement and the legacy of delayed mitigation action. *Nat. Commun.*, **9(1)**, 601, doi:10.1038/s41467-018-02985-8.

Mercure, J.F. et al., 2018: Macroeconomic impact of stranded fossil fuel assets. *Nat. Clim. Change*, **8(7)**, 588–593, doi:10.1038/s41558-018-0182-1.

Mercure, J.F. et al., 2019: Modelling innovation and the macroeconomics of low-carbon transitions: theory, perspectives and practical use. *Clim. Policy*, **19(8)**, 1019–1037, doi:10.1080/14693062.2019.1617665.

Messner, D., 2015: A social contract for low carbon and sustainable development. Reflections on non-linear dynamics of social realignments and technological innovations in transformation processes. *Technol. Forecast. Soc. Change*, **98**, 260–270, doi:10.1016/j.techfore.2015.05.013.

Meyer, M., A. Löschel, and C. Lutz, 2021: Carbon price dynamics in ambitious climate mitigation scenarios: an analysis based on the IAMC 1.5°C scenario explorer. *Environ. Res. Commun.*, **3(8)**, 81007, doi:10.1088/2515-7620/ac02ad.

Millward-Hopkins, J. and Y. Oswald, 2021: 'Fair' inequality, consumption and climate mitigation. *Environ. Res. Lett.*, **16(3)**, 34007, doi:10.1088/1748-9326/abe14f.

Millward-Hopkins, J., J.K. Steinberger, N.D. Rao, and Y. Oswald, 2020: Providing decent living with minimum energy: A global scenario. *Glob. Environ. Change*, **65**, 102168, doi.org/10.1016/j.gloenvcha.2020.102168.

Mima, S. and P. Criqui, 2015: The Costs of Climate Change for the European Energy System, an Assessment with the POLES Model. *Environ. Model. Assess.*, **20(4)**, 303–319, doi:10.1007/s10666-015-9449-3.

Mitchell, S.R., M.E. Harmon, and K.E.B. O'Connell, 2012: Carbon debt and carbon sequestration parity in forest bioenergy production. *GCB Bioenergy*, **4**, 818–827, doi:10.1111/j.1757-1707.2012.01173.x.

Mittal, S., H. Dai, S. Fujimori, T. Hanaoka, and R. Zhang, 2017: Key factors influencing the global passenger transport dynamics using the AIM/transport model. *Transp. Res. Part D Transp. Environ.*, **55**, 373–388, doi:10.1016/j.trd.2016.10.006.

Moallemi, E.A., L. Aye, F.J. de Haan, and J.M. Webb, 2017: A dual narrative-modelling approach for evaluating socio-technical transitions in electricity sectors. *J. Clean. Prod.*, **162**, 1210–1224, doi:10.1016/j.jclepro.2017.06.118.

Molotoks, A. et al., 2020: Comparing the impact of future cropland expansion on global biodiversity and carbon storage across models and scenarios. *Philos. Trans. R. Soc. B Biol. Sci.*, **375(1794)**, 20190189, doi:10.1098/rstb.2019.0189.

Moore, F.C. and D.B. Diaz, 2015: Temperature impacts on economic growth warrant stringent mitigation policy. *Nat. Clim. Change*, **5(2)**, 127–131, doi:10.1038/nclimate2481.

Moreno-Cruz, J.B. and S. Smulders, 2017: Revisiting the economics of climate change: the role of geoengineering. *Res. Econ.*, **71(2)**, 212–224, doi:10.1016/j.rie.2016.12.001.

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.

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. *Environ. Sci. Policy*, **64**, 48–58, doi:10.1016/J.ENVSCI.2016.06.007.

Moyer, E.J., M.D. Woolley, N.J. Matteson, M.J. Glotter, and D.A. Weisbach, 2014: Climate impacts on economic growth as drivers of uncertainty in the social cost of carbon. *J. Legal Stud.*, **43(2)**, 401–425, doi:10.1086/678140.

Muldoon-Smith, K. and P. Greenhalgh, 2019: Suspect foundations: Developing an understanding of climate-related stranded assets in the global real estate sector. *Energy Res. Soc. Sci.*, **54**, 60–67, doi:10.1016/j.erss.2019.03.013.

Müller-Casseres, E. et al., 2021a: Production of alternative marine fuels in Brazil: An integrated assessment perspective. *Energy*, **219**, 119444, doi.org/10.1016/j.energy.2020.119444.

Müller-Casseres, E., O.Y. Edelenbosch, A. Szklo, R. Schaeffer, and D.P. van Vuuren, 2021b: Global futures of trade impacting the challenge to decarbonize the international shipping sector. *Energy*, **237**, 121547, doi:10.1016/j.energy.2021.121547.

Mundaca, L., D. Ürge-Vorsatz, and C. Wilson, 2019: Demand-side approaches for limiting global warming to 1.5 °C. *Energy Effic.*, **12(2)**, 343–362, doi:10.1007/s12053-018-9722-9.

Muratori, M. et al., 2020: EMF-33 insights on bioenergy with carbon capture and storage (BECCS). *Clim. Change*,, doi:10.1007/s10584-020-02784-5.

Murphy, K.J., 2002: Explaining executive compensation: Managerial power versus the perceived cost of stock options. *Univ. Chicago Law Rev.*, **69(3)**, 847–869, doi:10.2307/1600633.

Murray, B. and N. Rivers, 2015: British Columbia's revenue-neutral carbon tax: A review of the latest 'grand experiment' in environmental policy. *Energy Policy*, **86**, 674–683, doi.org/10.1016/j.enpol.2015.08.011.

Napp, T. et al., 2017: Exploring the feasibility of low-carbon scenarios using historical energy transitions analysis. *Energies*, **10(1)**, doi:10.3390/en10010116.

Napp, T.A. et al., 2019: The role of advanced demand-sector technologies and energy demand reduction in achieving ambitious carbon budgets. *Appl. Energy*, **238** (January), 351–367, doi:10.1016/j.apenergy.2019.01.033.

NASEM, 2017: *Valuing climate damages: updating estimation of the social cost of carbon dioxide*. National Academies of Sciences, Engineering, and Medicine, National Academies Press, Washington, DC, 280 pp.

NASEM, 2019: *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.* National Academies of Sciences, Engineering, and Medicine, National Academies Press, Washington D.C, USA, 510 pp.

NASEM, 2021: *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*. National Academies of Sciences, Engineering, and Medicine, National Academies Press, Washington D.C, USA, 328 pp.

Naumann, G. et al., 2018: Global Changes in Drought Conditions Under Different Levels of Warming. *Geophys. Res. Lett.*, **45(7)**, 3285–3296, doi:10.1002/2017GL076521.

Nemet, G.F. et al., 2018: Negative emissions – Part 3: Innovation and upscaling. *Environ. Res. Lett.*, **13(6)**, 063003, doi:10.1088/1748-9326/aabff4.

Network for Greening the Financial System, 2021: NGFS Climate Scenarios for central banks and supervisors. https://www.ngfs.net/ngfs-scenarios-portal/.

Neumann, F. and T. Brown, 2021: The near-optimal feasible space of a renewable power system model. *Electr. Power Syst. Res.*, **190**, 106690, doi:10.1016/j.epsr.2020.106690.

Ng, T.L., J.W. Eheart, X. Cai, and F. Miguez, 2010: Modeling miscanthus in the Soil and Water Assessment Tool (SWAT) to simulate its water quality effects as a bioenergy crop. *Environ. Sci. Technol.*, **44(18)**, 7138–7144, doi:10.1021/es9039677.

Niamir, L., T. Filatova, A. Voinov, and H. Bressers, 2018: Transition to low-carbon economy: Assessing cumulative impacts of individual behavioral changes. *Energy Policy*, **118**, 325–345, doi:10.1016/j.enpol.2018.03.045.

Niamir, L. et al., 2020: Assessing the macroeconomic impacts of individual behavioral changes on carbon emissions. *Clim. Change*, **158(2)**, 141–160, doi:10.1007/s10584-019-02566-8.

Nicholls, Z. et al., 2021: Reduced Complexity Model Intercomparison Project Phase 2: Synthesizing Earth System Knowledge for Probabilistic Climate Projections. *Earth's Future*, **9(6)**, e2020EF001900, doi.org/10.1029/2020EF001900.

Nielsen, K.S. et al., 2020: Improving Climate Change Mitigation Analysis: A Framework for Examining Feasibility. *One Earth*, **3(3)**, 325–336, doi:10.1016/j.oneear.2020.08.007.

Nieto, J., Ó. Carpintero, L.J. Miguel, and I. de Blas, 2020: Macroeconomic modelling under energy constraints: {Global} low carbon transition scenarios. *Energy Policy*, **137**, 111090, doi:10.1016/j.enpol.2019.111090.

Nikas, A. et al., 2021: Perspective of comprehensive and comprehensible multi-model energy and climate science in Europe. *Energy*, **215**, 119153, doi:10.1016/j.energy.2020.119153.

Nordhaus, W., 2015: Climate clubs: Overcoming free-riding in international climate policy. *Am. Econ. Rev.*, **105(4)**, 1339–1370, doi:10.1257/aer.15000001.

Nordhaus, W., 2019: Economics of the disintegration of the Greenland ice sheet. *Proc. Natl. Acad. Sci.*, **116(25)**, 12261 LP–12269, doi:10.1073/pnas.1814990116.

Numminen, S. and P. Lund, 2019: Evaluation of the reliability of solar micro-grids in emerging markets – Issues and solutions. *Energy Sustain. Dev.*, **48**, 34–42, doi:10.1016/j.esd.2018.10.006.

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

O'Neill, B.C. et al., 2016: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci. Model Dev.*, **9(9)**, 3461–3482, doi:10.5194/gmd-9-3461-2016.

O'Neill, B.C. et al., 2017a: The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Change*, **42**, 169–180, doi:10.1016/j.gloenvcha.2015.01.004.

O'Neill, B.C. et al., 2017b: IPCC reasons for concern regarding climate change risks. *Nat. Clim. Change*, **7(1)**, 28–37, doi:10.1038/nclimate3179.

O'Neill, B., M. van Aalst, Z. Zaiton Ibrahim, L. Berrang Ford, S. Bhadwal, H. Buhaug, D. Diaz, K. Frieler, M. Garschagen, A. Magnan, G. Midgley, A. Mirzabaev, A. Thomas, and R. Warren, 2022: Key Risks Across Sectors and Regions. In: *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (in press).

O'Neill, B.C. et al., 2020b: Achievements and needs for the climate change scenario framework. *Nat. Clim. Change*, **10(12)**, 1074–1084, doi:10.1038/s41558-020-00952-0.

O'Sullivan, J.N., 2018: Synergy between Population Policy, Climate Adaptation and Mitigation BT – Pathways to a Sustainable Economy: Bridging the Gap between Paris Climate Change Commitments and Net Zero Emissions. [Hossain, M., R. Hales, and T. Sarker, (eds.)], Springer International Publishing, Cham, Switzerland, pp. 103–125.

Ó Broin, E. and C. Guivarch, 2017: Transport infrastructure costs in low-carbon pathways. *Transp. Res. Part D Transp. Environ.*, **55**, 389–403, doi:10.1016/j.trd.2016.11.002.

Obersteiner, M. et al., 2016: Assessing the land resource–food price nexus of the Sustainable Development Goals. *Sci. Adv.*, **2(9)**, e1501499, doi:10.1126/sciadv.1501499.

OECD, 2021: Real GDP long-term forecast (indicator). *OECD Data*, doi:10.1787/d927bc18-en.

Ohashi, H. et al., 2019: Biodiversity can benefit from climate stabilization despite adverse side effects of land-based mitigation. *Nat. Commun.*, **10(1)**, 5240, doi:10.1038/s41467-019-13241-y.

Ohlendorf, N., M. Jakob, J.C. Minx, C. Schröder, and J.C. Steckel, 2021: Distributional Impacts of Carbon Pricing: A Meta-Analysis. *Environ. Resour. Econ.*, **78(1)**, 1–42, doi:10.1007/s10640-020-00521-1.

Oswald, Y., J.K. Steinberger, D. Ivanova, and J. Millward-Hopkins, 2021: Global redistribution of income and household energy footprints: a computational thought experiment. *Glob. Sustain.*, **4**, e4, doi: 10.1017/sus.2021.1.

Otto, I.M., K.M. Kim, N. Dubrovsky, and W. Lucht, 2019: Shift the focus from the super-poor to the super-rich. *Nat. Clim. Change*, **9(2)**, 82–84, doi:10.1038/s41558-019-0402-3.

Ou, Y. et al., 2021: Deep Mitigation of CO_2 and non-CO_2 Greenhouse Gases towards 1.5°C and 2°C Futures. *Nat. Commun.*, **12,** 6245, doi; 10.1038/s41467-021-26509-z.

Pachauri, S., 2014: Household electricity access a trivial contributor to CO_2 emissions growth in India. *Nat. Clim. Change*, **4(12)**, 1073–1076, doi:10.1038/nclimate2414.

Pachauri, S. et al., 2013: Pathways to achieve universal household access to modern energy by 2030. *Environ. Res. Lett.*, **8(2)**, doi:10.1088/1748-9326/8/2/024015.

Pahle, M. et al., 2018: Sequencing to ratchet up climate policy stringency. *Nat. Clim. Change*, **8(10)**, 861–867, doi:10.1038/s41558-018-0287-6.

Pai, S., J. Emmerling, L. Drouet, H. Zerriffi, and J. Jewell, 2021: Meeting well-below 2°C target would increase energy sector jobs globally. *One Earth*, **4(7)**, 1026–1036, doi.org/10.1016/j.oneear.2021.06.005.

Paltsev, S., J. Morris, H. Kheshgi, and H. Herzog, 2021: Hard-to-Abate Sectors: The role of industrial carbon capture and storage (CCS) in emission mitigation. *Appl. Energy*, **300** (June), doi:10.1016/j.apenergy.2021.117322.

Pan, X., M. den Elzen, N. Höhne, F. Teng, and L. Wang, 2017: Exploring fair and ambitious mitigation contributions under the Paris Agreement goals. *Environ. Sci. Policy*, **74**, 49–56, doi:10.1016/j.envsci.2017.04.020.

Pan, X. et al., 2020: Implications of near-term mitigation on China's long-term energy transitions for aligning with the Paris goals. *Energy Econ.*, **90**, 104865, doi:10.1016/j.eneco.2020.104865.

Parkinson, S. et al., 2019: Balancing clean water-climate change mitigation trade-offs. *Environ. Res. Lett.*, **14(1)**, 014009, doi:10.1088/1748-9326/aaf2a3.

Parmesan, C. and M.E. Hanley, 2015: Plants and climate change: Complexities and surprises. *Ann. Bot.*, **116(6)**, 849–864, doi:10.1093/aob/mcv169.

Paroussos, L. et al., 2019: Climate clubs and the macro-economic benefits of international cooperation on climate policy. *Nat. Clim. Change*, **9(7)**, 542–546, doi:10.1038/s41558-019-0501-1.

Paslakis, G., G. Dimitropoulos, and D.K. Katzman, 2021: A call to action to address COVID-19–induced global food insecurity to prevent hunger, malnutrition, and eating pathology. *Nutr. Rev.*, **79(1)**, 114–116, doi:10.1093/nutrit/nuaa069.

Patterson, J.J. et al., 2018: Political feasibility of 1.5°C societal transformations: the role of social justice. *Curr. Opin. Environ. Sustain.*, **31**, 1–9, doi:10.1016/j.cosust.2017.11.002.

Pauliuk, S., A. Arvesen, K. Stadler, and E.G. Hertwich, 2017: Industrial ecology in integrated assessment models. *Nat. Clim. Change*, **7(1)**, 13–20, doi:10.1038/nclimate3148.

Pedersen, J.S.T. et al., 2020: Variability in historical emissions trends suggests a need for a wide range of global scenarios and regional analyses. *Commun. Earth Environ.*, **1(1)**, 1–7, doi:10.1038/s43247-020-00045-y.

Pehl, M. et al., 2017: Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. *Nat. Energy*, **2(12)**, 939–945, doi:10.1038/s41560-017-0032-9.

Perrier, Q. and P. Quirion, 2018: How shifting investment towards low-carbon sectors impacts employment: Three determinants under scrutiny. *Energy Econ.*, **75**, 464–483, doi:10.1016/j.eneco.2018.08.023.

Peters, G.P. and O. Geden, 2017: Catalysing a political shift from low to negative carbon. *Nat. Clim. Change*, **7(9)**, 619–621, doi:10.1038/nclimate3369.

Pfeiffer, A., C. Hepburn, A. Vogt-Schilb, and B. Caldecott, 2018: Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. *Environ. Res. Lett.*, **13(5)**, doi:10.1088/1748-9326/aabc5f.

Pfenninger, S. and J. Keirstead, 2015: Renewables, nuclear, or fossil fuels? Scenarios for Great Britain's power system considering costs, emissions and energy security. *Appl. Energy*, **152**, 83–93, doi.org/10.1016/j.apenergy.2015.04.102.

Pianta, S., E. Brutschin, B. van Ruijven, and V. Bosetti, 2021: Faster or slower decarbonization? Policymaker and stakeholder expectations on the effect of the COVID-19 pandemic on the global energy transition. *Energy Res. Soc. Sci.*, **76**, 102025, doi.org/10.1016/j.erss.2021.102025.

Pielke, R. and J. Ritchie, 2021: Distorting the view of our climate future: The misuse and abuse of climate pathways and scenarios. *Energy Res. Soc. Sci.*, **72**, 101890, doi.org/10.1016/j.erss.2020.101890.

Pierson, P., 2000: Increasing Returns, Path Dependence, and the Study of Politics. *Am. Polit. Sci. Rev.*, **94(2)**, 251–267, doi:10.2307/2586011.

Pietzcker, R.C. et al., 2014: Long-term transport energy demand and climate policy: Alternative visions on transport decarbonization in energy-economy models. *Energy*, **64**, 95–108, doi:10.1016/j.energy.2013.08.059.

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 Econ.*, **64**, 583–599, doi.org/10.1016/j.eneco.2016.11.018.

Pihl, H., 2020: A Climate Club as a complementary design to the UN Paris agreement. *Policy Des. Pract.*, **3(1)**, 45–57, doi:10.1080/25741292.2019.1710911.

Pindyck, R.S., 2017: The use and misuse of models for climate policy. *Rev. Environ. Econ. Policy*, **11(1)**, 100–114, doi:10.1093/reep/rew012.

Piontek, F. et al., 2019: Economic Growth Effects of Alternative Climate Change Impact Channels in Economic Modeling. *Environ. Resour. Econ.*, **73(4)**, 1357–1385, doi:10.1007/s10640-018-00306-7.

Pizer, W.A. and S. Sexton, 2019: The Distributional Impacts of Energy Taxes. *Rev. Environ. Econ. Policy*, **13(1)**, 104–123, doi:10.1093/reep/rey021.

Poblete-Cazenave, M., S. Pachauri, E. Byers, A. Mastrucci, and B. van Ruijven, 2021: Global scenarios of household access to modern energy services under climate mitigation policy. *Nat. Energy*, **6(8)**, 824–833, doi:10.1038/s41560-021-00871-0.

Pollitt, H. and J.F. Mercure, 2018: The role of money and the financial sector in energy-economy models used for assessing climate and energy policy. *Clim. Policy*, **18(2)**, 184–197, doi:10.1080/14693062.2016.1277685.

Pollitt, H., E. Alexandri, U. Chewpreecha, and G. Klaassen, 2015: Macroeconomic analysis of the employment impacts of future EU climate policies. *Clim. Policy*, **15(5)**, 604–625, doi:10.1080/14693062.2014.953907.

Pollitt, H., R. Lewney, B. Kiss-Dobronyi, and X. Lin, 2021: Modelling the economic effects of COVID-19 and possible green recovery plans: a post-Keynesian approach. *Clim. Policy*, **21 (10)**, 1257–1271, doi:10.1080/14693062.2021.1965525.

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. *Clim. 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. *Glob. Environ. Change*, **42**, 331–345, doi:10.1016/j.gloenvcha.2016.10.002.

Pretis, F., M. Schwarz, K. Tang, K. Haustein, and M.R. Allen, 2018: Uncertain impacts on economic growth when stabilizing global temperatures at 1.5°C or 2°C warming. *Phil. Trans. R. Soc. A*, **376(2119)**, 20160460, doi:10.1098/rsta.2016.0460.

Price, J., and I. Keppo, 2017: Modelling to generate alternatives: A technique to explore uncertainty in energy-environment-economy models. *Appl. Energy*, **195**, 356–369, doi:10.1016/j.apenergy.2017.03.065.

Pye, S. et al., 2018: Assessing qualitative and quantitative dimensions of uncertainty in energy modelling for policy support in the United Kingdom. *Energy Res. Soc. Sci.*, **46**, 332–344, doi.org/10.1016/j.erss.2018.07.028.

Rafaj, P. et al., 2018: Outlook for clean air in the context of sustainable development goals. *Glob. Environ. Change*, **53**, 1–11, doi.org/10.1016/j.gloenvcha.2018.08.008.

Rafaj, P. et al., 2021: Air quality and health implications of 1.5°C–2°C climate pathways under considerations of ageing population: a multi-model scenario analysis. *Environ. Res. Lett.*, **16(4)**, 45005, doi:10.1088/1748-9326/abdf0b.

Ranzani, A., M. Bonato, E.R. Patro, L. Gaudard, and C. De Michele, 2018: Hydropower future: Between climate change, renewable deployment, carbon and fuel prices. *Water (Switzerland)*, **10(9)**, 1–17, doi:10.3390/w10091197.

Rao, N.D., 2014: International and intranational equity in sharing climate change mitigation burdens. *Int. Environ. Agreements Polit. Law Econ.*, **14(2)**, 129–146, doi:10.1007/s10784-013-9212-7.

Rao, N.D. and J. Min, 2018: Less global inequality can improve climate outcomes. *Wiley Interdiscip. Rev. Clim. Change*, **9(2)**, 1–6, doi:10.1002/wcc.513.

Rao, N.D., B.J. Van Ruijven, K. Riahi, and V. Bosetti, 2017a: Improving poverty and inequality modelling in climate research. *Nat. Clim. Change*, **7(12)**, 857–862, doi:10.1038/s41558-017-0004-x.

Rao, N.D., J. Min, and A. Mastrucci, 2019a: Energy requirements for decent living in India, Brazil and South Africa. *Nat. Energy*, **4(12)**, 1025–1032, doi:10.1038/s41560-019-0497-9.

Rao, N.D., P. Sauer, M. Gidden, and K. Riahi, 2019b: Income inequality projections for the Shared Socioeconomic Pathways (SSPs). *Futures*, **105**, 27–39, doi.org/10.1016/j.futures.2018.07.001.

Rao, S. et al., 2016: A multi-model assessment of the co-benefits of climate mitigation for global air quality. *Environ. Res. Lett.*, **11(12)**, doi:10.1088/1748-9326/11/12/124013.

Rao, S. et al., 2017b: Future air pollution in the Shared Socio-economic Pathways. *Glob. Environ. Chang.*, **42**, 346–358, doi:10.1016/j.gloenvcha.2016.05.012.

Rauner, S. et al., 2020a: Coal-exit health and environmental damage reductions outweigh economic impacts. *Nat. Clim. Change*, **10**, 308–312, doi:10.1038/s41558-020-0728-x.

Rauner, S., J. Hilaire, D. Klein, J. Strefler, and G. Luderer, 2020b: Air quality co-benefits of ratcheting up the NDCs. *Clim. Change*, **163**,1481–1500, doi:10.1007/s10584-020-02699-1.

Realmonte, G. et al., 2019: An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nat. Commun.*, **10(1)**, 1–12, doi:10.1038/s41467-019-10842-5.

Reisinger, A. et al., 2021: How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals? *Philos. Trans. R. Soc. A*, **379(20200452)**. http://doi.org/10.1098/rsta.2020.0452.

Rengs, B., M. Scholz-Wäckerle, and J. van den Bergh, 2020: Evolutionary macroeconomic assessment of employment and innovation impacts of climate policy packages. *J. Econ. Behav. Organ.*, **169**, 332–368, doi.org/10.1016/j.jebo.2019.11.025.

3

Rezai, A., L. Taylor, and D. Foley, 2018: Economic Growth, Income Distribution, and Climate Change. *Ecol. Econ.*, **146**, 164–172, doi:10.1016/j.ecolecon.2017.10.020.

Riahi, K. et al., 2012: Chapter 17 – Energy Pathways for Sustainable Development. 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. 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. *Technol. Forecast. Soc. Change*, **90(A)**, 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. *Glob. Environ. Change*, **42**, 153–168, doi:10.1016/j.gloenvcha.2016.05.009.

Riahi, K. et al., 2021: Long-term economic benefits of stabilizing warming without overshoot – the ENGAGE model intercomparison. *Nat. Clim. Change* (in press), doi: 10.1038/s41558-021-01215-2.

Ribas, A., A.F.P. Lucena, and R. Schaeffer, 2017: Bridging the energy divide and securing higher collective well-being in a climate-constrained world. *Energy Policy*, **108**, 435–450, doi:10.1016/j.enpol.2017.06.017.

Ribas, A., A.F.P. Lucena, and R. Schaeffer, 2019: Closing the energy divide in a climate-constrained world: A focus on the buildings sector. *Energy Build.*, **199**, 264–274, doi:10.1016/j.enbuild.2019.06.053.

Rickards, L., J. Wiseman, and Y. Kashima, 2014: Barriers to effective climate change mitigation: the case of senior government and business decision makers. *WIREs Clim. Change*, **5(6)**, 753–773, doi.org/10.1002/wcc.305.

Ricke, K., L. Drouet, K. Caldeira, and M. Tavoni, 2018: Country-level social cost of carbon. *Nat. Clim. Change*, **8(10)**, 895–900, doi:10.1038/s41558-018-0282-y.

Rickels, W., F. Reith, D. Keller, A. Oschlies, and M.F. Quaas, 2018: Integrated Assessment of Carbon Dioxide Removal. *Earth's Future*, **6(3)**, 565–582, doi:10.1002/2017EF000724.

Rickels, W. et al., 2020: Who turns the global thermostat and by how much? *Energy Econ.*, **91**, 104852, doi.org/10.1016/j.eneco.2020.104852.

Roberts, J.T. et al., 2020: Four agendas for research and policy on emissions mitigation and well-being. *Glob. Sustain.*, **3**, doi:10.1017/sus.2019.25.

Robertson, S., 2020: Transparency, trust, and integrated assessment models: An ethical consideration for the Intergovernmental Panel on Climate Change. *Wiley Interdiscip. Rev. Clim. Change*, e679, doi:10.1002/wcc.679.

Rochedo, P.R.R. et al., 2018: The threat of political bargaining to climate mitigation in Brazil. *Nat. Clim. Change*, **8(8)**, 695–698, doi:10.1038/s41558-018-0213-y.

Rochedo, P.R.R. et al., 2021: Is Green Recovery Enough? Analysing the Impacts of Post-COVID-19 Economic Packages. *Energies*, **14**(17), doi:10.3390/en14175567.

Röder, M. et al., 2019: Understanding the timing and variation of greenhouse gas emissions of forest bioenergy systems. *Biomass and Bioenergy*, **121**, 99–114, doi.org/10.1016/j.biombioe.2018.12.019.

Roe, S. et al., 2019: Contribution of the land sector to a 1.5°C world. *Nat. Clim. Change*, **9**(11), 817–828, doi:10.1038/s41558-019-0591-9.

Roelfsema, M. et al., 2018: Reducing global GHG emissions by replicating successful sector examples: the 'good practice policies' scenario. *Clim. Policy*, **18(9)**, 1103–1113, doi:10.1080/14693062.2018.1481356.

Roelfsema, M. et al., 2020: Taking stock of national climate policies to evaluate implementation of the Paris Agreement. *Nat. Commun.*, **11(1)**, 2096, doi:10.1038/s41467-020-15414-6.

Rogelj, J., D.L. Mccollum, B.C. O'Neill, and K. Riahi, 2013a: 2020 emissions levels required to limit warming to below 2°C. *Nat. Clim. 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 CO_2 and short-lived climate forcer mitigation. *Proc. Natl. Acad. Sci.*, **111(46)**, 16325 LP–16330, doi:10.1073/pnas.1415631111.

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. *Environ. Res. Lett.*, **10(7)**, 075001, doi:10.1088/1748-9326/10/7/075001.

Rogelj, J. et al., 2015b: Mitigation choices impact carbon budget size compatible with low temperature goals. *Environ. Res. Lett.*, **10(7)**, 75003, doi:10.1088/1748-9326/10/7/075003.

Rogelj, J. et al., 2015c: Zero emission targets as long-term global goals for climate protection. *Environ. Res. Lett.*, **10(10)**, 105007, doi:10.1088/1748-9326/10/10/105007.

Rogelj, J. et al., 2016: 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., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférian, and M.V. Vilariño, 2018: Mitigation pathways compatible with 1.5°C in the context of sustainable development. In: *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* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Rogelj, J. et al., 2018b: Scenarios towards limiting global mean temperature increase below 1.5 °c. *Nat. Clim. Change*, **8(4)**, 325–332, doi:10.1038/s41558-018-0091-3.

Rogelj, J., P.M. Forster, E. Kriegler, C.J. Smith, and R. Séférian, 2019a: Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature*, **571(7765)**, 335–342, doi:10.1038/s41586-019-1368-z.

Rogelj, J. et al., 2019b: A new scenario logic for the Paris Agreement long-term temperature goal. *Nature*, **573(7774)**, 357–363, doi:10.1038/s41586-019-1541-4.

Rogelj, J., O. Geden, A. Cowie, and A. Reisinger, 2021: Net-zero emissions targets are vague: three ways to fix. *Nature*, **591**, 365–368, doi.org/10.1038/d41586-021-00662-3.

Rose, A., D. Wei, N. Miller, and T. Vandyck, 2017a: Equity, Emissions Allowance Trading and the Paris Agreement on Climate Change. *Econ. Disasters Clim. Change*, **1(3)**, 203–232, doi:10.1007/s41885-017-0012-3.

Rose, S.K., D.B. Diaz, and G.J. Blanford, 2017b: Understanding the social cost of carbon: a model diagnostic and inter-comparison study. *Clim. Change Econ.*, **08(02)**, 1750009, doi:10.1142/S2010007817500099.

Rosen, R.A., 2021: Why the shared socioeconomic pathway framework has not been useful for improving climate change mitigation policy analysis. *Technol. Forecast. Soc. Change*, **166**, 120611, doi.org/10.1016/j.techfore.2021.120611.

Rozenberg, J. and M. Fay, 2019: Making Infrastructure Needs Assessments Useful and Relevant. In: *Beyond the Gap: How Countries Can Afford the Infrastructure They Need while Protecting the Planet*, *Sustainable Infrastructure Series*, The World Bank, Washington, DC, pp. 29–46. https://openknowledge.worldbank.org/handle/10986/31291. (Accesssed December 1, 2021).

Rozenberg, J., S.J. Davis, U. Narloch, and S. Hallegatte, 2015: Climate constraints on the carbon intensity of economic growth. *Environ. Res. Lett.*, **10(9)**, 95006, doi:10.1088/1748-9326/10/9/095006.

Rozenberg, J., A. Vogt-Schilb, and S. Hallegatte, 2018: Instrument choice and stranded assets in the transition to clean capital. *J. Environ. Econ. Manage.*, **100**, 102183, doi:10.1016/j.jeem.2018.10.005.

3

Sachs, J.D. et al., 2019: Six Transformations to achieve the Sustainable Development Goals. *Nat. Sustain.*, **2(9)**, 805–814, doi:10.1038/s41893-019-0352-9.

Sager, L., 2019: Income inequality and carbon consumption: Evidence from Environmental Engel curves. *Energy Econ.*, **84**, 104507, doi:10.1016/j.eneco.2019.104507.

Samadi, S. et al., 2017: Sufficiency in energy scenario studies: Taking the potential benefits of lifestyle changes into account. *Technol. Forecast. Soc. Change*, **124**, 126–134, doi:10.1016/j.techfore.2016.09.013.

Sanderson, B.M. and B.C. O'Neill, 2020: Assessing the costs of historical inaction on climate change. *Sci. Rep.*, **10(1)**, 1–12, doi:10.1038/s41598-020-66275-4.

Sanderson, B.M., B.C. O'Neill, and C. Tebaldi, 2016: What would it take to achieve the Paris temperature targets? *Geophys. Res. Lett.*, **43(13)**, 7133–7142, doi:10.1002/2016GL069563.

Sanjuán, M.A., C. Argiz, P. Mora, and A. Zaragoza, 2020: Carbon Dioxide Uptake in the Roadmap 2050 of the Spanish Cement Industry. *Energies*, **13(13)**, doi:10.3390/en13133452.

Santangeli, A. et al., 2016: Global change synergies and trade-offs between renewable energy and biodiversity. *GCB Bioenergy*, **8(5)**, 941–951, doi.org/10.1111/gcbb.12299.

Savelsberg, J., M. Schillinger, I. Schlecht, and H. Weigt, 2018: The impact of climate change on Swiss hydropower. *Sustainability*, **10(7)**, doi:10.3390/su10072541.

Saygin, D., J. Rigter, B. Caldecott, N. Wagner, and D. Gielen, 2019: Power sector asset stranding effects of climate policies. *Energy Sources, Part B Econ. Plan. Policy*, **14(4)**, 99–124, doi:10.1080/15567249.2019.1618421.

Ščasný, M., E. Massetti, J. Melichar, and S. Carrara, 2015: Quantifying the Ancillary Benefits of the Representative Concentration Pathways on Air Quality in Europe. *Environ. Resour. Econ.*, **62(2)**, 383–415, doi:10.1007/s10640-015-9969-y.

Scherer, L. et al., 2018: Trade-offs between social and environmental Sustainable Development Goals. *Environ. Sci. Policy*, **90**, 65–72, doi:10.1016/j.envsci.2018.10.002.

Schewe, J. et al., 2014: Multimodel assessment of water scarcity under climate change. *Proc. Natl. Acad. Sci.*, **111(9)**, 3245–3250, doi:10.1073/pnas.1222460110.

Schinko, T., G. Bachner, S.P. Schleicher, and K.W. Steininger, 2017: Modeling for insights not numbers: The long-term low-carbon transformation. *Atmósfera*, **30(2)**, 137–161, doi.org/10.20937/ATM.2017.30.02.05.

Schleussner, C.F. et al., 2016a: Differential climate impacts for policy-relevant limits to global warming: The case of 1.5°C and 2°C. *Earth Syst. Dyn.*, **7(2)**, 327–351, doi:10.5194/esd-7-327-2016.

Schleussner, C.F. et al., 2016b: Science and policy characteristics of the Paris Agreement temperature goal. *Nat. Clim. Change*, **6**(9), 827–835, doi:10.1038/nclimate3096.

Schlosser, C.A. et al., 2014: The future of global water stress: An integrated assessment. *Earth's Future*, **2(8)**, 341–361, doi:10.1002/2014ef000238.

Schucht, S. et al., 2015: Moving towards ambitious climate policies: Monetised health benefits from improved air quality could offset mitigation costs in Europe. *Environ. Sci. Policy*, **50**, 252–269, doi.org/10.1016/j.envsci.2015.03.001.

Schultes, A. et al., 2018: Optimal international technology cooperation for the low-carbon transformation. *Clim. Policy*, **18(9)**, 1165–1176, doi:10.1080/14693062.2017.1409190.

Schultes, A. et al., 2021: Economic damages from on-going climate change imply deeper near-term emission cuts. *Environ. Res. Lett.*, **16**, 104053, doi:10.1088/1748-9326/ac27ce.

Scovronick, N. et al., 2017: Impact of population growth and population ethics on climate change mitigation policy. *Proc. Natl. Acad. Sci.*, **114(46)**, 12338 LP–12343, doi:10.1073/pnas.1618308114.

Scovronick, N. et al., 2019a: The impact of human health co-benefits on evaluations of global climate policy. *Nat. Commun.*, **10(1)**, 1–12, doi:10.1038/s41467-019-09499-x.

Scovronick, N. et al., 2019b: Human Health and the Social Cost of Carbon: A Primer and Call to Action. *Epidemiology*, **30(5)**, 642–647, doi: 10.1097/EDE.0000000000001057.

Scovronick, N. et al., 2021: The importance of health co-benefits under different climate policy cooperation frameworks. *Environ. Res. Lett.*, **16(5)**, 55027, doi:10.1088/1748-9326/abf2e7.

Séférian, R., M. Rocher, C. Guivarch, and J. Colin, 2018: Constraints on biomass energy deployment in mitigation pathways: The case of water scarcity. *Environ. Res. Lett.*, **13(5)**, doi:10.1088/1748-9326/aabcd7.

SEI, IISD, ODI, E3G, and UNEP, 2020: *The Production Gap Report: 2020 Special Report*. http://productiongap.org/2020report.

Semieniuk, G., L. Taylor, A. Rezai, and D.K. Foley, 2021: Plausible energy demand patterns in a growing global economy with climate policy. *Nat. Clim. Change*, **11(4)**, 313–318, doi:10.1038/s41558-020-00975-7.

Sepulveda, N.A., J.D. Jenkins, F.J. de Sisternes, and R.K. Lester, 2018: The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation. *Joule*, **2(11)**, 2403–2420, doi.org/10.1016/j.joule.2018.08.006.

Shan, Y. et al., 2021: Impacts of COVID-19 and fiscal stimuli on global emissions and the Paris Agreement. *Nat. Clim. Change*, **11(3)**, 200–206, doi:10.1038/s41558-020-00977-5.

Sharmina, M. et al., 2020: Decarbonising the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5–2°C. *Clim. Policy*, **0(0)**, 1–20, doi:10.1080/14693062.2020.1831430.

Shayegh, S., V. Bosetti, and M. Tavoni, 2021: Future Prospects of Direct Air Capture Technologies: Insights From an Expert Elicitation Survey. **3** (May), 1–14, doi:10.3389/fclim.2021.630893.

Shindell, D., 2020: Health and Economic Benefits of a 2°C Climate Policy. Testimony to the House Committee on Oversight and Reform. Hearing on 'The Devastating Impacts of Climate Change on Health'. https://nicholas.duke.edu/sites/default/files/documents/Shindell_Testimony_July2020_final.pdf.

Shindell, D. and C.J. Smith, 2019: Climate and air-quality benefits of a realistic phase-out of fossil fuels. *Nature*, **573(7774)**, 408–411, doi:10.1038/s41586-019-1554-z.

Shindell, D. 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. et al., 2017a: A climate policy pathway for near- and long-term benefits. *Science*, **356(6337)**, 493–494, doi:10.1126/science.aak9521.

Shindell, D., G. Faluvegi, K. Seltzer, and C. Shindell, 2018: Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. *Nat. Clim. Change*, **8(4)**, 291–295, doi:10.1038/s41558-018-0108-y.

Shindell, D.T., J.S. Fuglestvedt, and W.J. Collins, 2017b: The social cost of methane: theory and applications. *Faraday Discuss.*, **200(0)**, 429–451, doi:10.1039/C7FD00009J.

Simioni, T. and R. Schaeffer, 2019: Georeferenced operating-efficiency solar potential maps with local weather conditions – An application to Brazil. *Sol. Energy*, **184** (October 2018), 345–355, doi:10.1016/j.solener.2019.04.006.

Sinha, E., A.M. Michalak, K.V. Calvin, and P.J. Lawrence, 2019: Societal decisions about climate mitigation will have dramatic impacts on eutrophication in the 21st century. *Nat. Commun.*, **10(1)**, 939, doi:10.1038/s41467-019-08884-w.

Skeie, R.B., G.P. Peters, J. Fuglestvedt, and R. Andrew, 2021: A future perspective of historical contributions to climate change. *Clim. Change*, **164(1)**, 24, doi:10.1007/s10584-021-02982-9.

Smith, C.J. et al., 2018: FAIR v1.3: A simple emissions-based impulse response and carbon cycle model. *Geosci. Model Dev.*, **11(6)**, 2273–2297, doi:10.5194/gmd-11-2273-2018.

3

Smith, P. et al., 2016: Biophysical and economic limits to negative CO_2 emissions. *Nat. Clim. Change*, **6(1)**, 42–50, doi:10.1038/nclimate2870.

Smith, P., J. Nkem, K. Calvin, D. Campbell, F. Cherubini, G. Grassi, V. Korotkov, A.L. Hoang, S. Lwasa, P. McElwee, E. Nkonya, N. Saigusa, J.-F. Soussana, M.A. Taboada, 2019: Interlinkages Between Desertification, Land Degradation, Food Security and Greenhouse Gas Fluxes: Synergies, Trade-offs and Integrated Response Options. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Portner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 551–672.

Smith, P. et al., 2020a: Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? *Glob. Change Biol.*, **26(3)**, 1532–1575, doi:10.1111/gcb.14878.

Smith, S.J. et al., 2020b: Impact of methane and black carbon mitigation on forcing and temperature: a multi-model scenario analysis. *Clim. Change*, **163**, 1427–1442,, doi:10.1007/s10584-020-02794-3.

Smith, S.J. et al., 2020c: The Energy Modeling Forum (EMF)-30 study on short-lived climate forcers: introduction and overview. *Clim. Change*, **163(3)**, 1399–1408, doi:10.1007/s10584-020-02938-5.

Smith, S.M., 2021: A case for transparent net-zero carbon targets. *Commun. Earth Environ.*, **2(1)**, 24, doi:10.1038/s43247-021-00095-w.

Soergel, B. et al., 2021a: A sustainable development pathway for climate action within the UN 2030 Agenda. *Nat. Clim. Change*, **11(8)**, 656–664, doi:10.1038/s41558-021-01098-3.

Soergel, B. et al., 2021b: Combining ambitious climate policies with efforts to eradicate poverty. *Nat. Commun.*, **12(1)**, 2342, doi:10.1038/s41467-021-22315-9.

Sognnaes, I. et al., 2021: A multi-model analysis of long-term emissions and temperature implications of current mitigation efforts. *Nat. Clim. Change* (in press), doi:10.1038/s41558-021-01206-3.

Spencer, T. et al., 2015: Beyond the Numbers: Understanding the Transformation Induced by INDCs. IDDRI, ISSN 2258-7071. https://www.iddri.org/sites/default/files/import/publications/miles-report.pdf.

Spencer, T. et al., 2018: The 1.5°C target and coal sector transition: at the limits of societal feasibility. *Clim. Policy*, **18(3)**, 335–351, doi:10.1080/14693062.2017.1386540.

Springmann, M. et al., 2016a: Global and regional health effects of future food production under climate change: A modelling study. *Lancet*, **387(10031)**, 1937–1946, doi:10.1016/S0140-6736(15)01156-3.

Springmann, M., H.C.J. Godfray, M. Rayner, and P. Scarborough, 2016b: Analysis and valuation of the health and climate change cobenefits of dietary change. *Proc. Natl. Acad. Sci.*, **113(15)**, 4146–4151, doi:10.1073/pnas.1523119113.

Springmann, M. et al., 2018: Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. *Lancet Planet. Heal.*, **2(10)**, e451–e461, doi.org/10.1016/S2542-5196(18)30206-7.

Steckel, J.C., R.J. Brecha, M. Jakob, J. Strefler, and G. Luderer, 2013: Development without energy? Assessing future scenarios of energy consumption in developing countries. *Ecol. Econ.*, **90**, 53–67, doi.org/10.1016/j.ecolecon.2013.02.006.

Steckel, J.C. et al., 2021: Distributional impacts of carbon pricing in developing Asia. *Nat. Sustain.*, **4**, 1005–1014, doi:10.1038/s41893-021-00758-8.

Stehfest, E. et al., 2009: Climate benefits of changing diet. *Clim. Change*, **95(1)**, 83–102, doi:10.1007/s10584-008-9534-6.

Stehfest, E. et al., 2019: Key determinants of global land-use projections. *Nat. Commun.*, **10(1)**, 1–10, doi:10.1038/s41467-019-09945-w.

Steinberg, D.C. et al., 2020: Correction to: Decomposing supply-side and demand-side impacts of climate change on the US electricity system through 2050 *Clim. Change*, **158**, 125–139, doi:10.1007/s10584-020-02660-2.

Stern, D.I., J.C.V. Pezzey, and N.R. Lambie, 2012: Where in the world is it cheapest to cut carbon emissions? *Aust. J. Agric. Resour. Econ.*, **56(3)**, 315–331, doi:10.1111/j.1467-8489.2011.00576.x.

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. *J. Econ. Lit.*, **51(3)**, 838–859, doi:10.1257/jel.51.3.838.

Stern, N., 2016: Economics: Current climate models are grossly misleading. *Nature*, **530(7591)**, 407–409, doi:10.1038/530407a.

Stern, N., and J. Stiglitz, 2021: The economics of immense risk, urgent action and radical change: towards new approaches to the economics of climate change. *J. Econ. Methodol.* (in press).

Sterner, T. and U.M. Persson, 2008: An Even Sterner Review: Introducing Relative Prices into the Discounting Debate. *Rev. Environ. Econ. Policy*, **2(1)**, 61–76, doi:10.1093/reep/rem024.

Stoerk, T., G. Wagner, and R.E.T. Ward, 2018: Policy Brief – Recommendations for Improving the Treatment of Risk and Uncertainty in Economic Estimates of Climate Impacts in the Sixth Intergovernmental Panel on Climate Change Assessment Report. *Rev. Environ. Econ. Policy*, **12(2)**, 371–376, doi:10.1093/reep/rey005.

Stolbova, V., I. Monasterolo, and S. Battiston, 2018: A Financial Macro-Network Approach to Climate Policy Evaluation. *Ecol. Econ.*, **149**, 239–253, doi:10.1016/j.ecolecon.2018.03.013.

Strefler, J. et al., 2018: Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. *Environ. Res. Lett.*, **13(4)**, 044015, doi:10.1088/1748-9326/aab2ba.

Strefler, J. et al., 2021a: Carbon dioxide removal technologies are not born equal. *Environ. Res. Lett.*, **16(7)**, 74021, doi:10.1088/1748-9326/ac0a11.

Strefler, J. et al., 2021b: Alternative carbon price trajectories can avoid excessive carbon removal. *Nat. Commun.*, **12**, 2264, doi.org/10.1038/s41467-021-22211-2.

Stua, M., 2017: Article 6 of the Paris agreement as foundation for the mitigation alliance. In: *From the Paris Agreement to a Low-Carbon Bretton Woods: Rationale for the Establishment of a Mitigation Alliance* [Stua, M., (ed.)], Springer, Cham., Switzerland, pp. 49–66.

Sugiyama, M., Y. Arino, T. Kosugi, A. Kurosawa, and S. Watanabe, 2018: Next steps in geoengineering scenario research: limited deployment scenarios and beyond. *Clim. Policy*, **18(6)**, 681–689, doi:10.1080/14693062.2017.1323721.

Tachiiri, K., D. Silva Herran, X. Su, and M. Kawamiya, 2019: Effect on the Earth system of realizing a 1.5°C warming climate target after overshooting to the 2°C level. *Environ. Res. Lett.*, **14(12)**, 124063, doi:10.1088/1748-9326/ab5199.

Taconet, N., A. Méjean, and C. Guivarch, 2020: Influence of climate change impacts and mitigation costs on inequality between countries. *Clim. Change*, **160(1)**, 15–34, doi:10.1007/s10584-019-02637-w.

Taconet, N., C. Guivarch, and A. Pottier, 2021: Social Cost of Carbon Under Stochastic Tipping Points. *Environ. Resour. Econ.*, **78(4)**, 709–737, doi:10.1007/s10640-021-00549-x.

Tait, L. and H. Winkler, 2012: Estimating greenhouse gas emissions associated with achieving universal access to electricity for all households in South Africa. *J. Energy South. Africa*, **23(4)**, 8–17, doi:10.17159/2413-3051/2012/v23i4a3174.

Takakura, J. et al., 2019: Dependence of economic impacts of climate change on anthropogenically directed pathways. *Nat. Clim. Change*, **9(10)**, 737–741, doi:10.1038/s41558-019-0578-6.

Takemura, T. and K. Suzuki, 2019: Weak global warming mitigation by reducing black carbon emissions. *Sci. Rep.*, **9(1)**, 4419, doi:10.1038/s41598-019-41181-6.

Tan, C. and Q. Zhi, 2016: The energy-water nexus: A literature review of the dependence of energy on water. *Energy Procedia*, **88**, 277–284, doi:10.1016/j.egypro.2016.06.154.

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. *Nat. Clim. Change*, **8(4)**, 319–324, doi:10.1038/s41558-018-0097-x.

Tarroja, B., A. AghaKouchak, and S. Samuelsen, 2016: Quantifying climate change impacts on hydropower generation and implications on electric grid greenhouse gas emissions and operation. *Energy*, **111**, 295–305, doi:10.1016/j.energy.2016.05.131.

Tavoni, M. and R.S.J. Tol, 2010: Counting only the hits? The risk of underestimating the costs of stringent climate policy: A letter. *Clim. Change*, **100(3)**, 769–778, doi:10.1007/s10584-010-9867-9.

Tavoni, M. et al., 2015: Post-2020 climate agreements in the major economies assessed in the light of global models. *Nat. Clim. Change*, **5(2)**, 119–126, doi:10.1038/nclimate2475.

Tavoni, M. et al., 2017: Challenges and Opportunities for Integrated Modeling of Climate Engineering. *FEEM Work. Pap.*, **38**, doi:10.2139/ssrn.3035166.

The World Bank, 2021: World Development Indicators. *DataBank*. https://databank.worldbank.org/source/world-development-indicators.

Thompson, T.M., S. Rausch, R.K. Saari, and N.E. Selin, 2014: A systems approach to evaluating the air quality co-benefits of US carbon policies. *Nat. Clim. Chang.*, **4**(10), 917–923, doi:10.1038/nclimate2342.

Tokarska, K.B., K. Zickfeld, and J. Rogelj, 2019: Path Independence of Carbon Budgets When Meeting a Stringent Global Mean Temperature Target After an Overshoot. *Earth's Future*, **7(12)**, 1283–1295, doi:10.1029/2019EF001312.

Tol, R.S.J., 1994: The damage costs of climate change: a note on tangibles and intangibles, applied to DICE. *Energy Policy*, **22(5)**, 436–438, doi.org/10.1016/0301-4215(94)90173-2.

Tong, D. et al., 2019: Committed emissions from existing energy infrastructure jeopardize 1.5°C climate target. *Nature*, **3** (May), doi:10.1038/s41586-019-1364-3.

Trutnevyte, E., 2016: Does cost optimization approximate the real-world energy transition? *Energy*, **106**, 182–193, doi:10.1016/j.energy.2016.03.038.

Trutnevyte, E. et al., 2019a: Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step. *One Earth*, **1(4)**, 423–433, doi:10.1016/j.oneear.2019.12.002.

Trutnevyte, E. et al., 2019b: Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step. *One Earth*, **1(4)**, 423–433, doi:10.1016/j.oneear.2019.12.002.

Tsutsui, J., H. Yamamoto, S. Sakamoto, and M. Sugiyama, 2020: The role of advanced end-use technologies in long-term climate change mitigation: the interlinkage between primary bioenergy and energy end-use. *Clim. Change*, **163(3)**, 1659–1673, doi:10.1007/s10584-020-02839-7.

Turner, S.W.D., M. Hejazi, S.H. Kim, L. Clarke, and J. Edmonds, 2017: Climate impacts on hydropower and consequences for global electricity supply investment needs. *Energy*, **141**, 2081–2090, doi:10.1016/j.energy.2017.11.089.

Turnheim, B. and B. Nykvist, 2019: Opening up the feasibility of sustainability transitions pathways (STPs): Representations, potentials, and conditions. *Res. Policy*, **48(3)**, 775–788, doi:10.1016/j.respol.2018.12.002.

Turnheim, B. et al., 2015: Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Glob. Environ. Change*, **35**(2015), 239–253, doi:10.1016/j.gloenvcha.2015.08.010.

Ueckerdt, F. et al., 2019: The economically optimal warming limit of the planet. *Earth Syst. Dyn.*, **10(4)**, doi: 10.5194/esd-10-741-2019.

UN, 2019: *World Population Prospects 2019: Highlights (ST/ESA/SER.A/423)*. New York, USA, 1–39 pp. https://population.un.org/wpp/Publications/Files/WPP2019_Highlights.pdf.

UNEP, 2019: Bridging the Gap – Enhancing Mitigation Ambition and Action at G20 Level and Globally: Pre-release version of a chapter in the forthcoming UNEP Emissions Gap Report 2019. *Emiss. Gap Rep. 2019*, 62 pp. https://wedocs.unep.org/bitstream/handle/20.500.11822/30012/EGRgap.pdf?sequence=1&isAllowed=y.

UNEP, 2020: *Emissions Gap Report 2020*. UN Environment Programme, Nairobi, Kenya. https://www.unep.org/emissions-gap-report-2020, 128 pp.

Unruh, G.C., 2019: The Real Stranded Assets of Carbon Lock-In. *One Earth*, **1(4)**, 399–401, doi:10.1016/j.oneear.2019.11.012.

Ürge-Vorsatz, D. et al., 2020: Advances Toward a Net-Zero Global Building Sector. *Annu. Rev. Environ. Resour.*, **45(1)**, 227–269, doi:10.1146/annurev-environ-012420-045843.

van Beek, L., M. Hajer, P. Pelzer, D. van Vuuren, and C. Cassen, 2020: Anticipating futures through models: the rise of Integrated Assessment Modelling in the climate science-policy interface since 1970. *Glob. Environ. Change*, **65** (October), 102191, doi:10.1016/j.gloenvcha.2020.102191.

van de Ven, D.J., M. González-Eguino, and I. Arto, 2018: The potential of behavioural change for climate change mitigation: a case study for the European Union. *Mitig. Adapt. Strateg. Glob. Change*, **23(6)**, 853–886, doi:10.1007/s11027-017-9763-y.

van den Berg, N.J. et al., 2019: Improved modelling of lifestyle changes in Integrated Assessment Models: Cross-disciplinary insights from methodologies and theories. *Energy Strateg. Rev.*, **26**, 100420, doi:10.1016/j.esr.2019.100420.

van den Berg, N.J. et al., 2020: Implications of various effort-sharing approaches for national carbon budgets and emission pathways. *Clim. Change*, **162(4)**, 1805–1822, doi:10.1007/s10584-019-02368-y.

van den Bergh, J.C.J. M., and W.J.W. Botzen, 2014: A lower bound to the social cost of CO_2 emissions. *Nat. Clim. Change*, **4(4)**, 253–258, doi:10.1038/nclimate2135.

van der Ploeg, F. and A. de Zeeuw, 2018: Climate tipping and economic growth: Precautionary capital and the price of carbon. *J. Eur. Econ. Assoc.*, **16(5)**, 1577–1617, doi:10.1093/jeea/jvx036.

van der Wijst, K.-I., A.F. Hof, and D.P. van Vuuren, 2021a: Costs of avoiding net negative emissions under a carbon budget. *Environ. Res. Lett.*, **16(6)**, 64071, doi:10.1088/1748-9326/ac03d9.

van der Wijst, K.-I., A.F. Hof, and D.P. van Vuuren, 2021b: On the optimality of 2°C targets and a decomposition of uncertainty. *Nat. Commun.*, **12(1)**, 2575, doi:10.1038/s41467-021-22826-5.

van der Zwaan, B.C.C. et al., 2013: A Cross-Model Comparison of Global Long-Term Technology Diffusion Under a 2°C Climate Change Control Target. *Clim. Change Econ.*, **4(4)**, 1–25, doi:10.1142/S2010007813400137.

van Ruijven, B.J. et al., 2016: Long-term model-based projections of energy use and CO_2 emissions from the global steel and cement industries. *Resour. Conserv. Recycl.*, **112**, 15–36, doi:10.1016/j.resconrec.2016.04.016.

van Ruijven, B.J., E. De Cian, and I. Sue Wing, 2019: Amplification of future energy demand growth due to climate change. *Nat. Commun.*, **10(1)**, 1–12, doi:10.1038/s41467-019-10399-3.

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. *Technol. Forecast. Soc. Change*, **102**, 309–319, doi:10.1016/j.techfore.2015.08.013.

van Sluisveld, M.A.E. et al., 2018a: Comparing future patterns of energy system change in 2°C scenarios to expert projections. *Glob. Environ. Change*, **50** (March), 201–211, doi:10.1016/j.gloenvcha.2018.03.009.

van Sluisveld, M.A.E. et al., 2018b: Aligning integrated assessment modelling with socio-technical transition insights: An application to low-carbon energy scenario analysis in Europe. *Technol. Forecast. Soc. Change*,151, 119177, doi:10.1016/j.techfore.2017.10.024.

van Sluisveld, M.A.E., H.S. De Boer, V. Daioglou, A.F. Hof, and D.P. Van Vuuren, 2021: A race to zero – Assessing the position of heavy industry in a global net-zero CO_2 emissions context. *Energy Clim. Change*, **2** (July), doi:10.1016/j.egycc.2021.100051.

van Sluisveld, M.A.E. E. et al., 2015: Comparing future patterns of energy system change in 2°C scenarios with historically observed rates of change. *Glob. Environ. Change*, **35**, 436–449, doi:10.1016/j.gloenvcha.2015.09.019.

3

van Soest, H.L. et al., 2017a: Early action on Paris Agreement allows for more time to change energy systems. *Clim. Change*, **144(2)**, 165–179, doi:10.1007/s10584-017-2027-8.

van Soest, H.L. et al., 2017b: Low-emission pathways in 11 major economies: Comparison of cost-optimal pathways and Paris climate proposals. *Clim. Change*, **142(3–4)**, 491–504, doi:10.1007/s10584-017-1964-6.

van Soest, H.L. et al., 2019: Analysing interactions among Sustainable Development Goals with Integrated Assessment Models. *Glob. Transitions*, **1**, 210–225, doi:10.1016/j.glt.2019.10.004.

van Soest, H.L. et al., 2021a: A Global Roll-out of Nationally Relevant Policies can Bridge the Emissions Gap. *Nat. Commun.* (in press), doi:10.1038/s41467-021-26595-z.

van Soest, H.L., M.G.J. den Elzen, and D.P. van Vuuren, 2021b: Net-zero emission targets for major emitting countries consistent with the Paris Agreement. *Nat. Commun.*, **12(1)**, 1–9, doi:10.1038/s41467-021-22294-x.

van Vliet, J., M.G.J. den Elzen, and D.P. van Vuuren, 2009: Meeting radiative forcing targets under delayed participation. *Energy Econ.*, **31(sup2)**, S152–S162, doi:10.1016/j.eneco.2009.06.010.

van Vliet, M.T.H., D. Wiberg, S. Leduc, and K. Riahi, 2016: Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nat. Clim. Change*, **6(4)**, 375–380, doi:10.1038/nclimate2903.

van Vuuren, D.P. and K. Riahi, 2011: The relationship between short-term emissions and long-term concentration targets. *Clim. Change*, **104(3–4)**, 793–801, doi:10.1007/s10584-010-0004-6.

van Vuuren, D.P. et al., 2007: Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Clim. Change*, **81(2)**, 119–159, doi:10.1007/s10584-006-9172-9.

van Vuuren, D.P., B. de Vries, A. Beusen, and P.S.C. Heuberger, 2008: Conditional probabilistic estimates of 21st century greenhouse gas emissions based on the storylines of the IPCC-SRES scenarios. *Glob. Environ. Change*, **18(4)**, 635–654, doi:10.1016/j.gloenvcha.2008.06.001.

van Vuuren, D.P. et al., 2011: The representative concentration pathways: An overview. *Clim. 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. *Technol. Forecast. Soc. Change*, **98**, 303–323, doi:10.1016/J.TECHFORE.2015.03.005.

van Vuuren, D.P., A.F. Hof, M.A.E. van Sluisveld, and K. Riahi, 2017: Open discussion of negative emissions is urgently needed. *Nat. Energy*, **2(12)**, 902–904, doi:10.1038/s41560-017-0055-2.

van Vuuren, D.P. et al., 2018: Alternative pathways to the 1.5°C target reduce the need for negative emission technologies. *Nat. Clim. Change*, **8(5)**, 391–397, doi:10.1038/s41558-018-0119-8.

van Vuuren, D.P. et al., 2019: Integrated scenarios to support analysis of the food–energy–water nexus. *Nat. Sustain.*, **2(12)**, 1132–1141, doi:10.1038/s41893-019-0418-8.

van Vuuren, D.P. et al., 2020: The costs of achieving climate targets and the sources of uncertainty. *Nat. Clim. Change*, 10, 329–334, doi:10.1038/s41558-020-0732-1.

Vandyck, T., K. Keramidas, B. Saveyn, A. Kitous, and Z. Vrontisi, 2016: A global stocktake of the Paris pledges: Implications for energy systems and economy. *Glob. Environ. Change*, **41**, 46–63, doi:10.1016/j.gloenvcha.2016.08.006.

Vandyck, T. et al., 2018: Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges. *Nat. Commun.*, **9(1)**, 1–11, doi:10.1038/s41467-018-06885-9.

Vandyck, T., K. Keramidas, S. Tchung-Ming, M. Weitzel, and R. Van Dingenen, 2020: Quantifying air quality co-benefits of climate policy across sectors and regions. *Clim. Change*, **163(3)**, 1501–1517, doi:10.1007/s10584-020-02685-7.

Venton, D., 2016: Core Concept: Can bioenergy with carbon capture and storage make an impact? *Proc. Natl. Acad. Sci.*, **113(47)**, 13260 LP–13262, doi:10.1073/pnas.1617583113.

Vogt-Schilb, A., G. Meunier, and S. Hallegatte, 2018: When starting with the most expensive option makes sense: Optimal timing, cost and sectoral allocation of abatement investment. *J. Environ. Econ. Manage.*, **88**, 210–233, doi:10.1016/j.jeem.2017.12.001.

von Stechow, C. et al., 2015: Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. *Annu. Rev. Environ. Resour.*, **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? *Environ. Res. Lett.*, **11(3)**, doi:10.1088/1748-9326/11/3/034022.

Vrontisi, Z. et al., 2018: Enhancing global climate policy ambition towards a 1.5°C stabilization: a short-term multi-model assessment. *Environ. Res. Lett.*, **13(4)**, 44039, doi:10.1088/1748-9326/aab53e.

Vrontisi, Z., K. Fragkiadakis, M. Kannavou, and P. Capros, 2020: Energy system transition and macroeconomic impacts of a European decarbonization action towards a below 2°C climate stabilization. *Clim. Change*, 162, 1857–1875, doi: 10.1007/s10584-019-02440-7.

Wachsmuth, J. and V. Duscha, 2019: Achievability of the Paris targets in the EU – the role of demand-side-driven mitigation in different types of scenarios. *Energy Effic.*, **12(2)**, 403–421, doi:10.1007/s12053-018-9670-4.

Waisman, H. et al., 2019: A pathway design framework for national low greenhouse gas emission development strategies. *Nat. Clim. Change*, **9(4)**, 261–268, doi:10.1038/s41558-019-0442-8.

Wang, Y. et al., 2019: Vulnerability of existing and planned coal-fired power plants in Developing Asia to changes in climate and water resources. *Energy Environ. Sci.*, **12(10)**, 3164–3181, doi:10.1039/c9ee02058f.

Wangel, J., S. Gustafsson, and Ö. Svane, 2013: Goal-based socio-technical scenarios: Greening the mobility practices in the Stockholm City District of Bromma, Sweden. *Futures*, **47**, 79–92, doi:10.1016/j.futures.2013.01.005.

Warren, R., J. Price, E. Graham, N. Forstenhaeusler, and J. VanDerWal, 2018: The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5°C rather than 2°C. *Science*, **360(6390)**, 791 LP–795, doi:10.1126/science.aar3646.

Warszawski, L. et al., 2021: All options, not silver bullets, needed to limit global warming to 1.5°C: a scenario appraisal. *Environ. Res. Lett.*, **16(6)**, 64037, doi:10.1088/1748-9326/abfeec.

Watts, N., W.N. Adger, and P. Agnolucci, 2015: Health and climate change: Policy responses to protect public health. *Environnement, Risques et Sante*, **14(6)**, 466–468, doi:10.1016/S0140-6736(15)60854-6.

Wei, Y.-M. et al., 2020: Self-preservation strategy for approaching global warming targets in the post-Paris Agreement era. *Nat. Commun.*, **11(1)**, 1624, doi:10.1038/s41467-020-15453-z.

Welsby, D., J. Price, S. Pye, and P. Ekins, 2021: Unextractable fossil fuels in a 1.5°C world. *Nature*, **597(7875)**, 230–234, doi:10.1038/s41586-021-03821-8.

Weyant, J., 2017: Some Contributions of Integrated Assessment Models of Global Climate Change. *Rev. Environ. Econ. Policy*, **11(1)**, 115–137, doi:10.1093/reep/rew018.

Willett, W. et al., 2019: Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet*, **393(10170)**, 447–492, doi:10.1016/S0140-6736(18)31788-4.

Willis, R., 2017: How Members of Parliament understand and respond to climate change. *Sociol. Rev.*, **66(3)**, 475–491, doi:10.1177/0038026117731658.

Wilson, C., A. Grubler, N. Bauer, V. Krey, and K. Riahi, 2013: Future capacity growth of energy technologies: are scenarios consistent with historical evidence? *Clim. Change*, **118(2)**, 381–395, doi:10.1007/s10584-012-0618-y.

Wilson, C., H. Pettifor, E. Cassar, L. Kerr, and M. Wilson, 2019: The potential contribution of disruptive low-carbon innovations to 1.5°C climate mitigation. *Energy Effic.*, **12(2)**, 423–440, doi:10.1007/s12053-018-9679-8.

Winning, M. et al., 2019: Nationally Determined Contributions under the Paris Agreement and the costs of delayed action. *Clim. Policy*, **19(8)**, 947–958, doi:10.1080/14693062.2019.1615858.

Wise, M. et al., 2015: An approach to computing marginal land use change carbon intensities for bioenergy in policy applications. *Energy Econ.*, **50**, 337–347, doi:10.1016/j.eneco.2015.05.009.

Wise, M., M. Muratori, and P. Kyle, 2017: Biojet fuels and emissions mitigation in aviation: An integrated assessment modeling analysis. *Transp. Res. Part D Transp. Environ.*, **52**, 244–253, doi:10.1016/j.trd.2017.03.006.

Wiser, R. et al., 2021: Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050. *Nat. Energy*, **6(5)**, 555–565, doi:10.1038/s41560-021-00810-z.

Wolkinger, B. et al., 2018: Evaluating Health Co-Benefits of Climate Change Mitigation in Urban Mobility. *Int. J. Environ. Res. Public Health*, **15(5)**, doi:10.3390/ijerph15050880.

Xie, Y. et al., 2018: Co-benefits of climate mitigation on air quality and human health in Asian countries. *Environ. Int.*, **119**, 309–318, doi.org/10.1016/j.envint.2018.07.008.

Xu, H., M. Wu, and M. Ha, 2019: A county-level estimation of renewable surface water and groundwater availability associated with potential large-scale bioenergy feedstock production scenarios in the United States. *GCB Bioenergy*, **11(4)**, 606–622, doi.org/10.1111/gcbb.12576.

Xu, Y. and V. Ramanathan, 2017: Well below 2°C: Mitigation strategies for avoiding dangerous to catastrophic climate changes. *Proc. Natl. Acad. Sci.*, **114(39)**, 10315–10323, doi:10.1073/pnas.1618481114.

Yalew, S.G. et al., 2020: Impacts of climate change on energy systems in global and regional scenarios. *Nat. Energy*, **5(10)**, 794–802, doi:10.1038/s41560-020-0664-z.

Yamagata, Y. et al., 2018: Estimating water–food–ecosystem trade-offs for the global negative emission scenario (IPCC-RCP2.6). *Sustain. Sci.*, **13(2)**, 301–313, doi:10.1007/s11625-017-0522-5.

Yang, X., J. Pang, F. Teng, R. Gong, and C. Springer, 2021: The environmental co-benefit and economic impact of China's low-carbon pathways: Evidence from linking bottom-up and top-down models. *Renew. Sustain. Energy Rev.*, **136**, 110438, doi.org/10.1016/j.rser.2020.110438.

Yeh, S. et al., 2017: Detailed assessment of global transport-energy models' structures and projections. *Transp. Res. Part D Transp. Environ.*, **55**, 294–309, doi:10.1016/j.trd.2016.11.001.

Yumashev, D. et al., 2019: Climate policy implications of nonlinear decline of Arctic land permafrost and other cryosphere elements. *Nat. Commun.*, **10(1)**, 1900, doi:10.1038/s41467-019-09863-x.

Zanchi, G., N. Pena, and N. Bird, 2012: Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy*, **4(6)**, 761–772, doi.org/10.1111/j.1757-1707.2011.01149.x.

Zappa, W., M. Junginger, and M. van den Broek, 2019: Is a 100% renewable European power system feasible by 2050? *Appl. Energy*, **233–234**, 1027–1050, doi.org/10.1016/j.apenergy.2018.08.109.

Zenghelis, D., 2019: Securing Decarbonisation and Growth. *Natl. Inst. Econ. Rev.*, **250(1)**, R54–R60, doi:10.1177/002795011925000118.

Zhang, R. and S. Fujimori, 2020: The role of transport electrification in global climate change mitigation scenarios. *Environ. Res. Lett.*, **15(3)**, doi:10.1088/1748-9326/ab6658.

Zhang, R., S. Fujimori, H. Dai, and T. Hanaoka, 2018a: Contribution of the transport sector to climate change mitigation: Insights from a global passenger transport model coupled with a computable general equilibrium model. *Appl. Energy*, **211** (November 2017), 76–88, doi:10.1016/j.apenergy.2017.10.103.

Zhang, R., S. Fujimori, and T. Hanaoka, 2018b: The contribution of transport policies to the mitigation potential and cost of 2°C and 1.5°C goals. *Environ. Res. Lett.*, **13(5)**, 54008, doi:10.1088/1748-9326/aabb0d.

Zhang, X. et al., 2018d: Impacts of climate change, policy and Water-Energy-Food nexus on hydropower development. *Renew. Energy*, **116**, 827–834, doi:10.1016/j.renene.2017.10.030.

Zhou, T., N. Voisin, and T. Fu, 2018: Non-stationary hydropower generation projections constrained by environmental and electricity grid operations over the western United States. *Environ. Res. Lett.*, **13(7)**, doi:10.1088/1748-9326/aad19f.

Zhou, W. et al., 2019: A comparison of low carbon investment needs between China and Europe in stringent climate policy scenarios. *Environ. Res. Lett.*, **14(5)**, 054017, doi:10.1088/1748-9326/ab0dd8.

Zhou, Y. et al., 2014: Modeling the effect of climate change on U.S. state-level buildings energy demands in an integrated assessment framework. *Appl. Energy*, **113**, 1077–1088, doi:10.1016/j.apenergy.2013.08.034.

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. *Environ. Res. Lett.*, **11(5)**, 055006, doi:10.1088/1748-9326/11/5/055006.

Zickfeld, K., D. Azevedo, S. Mathesius, and H.D. Matthews, 2021: Asymmetry in the climate–carbon cycle response to positive and negative CO_2 emissions. *Nat. Clim. Change*, **11(7)**, 613–617, doi:10.1038/s41558-021-01061-2.

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