

2

Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development

Coordinating Lead Authors:

Joeri Rogelj (Austria/Belgium), Drew Shindell (USA), Kejun Jiang (China)

Lead Authors:

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

Contributing Authors:

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

Chapter Scientists:

Daniel Huppmann (Austria), Chris Smith (UK)

Review Editors:

Greg Flato (Canada), Jan Fuglestedt (Norway), Rachid Mrabet (Morocco), Roberto Schaeffer (Brazil)

This chapter should be cited as:

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, 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.)]. In Press.

Table of Contents

Executive Summary.....	95	2.6 Knowledge Gaps.....	157
2.1 Introduction to Mitigation Pathways and the Sustainable Development Context.....	98	2.6.1 Geophysical Understanding.....	157
2.1.1 Mitigation Pathways Consistent with 1.5°C.....	98	2.6.2 Integrated Assessment Approaches.....	158
2.1.2 The Use of Scenarios	98	2.6.3 Carbon Dioxide Removal (CDR).....	158
2.1.3 New Scenario Information since AR5	99		
2.1.4 Utility of Integrated Assessment Models (IAMs) in the Context of this Report.....	100	Frequently Asked Questions	
2.2 Geophysical Relationships and Constraints	101	FAQ 2.1: What Kind of Pathways Limit Warming to 1.5°C and are we on Track?	159
2.2.1 Geophysical Characteristics of Mitigation Pathways..	101	FAQ 2.2: What do Energy Supply and Demand have to do with Limiting Warming to 1.5°C?.....	161
2.2.2 The Remaining 1.5°C Carbon Budget.....	104		
2.3 Overview of 1.5°C Mitigation Pathways	108	References	163
2.3.1 Range of Assumptions Underlying 1.5°C Pathways....	109		
2.3.2 Key Characteristics of 1.5°C Pathways	112		
2.3.3 Emissions Evolution in 1.5°C Pathways.....	115		
2.3.4 CDR in 1.5°C Pathways	118		
Box 2.1: Bioenergy and BECCS Deployment in Integrated Assessment Modelling	124		
2.3.5 Implications of Near-Term Action in 1.5°C Pathways..	126		
2.4 Disentangling the Whole-System Transformation	129		
2.4.1 Energy System Transformation	129		
2.4.2 Energy Supply.....	130		
2.4.3 Energy End-Use Sectors.....	136		
2.4.4 Land-Use Transitions and Changes in the Agricultural Sector.....	144		
2.5 Challenges, Opportunities and Co-Impacts of Transformative Mitigation Pathways	148		
2.5.1 Policy Frameworks and Enabling Conditions	148		
Cross-Chapter Box 5 Economics of 1.5°C Pathways and the Social Cost of Carbon	150		
2.5.2 Economic and Investment Implications of 1.5°C Pathways.....	152		
2.5.3 Sustainable Development Features of 1.5°C Pathways.....	156		

Executive Summary

This chapter assesses mitigation pathways consistent with limiting warming to 1.5°C above pre-industrial levels. In doing so, it explores the following key questions: What role do CO₂ and non-CO₂ emissions play? {2.2, 2.3, 2.4, 2.6} To what extent do 1.5°C pathways involve overshooting and returning below 1.5°C during the 21st century? {2.2, 2.3} What are the implications for transitions in energy, land use and sustainable development? {2.3, 2.4, 2.5} How do policy frameworks affect the ability to limit warming to 1.5°C? {2.3, 2.5} What are the associated knowledge gaps? {2.6}

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

The Chances of Limiting Warming to 1.5°C and the Requirements for Urgent Action

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

Under emissions in line with current pledges under the Paris Agreement (known as Nationally Determined Contributions, or NDCs), global warming is expected to surpass 1.5°C above pre-industrial levels, even if these pledges are supplemented with very challenging increases in the scale and ambition of mitigation after 2030 (*high confidence*). This increased action would need to achieve net zero CO₂ emissions in less than 15 years. Even if this is achieved, temperatures would only be expected to remain below the 1.5°C threshold if the actual geophysical response ends up being towards the low end of the currently estimated uncertainty range. Transition challenges as well as identified trade-offs can be reduced if global emissions peak before 2030 and marked emissions reductions compared to today are already achieved by 2030. {2.2, 2.3.5, Cross-Chapter Box 11 in Chapter 4}

Limiting warming to 1.5°C depends on greenhouse gas (GHG) emissions over the next decades, where lower GHG emissions in 2030 lead to a higher chance of keeping peak warming to 1.5°C (*high confidence*). Available pathways that aim for no or limited (less than 0.1°C) overshoot of 1.5°C keep GHG emissions in 2030 to 25–30 GtCO₂e yr⁻¹ in 2030 (interquartile range). This contrasts with median estimates for current unconditional NDCs of 52–58 GtCO₂e yr⁻¹ in 2030. Pathways that aim for limiting warming to 1.5°C by 2100 after a temporary temperature overshoot rely on large-scale deployment of carbon dioxide removal (CDR) measures, which are uncertain and entail clear risks. In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO₂ emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range). For limiting global warming to below 2°C with at least 66% probability CO₂ emissions are projected to decline by about 25% by 2030 in most pathways (10–30% interquartile range) and reach net zero around 2070 (2065–2080 interquartile range).¹ {2.2, 2.3.3, 2.3.5, 2.5.3, Cross-Chapter Boxes 6 in Chapter 3 and 9 in Chapter 4, 4.3.7}

Limiting warming to 1.5°C implies reaching net zero CO₂ emissions globally around 2050 and concurrent deep reductions in emissions of non-CO₂ forcers, particularly methane (*high confidence*). Such mitigation pathways are characterized by energy-demand reductions, decarbonization of electricity and other fuels, electrification of energy end use, deep reductions in agricultural emissions, and some form of CDR with carbon storage on land or sequestration in geological reservoirs. Low energy demand and low demand for land- and GHG-intensive consumption goods facilitate limiting warming to as close as possible to 1.5°C. {2.2.2, 2.3.1, 2.3.5, 2.5.1, Cross-Chapter Box 9 in Chapter 4}

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

Policies reflecting a high price on emissions are necessary in models to achieve cost-effective 1.5°C pathways (*high confidence*). Other things being equal, modelling studies suggest the global average discounted marginal abatement costs for limiting warming to 1.5°C being about 3–4 times higher compared to 2°C over the 21st century, with large variations across models and socio-economic and policy assumptions. Carbon pricing can be imposed directly or implicitly by regulatory policies. Policy instruments, like technology policies or performance standards, can complement explicit carbon pricing in specific areas. {2.5.1, 2.5.2, 4.4.5}

Limiting warming to 1.5°C requires a marked shift in investment patterns (*medium confidence*). Additional annual average energy-related investments for the period 2016 to 2050 in pathways limiting warming to 1.5°C compared to pathways without new climate policies beyond those in place today (i.e., baseline) are estimated to be around

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

830 billion USD₂₀₁₀ (range of 150 billion to 1700 billion USD₂₀₁₀ across six models). Total energy-related investments increase by about 12% (range of 3% to 24%) in 1.5°C pathways relative to 2°C pathways. Average annual investment in low-carbon energy technologies and energy efficiency are upscaled by roughly a factor of six (range of factor of 4 to 10) by 2050 compared to 2015, overtaking fossil investments globally by around 2025 (*medium confidence*). Uncertainties and strategic mitigation portfolio choices affect the magnitude and focus of required investments. {2.5.2}

Future Emissions in 1.5°C Pathways

Mitigation requirements can be quantified using carbon budget approaches that relate cumulative CO₂ emissions to global mean temperature increase. Robust physical understanding underpins this relationship, but uncertainties become increasingly relevant as a specific temperature limit is approached. These uncertainties relate to the transient climate response to cumulative carbon emissions (TCRE), non-CO₂ emissions, radiative forcing and response, potential additional Earth system feedbacks (such as permafrost thawing), and historical emissions and temperature. {2.2.2, 2.6.1}

Cumulative CO₂ emissions are kept within a budget by reducing global annual CO₂ emissions to net zero. This assessment suggests a remaining budget of about 420 GtCO₂ for a two-thirds chance of limiting warming to 1.5°C, and of about 580 GtCO₂ for an even chance (*medium confidence*). The remaining carbon budget is defined here as cumulative CO₂ emissions from the start of 2018 until the time of net zero global emissions for global warming defined as a change in global near-surface air temperatures. Remaining budgets applicable to 2100 would be approximately 100 GtCO₂ lower than this to account for permafrost thawing and potential methane release from wetlands in the future, and more thereafter. These estimates come with an additional geophysical uncertainty of at least ±400 GtCO₂, related to non-CO₂ response and TCRE distribution. Uncertainties in the level of historic warming contribute ±250 GtCO₂. In addition, these estimates can vary by ±250 GtCO₂ depending on non-CO₂ mitigation strategies as found in available pathways. {2.2.2, 2.6.1}

Staying within a remaining carbon budget of 580 GtCO₂ implies that CO₂ emissions reach carbon neutrality in about 30 years, reduced to 20 years for a 420 GtCO₂ remaining carbon budget (*high confidence*). The ±400 GtCO₂ geophysical uncertainty range surrounding a carbon budget translates into a variation of this timing of carbon neutrality of roughly ±15–20 years. If emissions do not start declining in the next decade, the point of carbon neutrality would need to be reached at least two decades earlier to remain within the same carbon budget. {2.2.2, 2.3.5}

Non-CO₂ emissions contribute to peak warming and thus affect the remaining carbon budget. The evolution of methane and sulphur dioxide emissions strongly influences the chances of limiting warming to 1.5°C. In the near-term, a weakening of aerosol cooling would add to future warming, but can be tempered by reductions in methane emissions (*high confidence*). Uncertainty in radiative forcing estimates (particularly

aerosol) affects carbon budgets and the certainty of pathway categorizations. Some non-CO₂ forcers are emitted alongside CO₂, particularly in the energy and transport sectors, and can be largely addressed through CO₂ mitigation. Others require specific measures, for example, to target agricultural nitrous oxide (N₂O) and methane (CH₄), some sources of black carbon, or hydrofluorocarbons (*high confidence*). In many cases, non-CO₂ emissions reductions are similar in 2°C pathways, indicating reductions near their assumed maximum potential by integrated assessment models. Emissions of N₂O and NH₃ increase in some pathways with strongly increased bioenergy demand. {2.2.2, 2.3.1, 2.4.2, 2.5.3}

The Role of Carbon Dioxide Removal (CDR)

All analysed pathways limiting warming to 1.5°C with no or limited overshoot use CDR to some extent to neutralize emissions from sources for which no mitigation measures have been identified and, in most cases, also to achieve net negative emissions to return global warming to 1.5°C following a peak (*high confidence*). The longer the delay in reducing CO₂ emissions towards zero, the larger the likelihood of exceeding 1.5°C, and the heavier the implied reliance on net negative emissions after mid-century to return warming to 1.5°C (*high confidence*). The faster reduction of net CO₂ emissions in 1.5°C compared to 2°C pathways is predominantly achieved by measures that result in less CO₂ being produced and emitted, and only to a smaller degree through additional CDR. Limitations on the speed, scale and societal acceptability of CDR deployment also limit the conceivable extent of temperature overshoot. Limits to our understanding of how the carbon cycle responds to net negative emissions increase the uncertainty about the effectiveness of CDR to decline temperatures after a peak. {2.2, 2.3, 2.6, 4.3.7}

CDR deployed at scale is unproven, and reliance on such technology is a major risk in the ability to limit warming to 1.5°C. CDR is needed less in pathways with particularly strong emphasis on energy efficiency and low demand. The scale and type of CDR deployment varies widely across 1.5°C pathways, with different consequences for achieving sustainable development objectives (*high confidence*). Some pathways rely more on bioenergy with carbon capture and storage (BECCS), while others rely more on afforestation, which are the two CDR methods most often included in integrated pathways. Trade-offs with other sustainability objectives occur predominantly through increased land, energy, water and investment demand. Bioenergy use is substantial in 1.5°C pathways with or without BECCS due to its multiple roles in decarbonizing energy use. {2.3.1, 2.5.3, 2.6.3, 4.3.7}

Properties of Energy and Land Transitions in 1.5°C Pathways

The share of primary energy from renewables increases while coal usage decreases across pathways limiting warming to 1.5°C with no or limited overshoot (*high confidence*). By 2050, renewables (including bioenergy, hydro, wind, and solar, with direct-equivalence method) supply a share of 52–67% (interquartile range) of primary energy in 1.5°C pathways with no or limited overshoot; while the share from coal decreases to 1–7% (interquartile range),

with a large fraction of this coal use combined with carbon capture and storage (CCS). From 2020 to 2050 the primary energy supplied by oil declines in most pathways (–39 to –77% interquartile range). Natural gas changes by –13% to –62% (interquartile range), but some pathways show a marked increase albeit with widespread deployment of CCS. The overall deployment of CCS varies widely across 1.5°C pathways with no or limited overshoot, with cumulative CO₂ stored through 2050 ranging from zero up to 300 GtCO₂ (minimum–maximum range), of which zero up to 140 GtCO₂ is stored from biomass. Primary energy supplied by bioenergy ranges from 40–310 EJ yr^{–1} in 2050 (minimum–maximum range), and nuclear from 3–66 EJ yr^{–1} (minimum–maximum range). These ranges reflect both uncertainties in technological development and strategic mitigation portfolio choices. {2.4.2}

1.5°C pathways with no or limited overshoot include a rapid decline in the carbon intensity of electricity and an increase in electrification of energy end use (*high confidence*). By 2050, the carbon intensity of electricity decreases to –92 to +11 gCO₂ MJ^{–1} (minimum–maximum range) from about 140 gCO₂ MJ^{–1} in 2020, and electricity covers 34–71% (minimum–maximum range) of final energy across 1.5°C pathways with no or limited overshoot from about 20% in 2020. By 2050, the share of electricity supplied by renewables increases to 59–97% (minimum–maximum range) across 1.5°C pathways with no or limited overshoot. Pathways with higher chances of holding warming to below 1.5°C generally show a faster decline in the carbon intensity of electricity by 2030 than pathways that temporarily overshoot 1.5°C. {2.4.1, 2.4.2, 2.4.3}

Transitions in global and regional land use are found in all pathways limiting global warming to 1.5°C with no or limited overshoot, but their scale depends on the pursued mitigation portfolio (*high confidence*). Pathways that limit global warming to 1.5°C with no or limited overshoot project a 4 million km² reduction to a 2.5 million km² increase of non-pasture agricultural land for food and feed crops and a 0.5–11 million km² reduction of pasture land, to be converted into 0–6 million km² of agricultural land for energy crops and a 2 million km² reduction to 9.5 million km² increase in forests by 2050 relative to 2010 (*medium confidence*). Land-use transitions of similar magnitude can be observed in modelled 2°C pathways (*medium confidence*). Such large transitions pose profound challenges for sustainable management of the various demands on land for human settlements, food, livestock feed, fibre, bioenergy, carbon storage, biodiversity and other ecosystem services (*high confidence*). {2.3.4, 2.4.4}

Demand-Side Mitigation and Behavioural Changes

Demand-side measures are key elements of 1.5°C pathways. Lifestyle choices lowering energy demand and the land- and GHG-intensity of food consumption can further support achievement of 1.5°C pathways (*high confidence*). By 2030 and 2050, all end-use sectors (including building, transport, and industry) show marked energy demand reductions in modelled 1.5°C pathways, comparable and beyond those projected in 2°C pathways. Sectoral models support the scale of these reductions. {2.3.4, 2.4.3, 2.5.1}

Links between 1.5°C Pathways and Sustainable Development

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

2.1 Introduction to Mitigation Pathways and the Sustainable Development Context

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

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

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

2.1.1 Mitigation Pathways Consistent with 1.5°C

Emissions scenarios need to cover all sectors and regions over the 21st century to be associated with a climate change projection out to 2100. Assumptions regarding future trends in population, consumption of goods and services (including food), economic growth, behaviour, technology, policies and institutions are all required to generate

scenarios (Section 2.3.1). These societal choices must then be linked to the drivers of climate change, including emissions of well-mixed greenhouse gases and aerosol and ozone precursors as well as land-use and land-cover changes. Deliberate solar radiation modification is not included in these scenarios (see Cross-Chapter Box 10 in Chapter 4).

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

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

2.1.2 The Use of Scenarios

Variations in scenario assumptions and design define to a large degree which questions can be addressed with a specific scenario set, for example, the exploration of implications of delayed climate mitigation action. In this assessment, the following classes of 1.5°C- and 2°C-consistent scenarios are of particular interest to the topics addressed in this chapter: (i) scenarios with the same climate target over the 21st century but varying socio-economic assumptions (Sections 2.3 and 2.4), (ii) pairs of scenarios with similar socio-economic assumptions but with forcing targets aimed at 1.5°C and 2°C (Section 2.3), and (iii) scenarios that follow the Nationally Determined Contributions or NDCs² until 2030 with much more stringent mitigation action thereafter (Section 2.3.5).

² Current pledges include those from the United States although they have stated their intention to withdraw in the future.

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

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

2.1.3 New Scenario Information since AR5

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

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

Since the AR5, several new, integrated multimodel studies have appeared in the literature that explore specific characteristics of scenarios more stringent than the lowest scenario category assessed in AR5 that was assessed to limit warming below 2°C with greater than 66% likelihood (Rogelj et al., 2015b, 2018; Akimoto et al., 2017; Marcucci et al., 2017; Su et al., 2017; Bauer et al., 2018; Bertram et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018a; Liu et al., 2018; Luderer et al., 2018; Strefler et al., 2018a; van Vuuren et al., 2018; Vrontisi et al., 2018; Zhang et al., 2018). Those scenarios explore 1.5°C-consistent pathways from multiple perspectives

(see Supplementary Material 2.SM.1.3), examining sensitivity to assumptions regarding:

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

A large number of these scenarios were collected in a scenario database established for the assessment of this Special Report (Supplementary Material 2.SM.1.3). Mitigation pathways were classified by four factors: consistency with a temperature increase limit (as defined by Chapter 1), whether they temporarily overshoot that limit, the extent of this potential overshoot, and the likelihood of falling within these bounds.

Specifically, they were put into classes that either kept surface temperature increases below a given threshold throughout the 21st century or returned to a value below 1.5°C above pre-industrial levels at some point before 2100 after temporarily exceeding that level earlier – referred to as an overshoot (OS). Both groups were further separated based on the probability of being below the threshold and the degree of overshoot, respectively (Table 2.1). Pathways are uniquely classified, with 1.5°C-related classes given higher priority than 2°C classes in cases where a pathway would be applicable to either class.

The probability assessment used in the scenario classification is based on simulations using two reduced-complexity carbon cycle, atmospheric composition, and climate models: the ‘Model for the Assessment of Greenhouse Gas-Induced Climate Change’ (MAGICC) (Meinshausen et al., 2011a), and the ‘Finite Amplitude Impulse Response’ (FAIRv1.3) model (Smith et al., 2018). For the purpose of this report, and to facilitate comparison with AR5, the range of the key carbon cycle and climate parameters for MAGICC and its setup are identical to those used in AR5 WGIII (Clarke et al., 2014). For each mitigation pathway, MAGICC and FAIR simulations provide probabilistic estimates of atmospheric concentrations, radiative forcing and global temperature outcomes until 2100. However, the classification uses MAGICC probabilities directly for traceability with AR5 and because this model is more established in the literature. Nevertheless, the overall uncertainty assessment is based on results from both models, which are considered in the context of the latest radiative forcing estimates and observed temperatures (Etmann et al., 2016; Smith et al., 2018) (Section 2.2 and Supplementary Material 2.SM.1.1). The comparison of these lines of evidence shows *high agreement* in the relative temperature response of pathways, with *medium agreement* on the precise absolute magnitude of warming, introducing a level of imprecision in these attributes. Consideration of the combined evidence here leads to *medium confidence* in the overall geophysical characteristics of the pathways reported here.

In addition to the characteristics of the above-mentioned classes, four illustrative pathway archetypes have been selected and are used throughout this chapter to highlight specific features of and variations across 1.5°C pathways. These are chosen in particular to illustrate the spectrum of CO₂ emissions reduction patterns consistent with 1.5°C,

Table 2.1 | Classification of pathways that this chapter draws upon, along with the number of available pathways in each class. The definition of each class is based on probabilities derived from the MAGICC model in a setup identical to AR5 WGIII (Clarke et al., 2014), as detailed in Supplementary Material 2.SM.1.4.

Pathway group	Pathway Class	Pathway Selection Criteria and Description	Number of Scenarios	Number of Scenarios
1.5°C or 1.5°C-consistent**	Below-1.5°C	Pathways limiting peak warming to below 1.5°C during the entire 21st century with 50–66% likelihood*	9	90
	1.5°C-low-OS	Pathways limiting median warming to below 1.5°C in 2100 and with a 50–67% probability of temporarily overshooting that level earlier, generally implying less than 0.1°C higher peak warming than Below-1.5°C pathways	44	
	1.5°C-high-OS	Pathways limiting median warming to below 1.5°C in 2100 and with a greater than 67% probability of temporarily overshooting that level earlier, generally implying 0.1–0.4°C higher peak warming than Below-1.5°C pathways	37	
2°C or 2°C-consistent	Lower-2°C	Pathways limiting peak warming to below 2°C during the entire 21st century with greater than 66% likelihood	74	132
	Higher-2°C	Pathways assessed to keep peak warming to below 2°C during the entire 21st century with 50–66% likelihood	58	

* No pathways were available that achieve a greater than 66% probability of limiting warming below 1.5°C during the entire 21st century based on the MAGICC model projections.

** This chapter uses the term 1.5°C-consistent pathways to refer to pathways with no overshoot, with limited (low) overshoot, and with high overshoot. However, the Summary for Policymakers focusses on pathways with no or limited (low) overshoot.

ranging from very rapid and deep near-term decreases, facilitated by efficiency and demand-side measures that lead to limited CDR requirements, to relatively slower but still rapid emissions reductions that lead to a temperature overshoot and necessitate large CDR deployment later in the century (Section 2.3).

2.1.4 Utility of Integrated Assessment Models (IAMs) in the Context of this Report

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

Section 2.3 assesses the overall characteristics of 1.5°C pathways based on fully integrated pathways, while Sections 2.4 and 2.5 describe underlying sectoral transformations, including insights from sector-specific assessment models and pathways that are not derived from IAMs. Such models provide detail in their domain of application and make exogenous assumptions about cross-sectoral or global factors. They often focus on a specific sector, such as the energy (Bruckner et al., 2014; IEA, 2017a; Jacobson, 2017; OECD/IEA and IRENA, 2017), buildings (Lucon et al., 2014) or transport (Sims et al., 2014) sector, or

a specific country or region (Giannakidis et al., 2018). Sector-specific pathways are assessed in relation to integrated pathways because they cannot be directly linked to 1.5°C by themselves if they do not extend to 2100 or do not include all GHGs or aerosols from all sectors.

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

Detailed, process-based IAMs are a diverse set of models ranging from partial equilibrium energy–land models to computable general equilibrium models of the global economy, from myopic to perfect foresight models, and from models with to models without endogenous technological change (Supplementary Material 2.SM.1.2). The IAMs used in this chapter have limited to no coverage of climate impacts. They typically use GHG pricing mechanisms to induce emissions reductions and associated changes in energy and land uses consistent with the imposed climate goal. The scenarios generated by these models are defined by the choice of climate goals and assumptions about near-term climate policy developments. They are also shaped by assumptions about mitigation potentials and technologies as well as baseline developments such as, for example, those represented by

different Shared Socio-Economic Pathways (SSPs), especially those pertaining to energy and food demand (Riahi et al., 2017). See Section 2.3.1 for discussion of these assumptions. Since the AR5, the scenario literature has greatly expanded the exploration of these dimensions. This includes low-demand scenarios (Grubler et al., 2018; van Vuuren et al., 2018), scenarios taking into account a larger set of sustainable development goals (Bertram et al., 2018), scenarios with restricted availability of CDR technologies (Bauer et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018a; Strefler et al., 2018b; van Vuuren et al., 2018), scenarios with near-term action dominated by regulatory policies (Kriegler et al., 2018a) and scenario variations across the SSPs (Riahi et al., 2017; Rogelj et al., 2018). IAM results depend upon multiple underlying assumptions, for example, the extent to which global markets and economies are assumed to operate frictionless and policies are cost-optimized, assumptions about technological progress and availability and costs of mitigation and CDR measures, assumptions about underlying socio-economic developments and future energy, food and materials demand, and assumptions about the geographic and temporal pattern of future regulatory and carbon pricing policies (see Supplementary Material 2.SM.1.2 for additional discussion on IAMs and their limitations).

2.2 Geophysical Relationships and Constraints

Emissions pathways can be characterized by various geophysical characteristics, such as radiative forcing (Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; van Vuuren et al., 2011b), atmospheric concentrations (van Vuuren et al., 2007, 2011a; Clarke et al., 2014) or associated temperature outcomes (Meinshausen et al., 2009; Rogelj et al., 2011; Luderer et al., 2013). These attributes can be used to derive geophysical relationships for specific pathway classes, such as cumulative CO₂ emissions compatible with a specific level of warming, also known as ‘carbon budgets’ (Meinshausen et al., 2009; Rogelj et al., 2011; Stocker et al., 2013; Friedlingstein et al., 2014a), the consistent contributions of non-CO₂ GHGs and aerosols to the remaining carbon budget (Bowerman et al., 2011; Rogelj et al., 2015a, 2016b), or to temperature outcomes (Lamarque et al., 2011; Bowerman et al., 2013; Rogelj et al., 2014b). This section assesses geophysical relationships for both CO₂ and non-CO₂ emissions (see glossary).

2.2.1 Geophysical Characteristics of Mitigation Pathways

This section employs the pathway classification introduced in Section 2.1, with geophysical characteristics derived from simulations with the MAGICC reduced-complexity carbon cycle and climate model and supported by simulations with the FAIR reduced-complexity model (Section 2.1). Within a specific category and between models, there remains a large degree of variance. Most pathways exhibit a temperature overshoot which has been highlighted in several studies focusing on stringent mitigation pathways (Huntingford and Lowe, 2007; Wigley et al., 2007; Nohara et al., 2015; Rogelj et al., 2015d; Zickfeld and Herrington, 2015; Schleussner et al., 2016; Xu and Ramanathan, 2017). Only very few of the scenarios collected in the database for this report hold the average future warming projected by MAGICC below 1.5°C during the entire 21st century (Table 2.1, Figure 2.1). Most

1.5°C-consistent pathways available in the database overshoot 1.5°C around mid-century before peaking and then reducing temperatures so as to return below that level in 2100. However, because of numerous geophysical uncertainties and model dependencies (Section 2.2.1.1, Supplementary Material 2.SM.1.1), absolute temperature characteristics of the various pathway categories are more difficult to distinguish than relative features (Figure 2.1, Supplementary Material 2.SM.1.1), and actual probabilities of overshoot are imprecise. However, all lines of evidence available for temperature projections indicate a probability greater than 50% of overshooting 1.5°C by mid-century in all but the most stringent pathways currently available (Supplementary Material 2.SM.1.1, 2.SM.1.4).

Most 1.5°C-consistent pathways exhibit a peak in temperature by mid-century whereas 2°C-consistent pathways generally peak after 2050 (Supplementary Material 2.SM.1.4). The peak in median temperature in the various pathway categories occurs about ten years before reaching net zero CO₂ emissions due to strongly reduced annual CO₂ emissions and deep reductions in CH₄ emissions (Section 2.3.3). The two reduced-complexity climate models used in this assessment suggest that virtually all available 1.5°C-consistent pathways peak and then decline global mean temperature, but with varying rates of temperature decline after the peak (Figure 2.1). The estimated decadal rates of temperature change by the end of the century are smaller than the amplitude of the climate variability as assessed in AR5 (1 standard deviation of about ±0.1°C), which hence complicates the detection of a global peak and decline of warming in observations on time scales of one to two decades (Bindoff et al., 2013). In comparison, many pathways limiting warming to 2°C or higher by 2100 still have noticeable increasing trends at the end of the century, and thus imply continued warming.

By 2100, the difference between 1.5°C- and 2°C-consistent pathways becomes clearer compared to mid-century, not only for the temperature response (Figure 2.1) but also for atmospheric CO₂ concentrations. In 2100, the median CO₂ concentration in 1.5°C-consistent pathways is below 2016 levels (Le Quéré et al., 2018), whereas it remains higher by about 5–10% compared to 2016 in the 2°C-consistent pathways.

2.2.1.1 Geophysical uncertainties: non-CO₂ forcing agents

Impacts of non-CO₂ climate forcers on temperature outcomes are particularly important when evaluating stringent mitigation pathways (Weyant et al., 2006; Shindell et al., 2012; Rogelj et al., 2014b, 2015a; Samset et al., 2018). However, many uncertainties affect the role of non-CO₂ climate forcers in stringent mitigation pathways.

A first uncertainty arises from the magnitude of the radiative forcing attributed to non-CO₂ climate forcers. Figure 2.2 illustrates how, for one representative 1.5°C-consistent pathway (SSP2-1.9) (Fricko et al., 2017; Rogelj et al., 2018), the effective radiative forcings as estimated by MAGICC and FAIR can differ (see Supplementary Material 2.SM.1.1 for further details). This large spread in non-CO₂ effective radiative forcings leads to considerable uncertainty in the predicted temperature response. This uncertainty ultimately affects the assessed temperature outcomes for pathway classes used in this chapter (Section 2.1) and also affects the carbon budget (Section 2.2.2). Figure 2.2 highlights

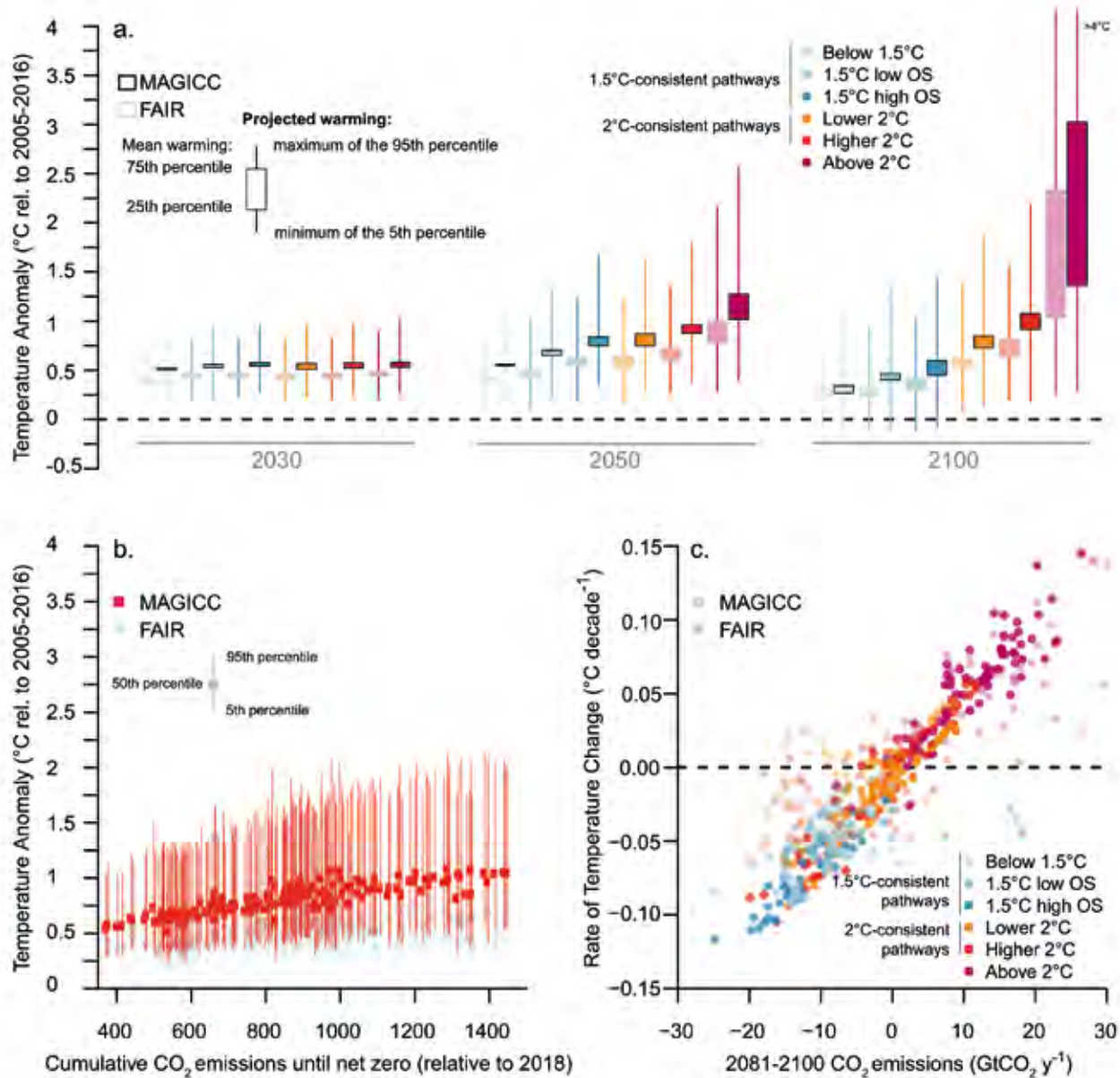


Figure 2.1 | Pathways classification overview. (a) Average global mean temperature increase relative to 2010 as projected by FAIR and MAGICCC in 2030, 2050 and 2100; (b) response of peak warming to cumulative CO₂ emissions until net zero by MAGICCC (red) and FAIR (blue); (c) decadal rate of average global mean temperature change from 2081 to 2100 as a function of the annual CO₂ emissions averaged over the same period as given by FAIR (transparent squares) and MAGICCC (filled circles). In panel (a), horizontal lines at 0.63°C and 1.13°C are indicative of the 1.5°C and 2°C warming thresholds with the respect to 1850–1900, taking into account the assessed historical warming of 0.87°C ± 0.12°C between the 1850–1900 and 2006–2015 periods (Chapter 1, Section 1.2.1). In panel (a), vertical lines illustrate both the physical and the scenario uncertainty as captured by MAGICCC and FAIR and show the minimal warming of the 5th percentile of projected warming and the maximal warming of the 95th percentile of projected warming per scenario class. Boxes show the interquartile range of mean warming across scenarios, and thus represent scenario uncertainty only.

the important role of methane emissions reduction in this scenario, in agreement with the recent literature focussing on stringent mitigation pathways (Shindell et al., 2012; Rogelj et al., 2014b, 2015a; Stohl et al., 2015; Collins et al., 2018).

For mitigation pathways that aim at halting and reversing radiative forcing increase during this century, the aerosol radiative forcing is a considerable source of uncertainty (Figure 2.2) (Samset et al., 2018; Smith et al., 2018). Indeed, reductions in SO₂ (and NO_x) emissions largely associated with fossil-fuel burning are expected to reduce the cooling effects of both aerosol radiative interactions and aerosol cloud

interactions, leading to warming (Myhre et al., 2013; Samset et al., 2018). A multimodel analysis (Myhre et al., 2017) and a study based on observational constraints (Malavelle et al., 2017) largely support the AR5 best estimate and uncertainty range of aerosol forcing. The partitioning of total aerosol radiative forcing between aerosol precursor emissions is important (Ghan et al., 2013; Jones et al., 2018; Smith et al., 2018) as this affects the estimate of the mitigation potential from different sectors that have aerosol precursor emission sources. The total aerosol effective radiative forcing change in stringent mitigation pathways is expected to be dominated by the effects from the phase-out of SO₂, although the magnitude of this aerosol-warming

effect depends on how much of the present-day aerosol cooling is attributable to SO_2 , particularly the cooling associated with aerosol–cloud interaction (Figure 2.2). Regional differences in the linearity of aerosol–cloud interactions (Carslaw et al., 2013; Kretzschmar et al., 2017) make it difficult to separate the role of individual precursors. Precursors that are not fully mitigated will continue to affect the Earth system. If, for example, the role of nitrate aerosol cooling is at the strongest end of the assessed IPCC AR5 uncertainty range, future temperature increases may be more modest if ammonia emissions continue to rise (Hauglustaine et al., 2014).

Figure 2.2 shows that there are substantial differences in the evolution of estimated effective radiative forcing of non- CO_2 forcers between MAGICC and FAIR. These forcing differences result in MAGICC simulating a larger warming trend in the near term compared to both the FAIR model and the recent observed trends of 0.2°C per decade reported in Chapter 1 (Figure 2.1, Supplementary Material 2.SM.1.1, Chapter 1, Section 1.2.1.3). The aerosol effective forcing is stronger in MAGICC compared to either FAIR or the AR5 best estimate, though it is still well within the AR5 uncertainty range (Supplementary Material 2.SM.1.1.1). A recent revision (Etminan et al., 2016) increases the methane forcing by 25%. This revision is used in the FAIR but not in the AR5 setup of MAGICC that is applied here. Other structural differences exist in how the two models relate emissions to concentrations that contribute to differences in forcing (see Supplementary Material 2.SM.1.1.1).

Non- CO_2 climate forcers exhibit a greater geographical variation in radiative forcings than CO_2 , which leads to important uncertainties in the temperature response (Myhre et al., 2013). This uncertainty increases the relative uncertainty of the temperature pathways associated with low emission scenarios compared to high emission scenarios (Clarke et al., 2014). It is also important to note that geographical patterns of temperature change and other climate responses, especially those related to precipitation, depend significantly on the forcing mechanism (Myhre et al., 2013; Shindell et al., 2015; Marvel et al., 2016; Samset et al., 2016) (see also Chapter 3, Section 3.6.2.2).

2.2.1.2 Geophysical uncertainties: climate and Earth system feedbacks

Climate sensitivity uncertainty impacts future projections as well as carbon-budget estimates (Schneider et al., 2017). AR5 assessed the equilibrium climate sensitivity (ECS) to be *likely* in the $1.5^\circ\text{--}4.5^\circ\text{C}$ range, *extremely unlikely* less than 1°C and *very unlikely* greater than 6°C . The lower bound of this estimate is lower than the range of CMIP5 models (Collins et al., 2013). The evidence for the 1.5°C lower bound on ECS in AR5 was based on analysis of energy-budget changes over the historical period. Work since AR5 has suggested that the climate sensitivity inferred from such changes has been lower than the $2 \times \text{CO}_2$ climate sensitivity for known reasons (Forster, 2016; Gregory and Andrews, 2016; Rugenstein et al., 2016; Armour, 2017; Ceppi and Gregory, 2017; Knutti et al., 2017; Proistosescu and Huybers, 2017). Both a revised interpretation of historical estimates and other lines of evidence based on analysis of climate models with the best representation of today's climate (Sherwood et al., 2014; Zhai et al., 2015; Tan et al., 2016; Brown and Caldeira, 2017; Knutti

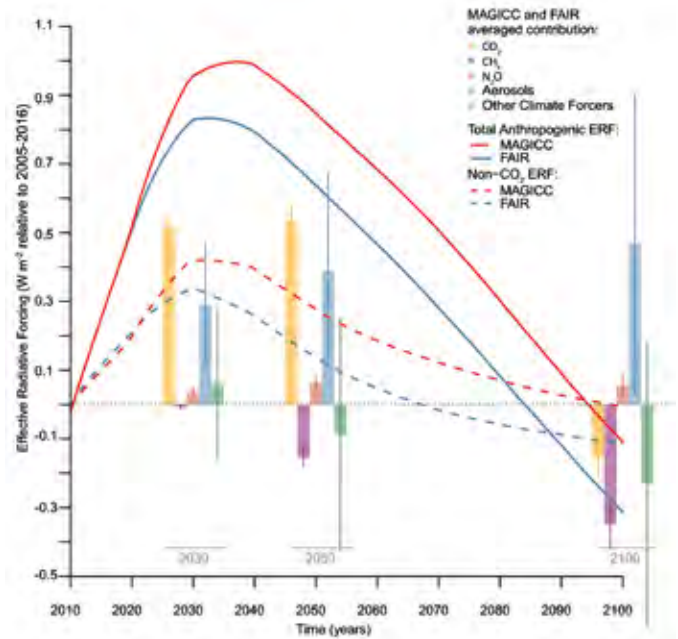


Figure 2.2 | Changes and uncertainties in effective radiative forcings (ERF) for one 1.5°C-consistent pathway (SSP2-19) as estimated by MAGICC and FAIR. The lines are indicative of the total effective radiative forcing from all anthropogenic sources (solid lines) and for non- CO_2 agents only (dashed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

et al., 2017) suggest that the lower bound of ECS could be revised upwards, which would decrease the chances of limiting warming below 1.5°C in assessed pathways. However, such a reassessment has been challenged (Lewis and Curry, 2018), albeit from a single line of evidence. Nevertheless, it is premature to make a major revision to the lower bound. The evidence for a possible revision of the upper bound on ECS is less clear, with cases argued from different lines of evidence for both decreasing (Lewis and Curry, 2015, 2018; Cox et al., 2018) and increasing (Brown and Caldeira, 2017) the bound presented in the literature. The tools used in this chapter employ ECS ranges consistent with the AR5 assessment. The MAGICC ECS distribution has not been selected to explicitly reflect this but is nevertheless consistent (Rogelj et al., 2014a). The FAIR model used here to estimate carbon budgets explicitly constructs log-normal distributions of ECS and transient climate response based on a multi-parameter fit to the AR5 assessed ranges of climate sensitivity and individual historic effective radiative forcings (Smith et al., 2018) (Supplementary Material 2.SM.1.1.1).

Several feedbacks of the Earth system, involving the carbon cycle, non- CO_2 GHGs and/or aerosols, may also impact the future dynamics of the coupled carbon–climate system's response to anthropogenic emissions. These feedbacks are caused by the effects of nutrient limitation (Duce et al., 2008; Mahowald et al., 2017), ozone exposure (de Vries et al., 2017), fire emissions (Narayan et al., 2007) and changes associated with natural aerosols (Cadule et al., 2009; Scott et al., 2018). Among these Earth system feedbacks, the importance of the permafrost feedback's influence has been highlighted in recent studies. Combined evidence

from both models (MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018) and field studies (like Schädel et al., 2014; Schuur et al., 2015) shows *high agreement* that permafrost thawing will release both CO₂ and CH₄ as the Earth warms, amplifying global warming. This thawing could also release N₂O (Voigt et al., 2017a, b). Field, laboratory and modelling studies estimate that the vulnerable fraction in permafrost is about 5–15% of the permafrost soil carbon (~5300–5600 GtCO₂ in Schuur et al., 2015) and that carbon emissions are expected to occur beyond 2100 because of system inertia and the large proportion of slowly decomposing carbon in permafrost (Schädel et al., 2014). Published model studies suggest that a large part of the carbon release to the atmosphere is in the form of CO₂ (Schädel et al., 2016), while the amount of CH₄ released by permafrost thawing is estimated to be much smaller than that CO₂. Cumulative CH₄ release by 2100 under RCP2.6 ranges from 0.13 to 0.45 Gt of methane (Burke et al., 2012; Schneider von Deimling et al., 2012, 2015), with fluxes being the highest in the middle of the century because of maximum thermokarst lake extent by mid-century (Schneider von Deimling et al., 2015).

The reduced complexity climate models employed in this assessment do not take into account permafrost or non-CO₂ Earth system feedbacks, although the MAGICC model has a permafrost module that can be enabled. Taking the current climate and Earth system feedbacks understanding together, there is a possibility that these models would underestimate the longer-term future temperature response to stringent emission pathways (Section 2.2.2).

2.2.2 The Remaining 1.5°C Carbon Budget

2.2.2.1 Carbon budget estimates

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

Carbon budgets can be derived from CO₂-only experiments as well as from multi-gas and aerosol scenarios. Some published estimates of carbon budgets compatible with 1.5°C or 2°C refer to budgets for CO₂-induced warming only, and hence do not take into account the contribution of non-CO₂ climate forcers (Allen et al., 2009;

Matthews et al., 2009; Zickfeld et al., 2009; IPCC, 2013a). However, because the projected changes in non-CO₂ climate forcers tend to amplify future warming, CO₂-only carbon budgets overestimate the total net cumulative carbon emissions compatible with 1.5°C or 2°C (Friedlingstein et al., 2014a; Rogelj et al., 2016b; Matthews et al., 2017; Mengis et al., 2018; Tokarska et al., 2018).

Since the AR5, many estimates of the remaining carbon budget for 1.5°C have been published (Friedlingstein et al., 2014a; MacDougall et al., 2015; Peters, 2016; Rogelj et al., 2016b, 2018; Matthews et al., 2017; Millar et al., 2017; Goodwin et al., 2018b; Kriegler et al., 2018b; Lowe and Bernie, 2018; Mengis et al., 2018; Millar and Friedlingstein, 2018; Schurer et al., 2018; Séférian et al., 2018; Tokarska and Gillett, 2018; Tokarska et al., 2018). These estimates cover a wide range as a result of differences in the models used, and of methodological choices, as well as physical uncertainties. Some estimates are exclusively model-based while others are based on observations or on a combination of both. Remaining carbon budgets limiting warming below 1.5°C or 2°C that are derived from Earth system models of intermediate complexity (MacDougall et al., 2015; Goodwin et al., 2018a), IAMs (Luderer et al., 2018; Rogelj et al., 2018), or are based on Earth-system model results (Lowe and Bernie, 2018; Séférian et al., 2018; Tokarska and Gillett, 2018) give remaining carbon budgets of the same order of magnitude as the IPCC AR5 Synthesis Report (SYR) estimates (IPCC, 2014a). This is unsurprising as similar sets of models were used for the AR5 (IPCC, 2013b). The range of variation across models stems mainly from either the inclusion or exclusion of specific Earth system feedbacks (MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018) or different budget definitions (Rogelj et al., 2018).

In contrast to the model-only estimates discussed above and employed in the AR5, this report additionally uses observations to inform its evaluation of the remaining carbon budget. Table 2.2 shows that the assessed range of remaining carbon budgets consistent with 1.5°C or 2°C is larger than the AR5 SYR estimate and is part way towards estimates constrained by recent observations (Millar et al., 2017; Goodwin et al., 2018a; Tokarska and Gillett, 2018). Figure 2.3 illustrates that the change since AR5 is, in very large part, due to the application of a more recent observed baseline to the historic temperature change and cumulative emissions; here adopting the baseline period of 2006–2015 (see Chapter 1, Section 1.2.1). AR5 SYR Figures SPM.10 and 2.3 already illustrated the discrepancy between models and observations, but did not apply this as a correction to the carbon budget because they were being used to illustrate the overall linear relationship between warming and cumulative carbon emissions in the CMIP5 models since 1870, and were not specifically designed to quantify residual carbon budgets relative to the present for ambitious temperature goals. The AR5 SYR estimate was also dependent on a subset of Earth system models illustrated in Figure 2.3 of this report. Although, as outlined below and in Table 2.2, considerable uncertainties remain, there is *high agreement* across various lines of evidence assessed in this report that the remaining carbon budget for 1.5°C or 2°C would be larger than the estimates at the time of the AR5. However, the overall remaining budget for 2100 is assessed to be smaller than that derived from the recent observational-informed estimates, as Earth system feedbacks such as permafrost thawing reduce the budget applicable to centennial scales (see Section 2.2.2.2).

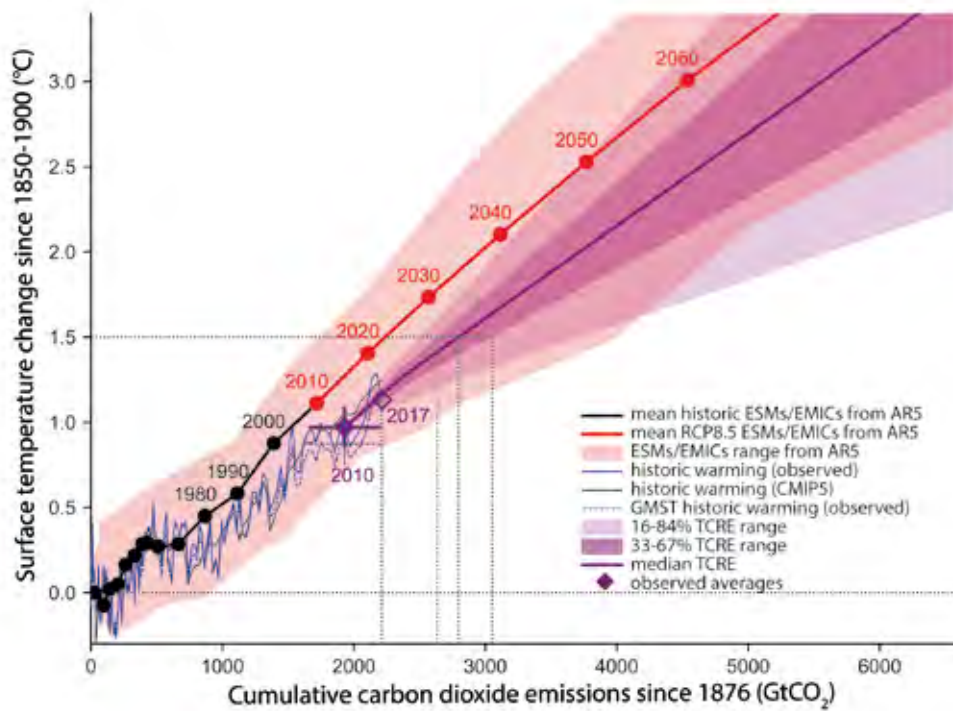


Figure 2.3 | Temperature changes from 1850–1900 versus cumulative CO₂ emissions since 1st January 1876. Solid lines with dots reproduce the globally averaged near-surface air temperature response to cumulative CO₂ emissions plus non-CO₂ forcings as assessed in Figure SPM10 of WGI AR5, except that points marked with years relate to a particular year, unlike in WGI AR5 Figure SPM.10, where each point relates to the mean over the previous decade. The AR5 data was derived from 15 Earth system models and 5 Earth system models of Intermediate Complexity for the historic observations (black) and RCP8.5 scenario (red), and the red shaded plume shows the range across the models as presented in the AR5. The purple shaded plume and the line are indicative of the temperature response to cumulative CO₂ emissions and non-CO₂ warming adopted in this report. The non-CO₂ warming contribution is averaged from the MAGICC and FAIR models, and the purple shaded range assumes the AR5 WGI TCRE distribution (Supplementary Material 2.SM.1.1.2). The 2010 observation of surface temperature change (0.97°C based on 2006–2015 mean compared to 1850–1900, Chapter 1, Section 1.2.1) and cumulative carbon dioxide emissions from 1876 to the end of 2010 of 1,930 GtCO₂ (Le Quéré et al., 2018) is shown as a filled purple diamond. The value for 2017 based on the latest cumulative carbon emissions up to the end of 2017 of 2,220 GtCO₂ (Version 1.3 accessed 22 May 2018) and a surface temperature anomaly of 1.1°C based on an assumed temperature increase of 0.2°C per decade is shown as a hollow purple diamond. The thin blue line shows annual observations, with CO₂ emissions from Le Quéré et al. (2018) and estimated globally averaged near-surface temperature from scaling the incomplete coverage and blended HadCRUT4 dataset in Chapter 1. The thin black line shows the CMIP5 multimodel mean estimate with CO₂ emissions also from (Le Quéré et al., 2018). The thin black line shows the GMST historic temperature trends from Chapter 1, which give lower temperature changes up to 2006–2015 of 0.87°C and would lead to a larger remaining carbon budget. The dotted black lines illustrate the remaining carbon budget estimates for 1.5°C given in Table 2.2. Note these remaining budgets exclude possible Earth system feedbacks that could reduce the budget, such as CO₂ and CH₄ release from permafrost thawing and tropical wetlands (see Section 2.2.2.2).

2.2.2.2 CO₂ and non-CO₂ contributions to the remaining carbon budget

A remaining carbon budget can be estimated from calculating the amount of CO₂ emissions consistent (given a certain value of TCRE) with an allowable additional amount of warming. Here, the allowable warming is the 1.5°C warming threshold minus the current warming taken as the 2006–2015 average, with a further amount removed to account for the estimated non-CO₂ temperature contribution to the remaining warming (Peters, 2016; Rogelj et al., 2016b). This assessment uses the TCRE range from AR5 WGI (Collins et al., 2013) supported by estimates of non-CO₂ contributions that are based on published methods and integrated pathways (Friedlingstein et al., 2014a; Allen et al., 2016, 2018; Peters, 2016; Smith et al., 2018). Table 2.2 and Figure 2.3 show the assessed remaining carbon budgets and key uncertainties for a set of additional warming levels relative to the 2006–2015 period (see Supplementary Material 2.SM.1.1.2 for details). With an assessed historical warming of 0.87°C ± 0.12°C from 1850–1900 to 2006–2015 (Chapter 1, Section 1.2.1), 0.63°C of additional warming would be

approximately consistent with a global mean temperature increase of 1.5°C relative to pre-industrial levels. For this level of additional warming, remaining carbon budgets have been estimated (Table 2.2, Supplementary Material 2.SM.1.1.2).

The remaining carbon budget calculation presented in the Table 2.2 and illustrated in Figure 2.3 does not consider additional Earth system feedbacks such as permafrost thawing. These are uncertain but estimated to reduce the remaining carbon budget by an order of magnitude of about 100 GtCO₂ and more thereafter. Accounting for such feedbacks would make the carbon budget more applicable for 2100 temperature targets, but would also increase uncertainty (Table 2.2 and see below). Excluding such feedbacks, the assessed range for the remaining carbon budget is estimated to be 840, 580, and 420 GtCO₂ for the 33rd, 50th and, 67th percentile of TCRE, respectively, with a median non-CO₂ warming contribution and starting from 1 January 2018 onward. Consistent with the approach used in the IPCC Fifth Assessment Report (IPCC, 2013b), the latter estimates use global near-surface air temperatures both over the ocean and

over land to estimate global surface temperature change since pre-industrial. The global warming from the pre-industrial period until the 2006–2015 reference period is estimated to amount to 0.97°C with an uncertainty range of about $\pm 0.1^\circ\text{C}$ (see Chapter 1, Section 1.2.1). Three methodological improvements lead to these estimates of the remaining carbon budget being about 300 GtCO₂ larger than those reported in Table 2.2 of the IPCC AR5 SYR (IPCC, 2014a) (*medium confidence*). The AR5 used 15 Earth System Models (ESM) and 5 Earth-system Models of Intermediate Complexity (EMIC) to derive an estimate of the remaining carbon budget. Their approach hence made implicit assumptions about the level of warming to date, the future contribution of non-CO₂ emissions, and the temperature response to CO₂ (TCRE). In this report, each of these aspects are considered explicitly. When estimating global warming until the 2006–2015 reference period as a blend of near-surface air temperature over land and sea-ice regions, and sea-surface temperature over open ocean, by averaging the four global mean surface temperature time series listed in Chapter 1 Section 1.2.1, the global warming would amount to 0.87°C $\pm 0.1^\circ\text{C}$. Using the latter estimate of historical warming and projecting global warming using global near-surface air temperatures from model projections leads to remaining carbon budgets for limiting global warming to 1.5°C of 1080, 770, and 570 GtCO₂ for the 33rd, 50th, and 67th percentile of TCRE, respectively. Note that future research and ongoing observations over the next years will provide a better indication as to how the 2006–2015 base period compares with the long-term trends and might affect the budget estimates. Similarly, improved understanding in Earth system feedbacks would result in a better quantification of their impacts on remaining carbon budgets for 1.5°C and 2°C.

After TCRE uncertainty, a major additional source of uncertainty is the magnitude of non-CO₂ forcing and its contribution to the temperature change between the present day and the time of peak warming. Integrated emissions pathways can be used to ensure consistency between CO₂ and non-CO₂ emissions (Bowerman et al., 2013; Collins et al., 2013; Clarke et al., 2014; Rogelj et al., 2014b, 2015a; Tokarska et al., 2018). Friedlingstein et al. (2014a) used pathways with limited to no climate mitigation to find a variation due to non-CO₂ contributions of about $\pm 33\%$ for a 2°C carbon budget. Rogelj et al. (2016b) showed no particular bias in non-CO₂ radiative forcing or warming at the time of exceedance of 2°C or at peak warming between scenarios with increasing emissions and strongly mitigated scenarios (consistent with Stocker et al., 2013). However, clear differences of the non-CO₂ warming contribution at the time of deriving a 2°C-consistent carbon budget were reported for the four RCPs. Although the spread in non-CO₂ forcing across scenarios can be smaller in absolute terms at lower levels of cumulative emissions, it can be larger in relative terms compared to the remaining carbon budget (Stocker et al., 2013; Friedlingstein et al., 2014a; Rogelj et al., 2016b). Tokarska and Gillett (2018) find no statistically significant differences in 1.5°C-consistent cumulative emissions budgets when calculated for different RCPs from consistent sets of CMIP5 simulations.

The mitigation pathways assessed in this report indicate that emissions of non-CO₂ forcers contribute an average additional warming of around 0.15°C relative to 2006–2015 at the time of net zero CO₂ emissions, reducing the remaining carbon budget by roughly 320 GtCO₂. This

arises from a weakening of aerosol cooling and continued emissions of non-CO₂ GHGs (Sections 2.2.1, 2.3.3). This non-CO₂ contribution at the time of net zero CO₂ emissions varies by about $\pm 0.1^\circ\text{C}$ across scenarios, resulting in a carbon budget uncertainty of about ± 250 GtCO₂, and takes into account marked reductions in methane emissions (Section 2.3.3). If these reductions are not achieved, remaining carbon budgets are further reduced. Uncertainties in the non-CO₂ forcing and temperature response are asymmetric and can influence the remaining carbon budget by -400 to $+200$ GtCO₂, with the uncertainty in aerosol radiative forcing being the largest contributing factor (Table 2.2). The MAGICC and FAIR models in their respective parameter setups and model versions used to assess the non-CO₂ warming contribution give noticeable different non-CO₂ effective radiative forcing and warming for the same scenarios while both being within plausible ranges of future response (Figure 2.2 and Supplementary Material 2.SM.1.1, 2.SM.1.2). For this assessment, it is premature to assess the accuracy of their results, so it is assumed that both are equally representative of possible futures. Their non-CO₂ warming estimates are therefore averaged for the carbon budget assessment and their differences used to guide the uncertainty assessment of the role of non-CO₂ forcers. Nevertheless, the findings are robust enough to give *high confidence* that the changing emissions of non-CO₂ forcers (particularly the reduction in cooling aerosol precursors) cause additional near-term warming and reduce the remaining carbon budget compared to the CO₂-only budget.

TCRE uncertainty directly impacts carbon budget estimates (Peters, 2016; Matthews et al., 2017; Millar and Friedlingstein, 2018). Based on multiple lines of evidence, AR5 WGI assessed a *likely* range for TCRE of 0.2°–0.7°C per 1000 GtCO₂ (Collins et al., 2013). The TCRE of the CMIP5 Earth system models ranges from 0.23°C to 0.66°C per 1000 GtCO₂ (Gillett et al., 2013). At the same time, studies using observational constraints find best estimates of TCRE of 0.35°–0.41°C per 1000 GtCO₂ (Matthews et al., 2009; Gillett et al., 2013; Tachiiri et al., 2015; Millar and Friedlingstein, 2018). This assessment continues to use the assessed AR5 TCRE range under the working assumption that TCRE is normally distributed (Stocker et al., 2013). Observation-based estimates have reported log-normal distributions of TCRE (Millar and Friedlingstein, 2018). Assuming a log-normal instead of normal distribution of the assessed AR5 TCRE range would result in about a 200 GtCO₂ increase for the median budget estimates but only about half at the 67th percentile, while historical temperature uncertainty and uncertainty in recent emissions contribute ± 150 and ± 50 GtCO₂ to the uncertainty, respectively (Table 2.2).

Calculating carbon budgets from the TCRE requires the assumption that the instantaneous warming in response to cumulative CO₂ emissions equals the long-term warming or, equivalently, that the residual warming after CO₂ emissions cease is negligible. The magnitude of this residual warming, referred to as the zero-emission commitment, ranges from slightly negative (i.e., a slight cooling) to slightly positive for CO₂ emissions up to present-day (Chapter 1, Section 1.2.4) (Lowe et al., 2009; Frölicher and Joos, 2010; Gillett et al., 2011; Matthews and Zickfeld, 2012). The delayed temperature change from a pulse CO₂ emission introduces uncertainties in emission budgets, which have not been quantified in the literature for budgets consistent with limiting warming to 1.5°C. As a consequence, this

uncertainty does not affect our carbon budget estimates directly but it is included as an additional factor in the assessed Earth system feedback uncertainty (as detailed below) of roughly 100 GtCO₂ on decadal time scales presented in Table 2.2.

Remaining carbon budgets are further influenced by Earth system feedbacks not accounted for in CMIP5 models, such as the permafrost carbon feedback (Friedlingstein et al., 2014b; MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018), and their influence on the TCRE. Lowe and Bernie (2018) used a simple climate sensitivity scaling approach to estimate that Earth system feedbacks (such as CO₂ released by permafrost thawing or methane released by wetlands) could reduce carbon budgets for 1.5°C and 2°C by roughly 100 GtCO₂ on centennial time scales. Their findings are based on an older understanding of Earth system feedbacks (Arneeth et al., 2010). This estimate is broadly supported by more recent analysis of individual feedbacks. Schädel et al. (2014) suggest an upper bound of 24.4 PgC (90 GtCO₂) emitted from carbon release from permafrost over the next forty years for a RCP4.5 scenario. Burke et al. (2017) use a single model to estimate permafrost emissions between 0.3 and 0.6 GtCO₂ y⁻¹ from the point of 1.5°C stabilization, which would reduce the budget by around 20 GtCO₂ by 2100. Comyn-Platt et al. (2018) include carbon and methane emissions from permafrost and wetlands and suggest the 1.5°C remaining carbon budget is reduced by 116 GtCO₂. Additionally, Mahowald et al. (2017) find there is possibility of 0.5–1.5 GtCO₂ y⁻¹ being released from aerosol-biogeochemistry changes if aerosol emissions cease. In summary, these additional Earth system feedbacks taken together are assessed to reduce the remaining carbon budget applicable to 2100 by an order of magnitude of 100 GtCO₂, compared to the budgets based on the assumption of a constant TCRE presented in Table 2.2 (*limited evidence, medium agreement*), leading to overall *medium confidence* in their assessed impact. After 2100, the impact of additional Earth system feedbacks is expected to further reduce the remaining carbon budget (*medium confidence*).

The uncertainties presented in Table 2.2 cannot be formally combined, but current understanding of the assessed geophysical uncertainties suggests at least a ±50% possible variation for remaining carbon budgets for 1.5°C-consistent pathways. By the end of 2017, anthropogenic CO₂ emissions since the pre-industrial period are estimated to have amounted to approximately 2200 ±320 GtCO₂ (*medium confidence*) (Le Quéré et al., 2018). When put in the context of year-2017 CO₂ emissions (about 42 GtCO₂ yr⁻¹, ±3 GtCO₂ yr⁻¹, *high confidence*) (Le Quéré et al., 2018), a remaining carbon budget of 580 GtCO₂ (420 GtCO₂) suggests meeting net zero global CO₂ emissions in about 30 years (20 years) following a linear decline starting from 2018 (rounded to the nearest five years), with a variation of ±15–20 years due to the geophysical uncertainties mentioned above (*high confidence*).

The remaining carbon budgets assessed in this section are consistent with limiting peak warming to the indicated levels of additional warming. However, if these budgets are exceeded and the use of CDR (see Sections 2.3 and 2.4) is envisaged to return cumulative CO₂ emissions to within the carbon budget at a later point in time, additional uncertainties apply because the TCRE is different under increasing and decreasing atmospheric CO₂ concentrations due to

ocean thermal and carbon cycle inertia (Herrington and Zickfeld, 2014; Krasting et al., 2014; Zickfeld et al., 2016). This asymmetrical behaviour makes carbon budgets path-dependent in the case of a budget and/or temperature overshoot (MacDougall et al., 2015). Although potentially large for scenarios with large overshoot (MacDougall et al., 2015), this path-dependence of carbon budgets has not been well quantified for 1.5°C- and 2°C-consistent scenarios and as such remains an important knowledge gap. This assessment does not explicitly account for path dependence but takes it into consideration for its overall confidence assessment.

This assessment finds a larger remaining budget from the 2006–2015 base period than the 1.5°C and 2°C remaining budgets inferred from AR5 from the start of 2011, which were approximately 1000 GtCO₂ for the 2°C (66% of model simulations) and approximately 400 GtCO₂ for the 1.5°C budget (66% of model simulations). In contrast, this assessment finds approximately 1600 GtCO₂ for the 2°C (66th TCRE percentile) and approximately 860 GtCO₂ for the 1.5°C budget (66th TCRE percentile) from 2011. However, these budgets are not directly equivalent as AR5 reported budgets for fractions of CMIP5 simulations and other lines of evidence, while this report uses the assessed range of TCRE and an assessment of the non-CO₂ contribution at net zero CO₂ emissions to provide remaining carbon budget estimates at various percentiles of TCRE. Furthermore, AR5 did not specify remaining budgets to carbon neutrality as we do here, but budgets until the time the temperature limit of interest was reached, assuming negligible zero emission commitment and taking into account the non-CO₂ forcing at that point in time.

In summary, although robust physical understanding underpins the carbon budget concept, relative uncertainties become larger as a specific temperature limit is approached. For the budget, applicable to the mid-century, the main uncertainties relate to the TCRE, non-CO₂ emissions, radiative forcing and response. For 2100, uncertain Earth system feedbacks such as permafrost thawing would further reduce the available budget. The remaining budget is also conditional upon the choice of baseline, which is affected by uncertainties in both historical emissions, and in deriving the estimate of globally averaged human-induced warming. As a result, only *medium confidence* can be assigned to the assessed remaining budget values for 1.5°C and 2.0°C and their uncertainty.

Table 2.2 | The assessed remaining carbon budget and its uncertainties. Shaded blue horizontal bands illustrate the uncertainty in historical temperature increase from the 1850–1900 base period until the 2006–2015 period as estimated from global near-surface air temperatures, which impacts the additional warming until a specific temperature limit like 1.5°C or 2°C relative to the 1850–1900 period. Shaded grey cells indicate values for when historical temperature increase is estimated from a blend of near-surface air temperatures over land and sea ice regions and sea-surface temperatures over oceans.

Additional Warming since 2006–2015 [°C] ^{*(1)}	Approximate Warming since 1850–1900 [°C] ^{*(1)}	Remaining Carbon Budget (Excluding Additional Earth System Feedbacks ^{*(5)}) [GtCO ₂ from 1.1.2018] ^{*(2)}			Key Uncertainties and Variations ^{*(4)}					
		Percentiles of TCRE ^{*(3)}			Earth System Feedbacks ^{*(5)}	Non-CO ₂ scenario variation ^{*(6)}	Non-CO ₂ forcing and response uncertainty	TCRE distribution uncertainty ^{*(7)}	Historical temperature uncertainty ^{*(1)}	Recent emissions uncertainty ^{*(8)}
33rd	50th	67th	[GtCO ₂]	[GtCO ₂]						
0.3		290	160	80	Budgets on the left are reduced by about –100 on centennial time scales	±250	–400 to +200	+100 to +200	±250	±20
0.4		530	350	230						
0.5		770	530	380						
0.53	~1.5°C	840	580	420						
0.6		1010	710	530						
0.63		1080	770	570						
0.7		1240	900	680						
0.78		1440	1040	800						
0.8		1480	1080	830						
0.9		1720	1260	980						
1		1960	1450	1130						
1.03	~2°C	2030	1500	1170						
1.1		2200	1630	1280						
1.13		2270	1690	1320						
1.2		2440	1820	1430						

Notes:

- * (1) Chapter 1 has assessed historical warming between the 1850–1900 and 2006–2015 periods to be 0.87°C with a ±0.12°C *likely* (1-standard deviation) range, and global near-surface air temperature to be 0.97°C. The temperature changes from the 2006–2015 period are expressed in changes of global near-surface air temperature.
- * (2) Historical CO₂ emissions since the middle of the 1850–1900 historical base period (mid-1875) are estimated at 1940 GtCO₂ (1640–2240 GtCO₂, one standard deviation range) until end 2010. Since 1 January 2011, an additional 290 GtCO₂ (270–310 GtCO₂, one sigma range) has been emitted until the end of 2017 (Le Quéré et al., 2018).
- * (3) TCRE: transient climate response to cumulative emissions of carbon, assessed by AR5 to fall *likely* between 0.8–2.5°C/1000 PgC (Collins et al., 2013), considering a normal distribution consistent with AR5 (Stocker et al., 2013). Values are rounded to the nearest 10 GtCO₂.
- * (4) Focussing on the impact of various key uncertainties on median budgets for 0.53°C of additional warming.
- * (5) Earth system feedbacks include CO₂ released by permafrost thawing or methane released by wetlands, see main text.
- * (6) Variations due to different scenario assumptions related to the future evolution of non-CO₂ emissions.
- * (7) The distribution of TCRE is not precisely defined. Here the influence of assuming a lognormal instead of a normal distribution shown.
- * (8) Historical emissions uncertainty reflects the uncertainty in historical emissions since 1 January 2011.

2.3 Overview of 1.5°C Mitigation Pathways

Limiting global mean temperature increase at any level requires global CO₂ emissions to become net zero at some point in the future (Zickfeld et al., 2009; Collins et al., 2013). At the same time, limiting the residual warming of short-lived non-CO₂ emissions can be achieved by reducing their annual emissions as much as possible (Section 2.2, Cross-Chapter Box 2 in Chapter 1). This would require large-scale transformations of the global energy–agriculture–land–economy system, affecting the way in which energy is produced, agricultural systems are organized, and food, energy and materials are consumed (Clarke et al., 2014). This section assesses key properties of pathways consistent with limiting global mean temperature to 1.5°C relative to pre-industrial levels, including their underlying assumptions and variations.

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

The overwhelming majority of published integrated pathways have been developed by global IAMs that represent key societal systems

and their interactions, like the energy system, agriculture and land use, and the economy (see Section 6.2 in Clarke et al., 2014). Very often these models also include interactions with a representation of the geophysical system, for example, by including spatially explicit land models or carbon cycle and climate models. The complex features of these subsystems are approximated and simplified in these models. IAMs are briefly introduced in Section 2.1 and important knowledge gaps identified in Section 2.6. An overview to the use, scope and limitations of IAMs is provided in Supplementary Material 2.SM.1.2.

The pathway literature is assessed in two ways in this section. First, various insights on specific questions reported by studies can be assessed to identify robust or divergent findings. Second, the combined body of scenarios can be assessed to identify salient features of pathways in line with a specific climate goal across a wide range of models. The latter can be achieved by assessing pathways available in the database to this assessment (Section 2.1, Supplementary Material 2.SM.1.2–4). The ensemble of scenarios available to this assessment is an ensemble of opportunity: it is a collection of scenarios from a diverse set of studies that was not developed with a common set of questions and a statistical analysis of outcomes in mind. This means that ranges can be useful to identify robust and sensitive features across available scenarios and contributing modelling frameworks, but do not lend themselves to a statistical interpretation. To understand the reasons underlying the ranges, an assessment of the underlying scenarios and studies is required. To this end, this section highlights illustrative pathway archetypes that help to clarify the variation in assessed ranges for 1.5°C-consistent pathways.

2.3.1 Range of Assumptions Underlying 1.5°C Pathways

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

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

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

There is deep uncertainty about the ways humankind will use energy and land in the 21st century. These ways are intricately linked to

future population levels, secular trends in economic growth and income convergence, behavioural change and technological progress. These dimensions have been recently explored in the context of the SSPs (Kriegler et al., 2012; O'Neill et al., 2014), which provide narratives (O'Neill et al., 2017) and quantifications (Crespo Cuaresma, 2017; Dellink et al., 2017; KC and Lutz, 2017; Leimbach et al., 2017; Riahi et al., 2017) of different world futures across which scenario dimensions are varied to explore differential challenges to adaptation and mitigation (Cross-Chapter Box 1 in Chapter 1). This framework is increasingly adopted by IAMs to systematically explore the impact of socio-economic assumptions on mitigation pathways (Riahi et al., 2017), including 1.5°C-consistent pathways (Rogelj et al., 2018). The narratives describe five worlds (SSP1–5) with different socio-economic predispositions to mitigate and adapt to climate change (Table 2.3). As a result, population and economic growth projections can vary strongly across integrated scenarios, including available 1.5°C-consistent pathways (Figure 2.4). For example, based on alternative future fertility, mortality, migration and educational assumptions, population projections vary between 8.5 and 10.0 billion people by 2050 and between 6.9 and 12.6 billion people by 2100 across the SSPs. An important factor for these differences is future female educational attainment, with higher attainment leading to lower fertility rates and therefore decreased population growth up to a level of 1 billion people by 2050 (Lutz and KC, 2011; Snopkowski et al., 2016; KC and Lutz, 2017). Consistent with population development, GDP per capita also varies strongly in SSP baselines, ranging from about 20 to more than 50 thousand USD₂₀₁₀ per capita in 2050 (in purchasing power parity values, PPP), in part driven by assumptions on human development, technological progress and development convergence between and within regions (Crespo Cuaresma, 2017; Dellink et al., 2017; Leimbach et al., 2017). Importantly, none of the GDP projections in the mitigation pathway literature assessed in this chapter included the feedback of climate damages on economic growth (Hsiang et al., 2017).

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

Table 2.3 | Key Characteristics of the Five Shared Socio-Economic Pathways (SSPs) (O'Neill et al., 2017).

Socio-Economic Challenges to Mitigation	Socio-Economic Challenges to Adaptation		
	Low	Medium	High
High	SSP5: Fossil-fuelled development <ul style="list-style-type: none"> • low population • very high economic growth per capita • high human development • high technological progress • ample fossil fuel resources • very resource intensive lifestyles • high energy and food demand per capita • economic convergence and global cooperation 		SSP3: Regional rivalry <ul style="list-style-type: none"> • high population • low economic growth per capita • low human development • low technological progress • resource-intensive lifestyles • resource-constrained energy and food demand per capita • focus on regional food and energy security • regionalization and lack of global cooperation
Medium		SSP2: Middle of the road <ul style="list-style-type: none"> • medium population • medium and uneven economic growth • medium and uneven human development • medium and uneven technological progress • resource-intensive lifestyles • medium and uneven energy and food demand per capita • limited global cooperation and economic convergence 	
Low	SSP1: Sustainable development <ul style="list-style-type: none"> • low population • high economic growth per capita • high human development • high technological progress • environmentally oriented technological and behavioural change • resource-efficient lifestyles • low energy and food demand per capita • economic convergence and global cooperation 		SSP4: Inequality <ul style="list-style-type: none"> • Medium to high population • Unequal low to medium economic growth per capita • Unequal low to medium human development • unequal technological progress: high in globalized high-tech sectors, slow in domestic sectors • unequal lifestyles and energy /food consumption: resource intensity depending on income • Globally connected elite, disconnected domestic work forces

1.5°C-consistent pathways in a sustainability oriented world (SSP1) and four of six models found 1.5°C-consistent pathways for middle-of-the-road developments (SSP2). These results show that 1.5°C-consistent pathways can be identified under a broad range of assumptions, but that lack of global cooperation (SSP3), high inequality (SSP4) and/or high population growth (SSP3) that limit the ability to control land use emissions, and rapidly growing resource-intensive consumption (SSP5) are key impediments.

Figure 2.4 compares the range of underlying socio-economic developments as well as energy and food demand in available 1.5°C-consistent pathways with the full set of published scenarios that were submitted to this assessment. While 1.5°C-consistent pathways broadly cover the full range of population and economic growth developments (except for the high population development in SSP3-based scenarios), they tend to cluster on the lower end for energy and food demand. They still encompass, however, a wide range of developments from decreasing to increasing demand levels relative to today. For the purpose of this assessment, a set of four illustrative 1.5°C-consistent pathway archetypes were selected to show the variety of underlying assumptions and characteristics (Figure 2.4). They comprise three 1.5°C-consistent pathways based on the SSPs (Rogelj et al., 2018): a sustainability oriented scenario (S1 based on SSP1) developed with the AIM model (Fujimori, 2017), a fossil-fuel intensive

and high energy demand scenario (S5, based on SSP5) developed with the REMIND-MAGPIE model (Kriegler et al., 2017), and a middle-of-the-road scenario (S2, based on SSP2) developed with the MESSAGE-GLOBIOM model (Fricko et al., 2017). In addition, we include a scenario with low energy demand (LED) (Grubler et al., 2018), which reflects recent literature with a stronger focus on demand-side measures (Bertram et al., 2018; Grubler et al., 2018; Liu et al., 2018; van Vuuren et al., 2018). Pathways LED, S1, S2, and S5 are referred to as P1, P2, P3, and P4 in the Summary for Policymakers.

2.3.1.2 Mitigation options in 1.5°C pathways

In the context of 1.5°C pathways, the portfolio of mitigation options available to the model becomes an increasingly important factor. IAMs include a wide variety of mitigation options, as well as measures that achieve CDR from the atmosphere (Krey et al., 2014a, b) (see Chapter 4, Section 4.3 for a broad assessment of available mitigation measures). For the purpose of this assessment, we elicited technology availability in models that submitted scenarios to the database as summarized in Supplementary Material 2.SM.1.2, where a detailed picture of the technology variety underlying available 1.5°C-consistent pathways is provided. Modelling choices on whether a particular mitigation measure is included are influenced by an assessment of its global mitigation potential, the availability of data and literature describing

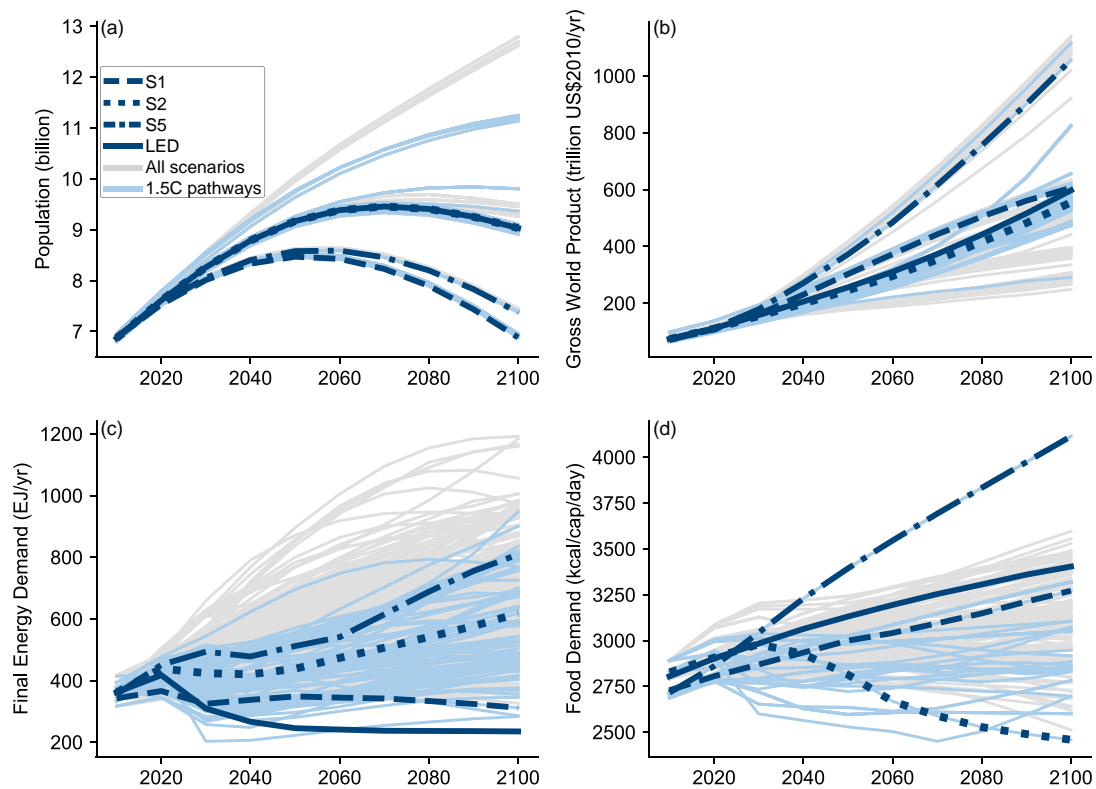


Figure 2.4 | Range of assumptions about socio-economic drivers and projections for energy and food demand in the pathways available to this assessment. 1.5°C-consistent pathways are blue, other pathways grey. Trajectories for the illustrative 1.5°C-consistent archetypes used in this Chapter (LED, S1, S2, S5; referred to as P1, P2, P3, and P4 in the Summary for Policymakers.) are highlighted. S1 is a sustainability oriented scenario, S2 is a middle-of-the-road scenario, and S5 is a fossil-fuel intensive and high energy demand scenario. LED is a scenario with particularly low energy demand. Population assumptions in S2 and LED are identical. Panels show (a) world population, (b) gross world product in purchasing power parity values, (c) final energy demand, and (d) food demand.

its techno-economic characteristics and future prospects, and the computational challenge of representing the measure, e.g., in terms of required spatio-temporal and process detail.

This elicitation (Supplementary Material 2.SM.1.2) confirms that IAMs cover most supply-side mitigation options on the process level, while many demand-side options are treated as part of underlying assumptions, which can be varied (Clarke et al., 2014). In recent years, there has been increasing attention on improving the modelling of integrating variable renewable energy into the power system (Creutzig et al., 2017; Luderer et al., 2017; Pietzcker et al., 2017) and of behavioural change and other factors influencing future demand for energy and food (van Sluiseveld et al., 2016; McCollum et al., 2017; Weindl et al., 2017), including in the context of 1.5°C-consistent pathways (Grubler et al., 2018; van Vuuren et al., 2018). The literature on the many diverse CDR options only recently started to develop strongly (Minx et al., 2017) (see Chapter 4, Section 4.3.7 for a detailed assessment), and hence these options are only partially included in IAM analyses. IAMs mostly incorporate afforestation and bioenergy with carbon capture and storage (BECCS) and only in few cases also include direct air capture with CCS (DACCS) (Chen and Tavoni, 2013; Marcucci et al., 2017; Strefler et al., 2018b).

Several studies have either directly or indirectly explored the dependence of 1.5°C-consistent pathways on specific (sets of) mitigation and CDR technologies (Bauer et al., 2018; Grubler et al.,

2018; Holz et al., 2018b; Kriegler et al., 2018a; Liu et al., 2018; Rogelj et al., 2018; Strefler et al., 2018b; van Vuuren et al., 2018). However, there are a few potentially disruptive technologies that are typically not yet well covered in IAMs and that have the potential to alter the shape of mitigation pathways beyond the ranges in the IAM-based literature. Those are also included in Supplementary Material 2.SM.1.2. The configuration of carbon-neutral energy systems projected in mitigation pathways can vary widely, but they all share a substantial reliance on bioenergy under the assumption of effective land-use emissions control. There are other configurations with less reliance on bioenergy that are not yet comprehensively covered by global mitigation pathway modelling. One approach is to dramatically reduce and electrify energy demand for transportation and manufacturing to levels that make residual non-electric fuel use negligible or replaceable by limited amounts of electrolytic hydrogen. Such an approach is presented in a first-of-its kind low-energy-demand scenario (Grubler et al., 2018) which is part of this assessment. Other approaches rely less on energy demand reductions, but employ cheap renewable electricity to push the boundaries of electrification in the industry and transport sectors (Breyer et al., 2017; Jacobson, 2017). In addition, these approaches deploy renewable-based Power-2-X (read: Power to “x”) technologies to substitute residual fossil-fuel use (Brynnolf et al., 2018). An important element of carbon-neutral Power-2-X applications is the combination of hydrogen generated from renewable electricity and CO₂ captured from the atmosphere (Zeman and Keith, 2008). Alternatively, algae are considered as a bioenergy source with more limited implications

for land use and agricultural systems than energy crops (Williams and Laurens, 2010; Walsh et al., 2016; Greene et al., 2017).

Furthermore, a range of measures could radically reduce agricultural and land-use emissions and are not yet well-covered in IAM modelling. This includes plant-based proteins (Joshi and Kumar, 2015) and cultured meat (Post, 2012) with the potential to substitute for livestock products at much lower GHG footprints (Tuomisto and Teixeira de Mattos, 2011). Large-scale use of synthetic or algae-based proteins for animal feed could free pasture land for other uses (Madeira et al., 2017; Pikaar et al., 2018). Novel technologies such as methanogen inhibitors and vaccines (Wedlock et al., 2013; Hristov et al., 2015; Herrero et al., 2016; Subharat et al., 2016) as well as synthetic and biological nitrification inhibitors (Subbarao et al., 2013; Di and Cameron, 2016) could substantially reduce future non-CO₂ emissions from agriculture if commercialized successfully. Enhancing carbon sequestration in soils (Paustian et al., 2016; Frank et al., 2017; Zomer et al., 2017) can provide the dual benefit of CDR and improved soil quality. A range of conservation, restoration and land management options can also increase terrestrial carbon uptake (Griscom et al., 2017). In addition, the literature discusses CDR measures to permanently sequester atmospheric carbon in rocks (mineralization and enhanced weathering, see Chapter 4, Section 4.3.7) as well as carbon capture and usage in long-lived products like plastics and carbon fibres (Mazzotti et al., 2005; Hartmann et al., 2013). Progress in the understanding of the technical viability, economics and sustainability of these ways to achieve and maintain carbon neutral energy and land use can affect the characteristics, costs and feasibility of 1.5°C-consistent pathways significantly.

2.3.1.3 Policy assumptions in 1.5°C pathways

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

and a variety of ancillary policies to safeguard other sustainable development goals (Bertram et al., 2018; van Vuuren et al., 2018). A further discussion of policy implications of 1.5°C-consistent pathways is provided in Section 2.5.1, while a general discussion of policies and options to strengthen action are subject of Chapter 4, Section 4.4.

2.3.2 Key Characteristics of 1.5°C Pathways

1.5°C-consistent pathways are characterized by a rapid phase out of CO₂ emissions and deep emissions reductions in other GHGs and climate forcers (Section 2.2.2 and 2.3.3). This is achieved by broad transformations in the energy; industry; transport; buildings; and agriculture, forestry and other land-use (AFOLU) sectors (Section 2.4) (Bauer et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018b; Liu et al., 2018; Luderer et al., 2018; Rogelj et al., 2018; van Vuuren et al., 2018; Zhang et al., 2018). Here we assess 1.5°C-consistent pathways with and without overshoot during the 21st century. One study also explores pathways overshooting 1.5°C for longer than the 21st century (Akimoto et al., 2017), but these are not considered 1.5°C-consistent pathways in this report (Chapter 1, Section 1.1.3). This subsection summarizes robust and varying properties of 1.5°C-consistent pathways regarding system transformations, emission reductions and overshoot. It aims to provide an introduction to the detailed assessment of the emissions evolution (Section 2.3.3), CDR deployment (Section 2.3.4), energy (Section 2.4.1, 2.4.2), industry (2.4.3.1), buildings (2.4.3.2), transport (2.4.3.3) and land-use transformations (Section 2.4.4) in 1.5°C-consistent pathways. Throughout Sections 2.3 and 2.4, pathway properties are highlighted with four 1.5°C-consistent pathway archetypes (LED, S1, S2, S5; referred to as P1, P2, P3, and P4 in the Summary for Policymakers) covering a wide range of different socio-economic and technology assumptions (Figure 2.5, Section 2.3.1).

2.3.2.1 Variation in system transformations underlying 1.5°C pathways

Be it for the energy, transport, buildings, industry, or AFOLU sector, the literature shows that multiple options and choices are available in each of these sectors to pursue stringent emissions reductions (Section 2.3.1.2, Supplementary Material 2.SM.1.2, Chapter 4, Section 4.3). Because the overall emissions total under a pathway is limited by a geophysical carbon budget (Section 2.2.2), choices in one sector affect the efforts that are required from others (Clarke et al., 2014). A robust feature of 1.5°C-consistent pathways, as highlighted by the set of pathway archetypes in Figure 2.5, is a virtually full decarbonization of the power sector around mid-century, a feature shared with 2°C-consistent pathways. The additional emissions reductions in 1.5°C-consistent compared to 2°C-consistent pathways come predominantly from the transport and industry sectors (Luderer et al., 2018). Emissions can be apportioned differently across sectors, for example, by focussing on reducing the overall amount of CO₂ produced in the energy end-use sectors, and using limited contributions of CDR by the AFOLU sector (afforestation and reforestation, S1 and LED pathways in Figure 2.5) (Grubler et al., 2018; Holz et al., 2018b; van Vuuren et al., 2018), or by being more lenient about the amount of CO₂ that continues to be produced in the above-mentioned end-use sectors (both by 2030 and mid-century) and strongly relying on technological CDR options

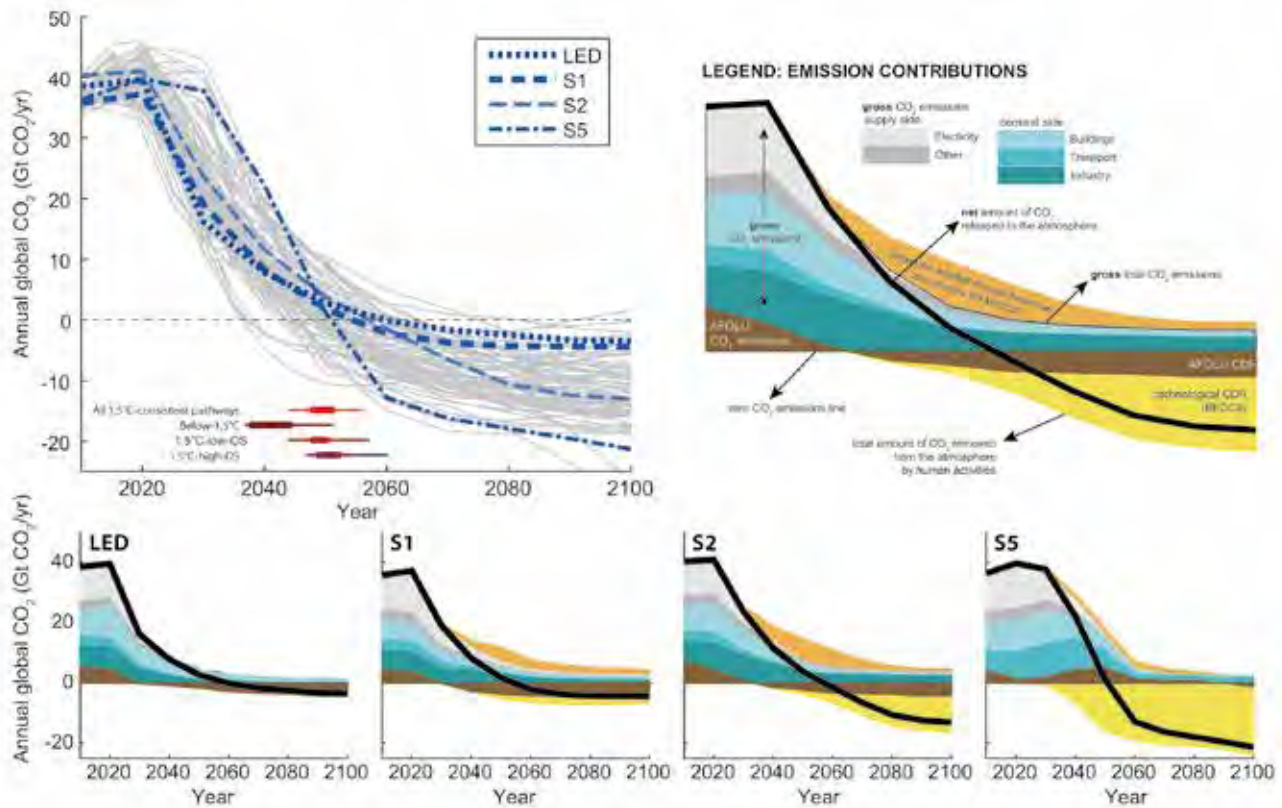


Figure 2.5 | Evolution and break down of global anthropogenic CO₂ emissions until 2100. The top-left panel shows global net CO₂ emissions in Below-1.5°C, 1.5°C-low-overshoot (OS), and 1.5°C-high-OS pathways, with the four illustrative 1.5°C-consistent pathway archetypes of this chapter highlighted. Ranges at the bottom of the top-left panel show the 10th–90th percentile range (thin line) and interquartile range (thick line) of the time that global CO₂ emissions reach net zero per pathway class, and for all pathways classes combined. The top-right panel provides a schematic legend explaining all CO₂ emissions contributions to global CO₂ emissions. The bottom row shows how various CO₂ contributions are deployed and used in the four illustrative pathway archetypes (LED, S1, S2, S5, referred to as P1, P2, P3, and P4 in the Summary for Policymakers) used in this chapter (see Section 2.3.1.1). Note that the S5 scenario reports the building and industry sector emissions jointly. Green-blue areas hence show emissions from the transport sector and the joint building and industry demand sector, respectively.

like BECCS (S2 and S5 pathways in Figure 2.5) (Luderer et al., 2018; Rogelj et al., 2018). Major drivers of these differences are assumptions about energy and food demand and the stringency of near-term climate policy (see the difference between early action in the scenarios S1, LED and more moderate action until 2030 in the scenarios S2, S5). Furthermore, the carbon budget in each of these pathways depends also on the non-CO₂ mitigation measures implemented in each of them, particularly for agricultural emissions (Sections 2.2.2, 2.3.3) (Gernaat et al., 2015). Those pathways differ not only in terms of their deployment of mitigation and CDR measures (Sections 2.3.4 and 2.4), but also in terms of the resulting temperature overshoot (Figure 2.1). Furthermore, they have very different implications for the achievement of sustainable development objectives, as further discussed in Section 2.5.3.

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

This subsection explores the conditions that would need to be fulfilled to stay below 1.5°C warming without overshoot. As discussed in Section 2.2.2, to keep warming below 1.5°C with a two-in-three (one-in-two) chance, the cumulative amount of CO₂ emissions from 2018 onwards need to remain below a carbon budget of 420 (580) GtCO₂; accounting for the effects of additional Earth system feedbacks until 2100 reduces this estimate by 100 GtCO₂. Based on the current state of knowledge,

exceeding this remaining carbon budget at some point in time would give a one-in-three (one-in-two) chance that the 1.5°C limit is overshoot (Table 2.2). For comparison, around 290 ± 20 (1 standard deviation range) GtCO₂ have been emitted in the years 2011–2017, with annual CO₂ emissions in 2017 around 42 ± 3 GtCO₂ yr⁻¹ (Jackson et al., 2017; Le Quéré et al., 2018). Committed fossil-fuel emissions from existing fossil-fuel infrastructure as of 2010 have been estimated at around 500 ± 200 GtCO₂ (with about 200 GtCO₂ already emitted through 2017) (Davis and Caldeira, 2010). Coal-fired power plants contribute the largest part. Committed emissions from existing coal-fired power plants built through the end of 2016 are estimated to add up to roughly 200 GtCO₂, and a further 100–150 GtCO₂ from coal-fired power plants under construction or planned (González-Eguino et al., 2017; Edenhofer et al., 2018). However, there has been a marked slowdown of planned coal-power projects in recent years, and some estimates indicate that the committed emissions from coal plants that are under construction or planned have halved since 2015 (Shearer et al., 2018). Despite these uncertainties, the committed fossil-fuel emissions are assessed to already amount to more than two thirds (half) of the remaining carbon budget.

An important question is to what extent the nationally determined contributions (NDCs) under the Paris Agreement are aligned with the remaining carbon budget. It was estimated that the NDCs, if successfully

implemented, imply a total of 400–560 GtCO₂ emissions over the 2018–2030 period (considering both conditional and unconditional NDCs) (Rogelj et al., 2016a). Thus, following an NDC trajectory would already exhaust 95–130% (70–95%) of the remaining two-in-three (one-in-two) 1.5°C carbon budget (unadjusted for additional Earth system feedbacks) by 2030. This would leave no time (0–9 years) to bring down global emissions from NDC levels of around 40 GtCO₂ yr⁻¹ in 2030 (Fawcett et al., 2015; Rogelj et al., 2016a) to net zero (further discussion in Section 2.3.5).

Most 1.5°C-consistent pathways show more stringent emissions reductions by 2030 than implied by the NDCs (Section 2.3.5). The lower end of those pathways reach down to below 20 GtCO₂ yr⁻¹ in 2030 (Section 2.3.3, Table 2.4), less than half of what is implied by the NDCs. Whether such pathways will be able to limit warming to 1.5°C without overshoot will depend on whether cumulative net CO₂ emissions over the 21st century can be kept below the remaining carbon budget at any time. Net global CO₂ emissions are derived from the gross amount of CO₂ that humans annually emit into the atmosphere reduced by the amount of anthropogenic CDR in each year. New research has looked more closely at the amount and the drivers of gross CO₂ emissions from fossil-fuel combustion and industrial processes (FFI) in deep mitigation pathways (Luderer et al., 2018), and found that the larger part of remaining CO₂ emissions come from direct fossil-fuel use in the transport and industry sectors, while residual energy supply sector emissions (mostly from the power sector) are limited by a rapid approach to net zero CO₂ emissions until mid-century. The 1.5°C pathways with no or limited (<0.1°C) overshoot that were reported in the scenario database project remaining FFI CO₂ emissions of 610–1260 GtCO₂ over the period 2018–2100 (5th–95th percentile range; median: 880 GtCO₂). Kriegler et al. (2018b) conducted a sensitivity analysis that explores the four central options for reducing fossil-fuel emissions: lowering energy demand, electrifying energy services, decarbonizing the power sector and decarbonizing non-electric fuel use in energy end-use sectors. By exploring these options to their extremes, they found a lowest value of 500 GtCO₂ (2018–2100) gross fossil-fuel CO₂ emissions for the hypothetical case of aligning the strongest assumptions for all four mitigation options. The two lines of evidence and the fact that available 1.5°C pathways cover a wide range of assumptions (Section 2.3.1) give a robust indication of a lower limit of about 500 GtCO₂ remaining fossil-fuel and industry CO₂ emissions in the 21st century.

To compare these numbers with the remaining carbon budget, CO₂ emissions from agriculture, forestry and other land use (AFOLU) need to be taken into account. In many of the 1.5°C-consistent pathways, AFOLU CO₂ emissions reach zero at or before mid-century and then turn to negative values (Table 2.4). This means human changes to the land lead to atmospheric carbon being stored in plants and soils. This needs to be distinguished from the natural CO₂ uptake by land, which is not accounted for in the anthropogenic AFOLU CO₂ emissions reported in the pathways. Given the difference in estimating the ‘anthropogenic’ sink between countries and the global integrated assessment and carbon modelling community (Grassi et al., 2017), the AFOLU CO₂ estimates included here are not necessarily directly comparable with countries’ estimates at global level. The cumulated amount of AFOLU CO₂ emissions until the time they reach zero combine with the fossil-fuel and industry CO₂ emissions to give a total amount of gross emissions

of 650–1270 GtCO₂ for the period 2018–2100 (5th–95th percentile; median 950 GtCO₂) in 1.5°C pathways with no or limited overshoot. The lower end of the range is close to what emerges from a scenario of transformative change that halves CO₂ emissions every decade from 2020 to 2050 (Rockström et al., 2017). All these estimates are above the remaining carbon budget for a one-in-two chance of limiting warming below 1.5°C without overshoot, including the low end of the hypothetical sensitivity analysis of Kriegler et al. (2018b), who assumes 75 Gt AFOLU CO₂ emissions adding to a total of 575 GtCO₂ gross CO₂ emissions. As almost no cases have been identified that keep gross CO₂ emissions within the remaining carbon budget for a one-in-two chance of limiting warming to 1.5°C, and based on current understanding of the geophysical response and its uncertainties, the available evidence indicates that avoiding overshoot of 1.5°C will require some type of CDR in a broad sense, e.g., via net negative AFOLU CO₂ emissions (*medium confidence*). (Table 2.2).

Net CO₂ emissions can fall below gross CO₂ emissions, if CDR is brought into the mix. Studies have looked at mitigation and CDR in combination to identify strategies for limiting warming to 1.5°C (Sanderson et al., 2016; Ricke et al., 2017). CDR, which may include net negative AFOLU CO₂ emissions, is deployed by all 1.5°C-consistent pathways available to this assessment, but the scale of deployment and choice of CDR measures varies widely (Section 2.3.4). Furthermore, no CDR technology has been deployed at scale yet, and all come with concerns about their potential (Fuss et al., 2018), feasibility (Nemet et al., 2018) and/or sustainability (Smith et al., 2015; Fuss et al., 2018) (see Sections 2.3.4, 4.3.2 and 4.3.7 and Cross-Chapter Box 7 in Chapter 3 for further discussion). CDR can have two very different functions in 1.5°C-consistent pathways. If deployed in the first half of the century, before net zero CO₂ emissions are reached, it neutralizes some of the remaining CO₂ emissions year by year and thus slows the accumulation of CO₂ in the atmosphere. In this first function it can be used to remain within the carbon budget and avoid overshoot. If CDR is deployed in the second half of the century after carbon neutrality has been established, it can still be used to neutralize some residual emissions from other sectors, but also to create net negative emissions that actively draw down the cumulative amount of CO₂ emissions to return below a 1.5°C warming level. In the second function, CDR enables temporary overshoot. The literature points to strong limitations to upscaling CDR (limiting its first abovementioned function) and to sustainability constraints (limiting both abovementioned functions) (Fuss et al., 2018; Minx et al., 2018; Nemet et al., 2018). Large uncertainty hence exists about what amount of CDR could actually be available before mid-century. Kriegler et al. (2018b) explore a case limiting CDR to 100 GtCO₂ until 2050, and the 1.5°C pathways with no or limited overshoot available in the report’s database project 40–260 GtCO₂ CDR until the point of carbon neutrality (5th to 95th percentile; median 110 GtCO₂). Because gross CO₂ emissions in most cases exceed the remaining carbon budget by several hundred GtCO₂ and given the limits to CDR deployment until 2050, most of the 1.5°C-consistent pathways available to this assessment are overshoot pathways. However, the scenario database also contains nine non-overshoot pathways that remain below 1.5°C throughout the 21st century (Table 2.1).

2.3.3 Emissions Evolution in 1.5°C Pathways

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

Estimates of aggregated GHG emissions in line with specific policy choices are often compared to near-term benchmark values from mitigation pathways to explore their consistency with long-term climate goals (Clarke et al., 2014; UNEP, 2016, 2017; UNFCCC, 2016). Benchmark emissions or estimates of peak years derived from IAMs provide guidelines or milestones that are consistent with achieving a given temperature level. While they do not set mitigation requirements in a strict sense, exceeding these levels in a given year almost invariably increases the mitigation challenges afterwards by increasing the rates of change and increasing the reliance on speculative technologies, including the possibility that its implementation becomes unachievable (see Cross-Chapter Box 3 in Chapter 1 for a discussion of feasibility concepts) (Luderer et al., 2013; Rogelj et al., 2013b; Clarke et al., 2014; Fawcett et al., 2015; Riahi et al., 2015; Kriegler et al., 2018a). These trade-offs are particularly pronounced in 1.5°C pathways and are discussed in Section 2.3.5. This section assesses Kyoto-GHG emissions in 2030 expressed in CO₂ equivalent (CO₂e) emissions using 100-year global warming potentials.³

Appropriate benchmark values of aggregated GHG emissions depend on a variety of factors. First and foremost, they are determined by the desired likelihood to keep warming below 1.5°C and the extent to which projected temporary overshoot is to be avoided (Sections 2.2, 2.3.2, and 2.3.5). For instance, median aggregated 2030 GHG emissions are about 10 GtCO₂e yr⁻¹ lower in 1.5°C-low-OS compared to 1.5°C-high-OS pathways, with respective interquartile ranges of 26–31 and 36–49 GtCO₂e yr⁻¹ (Table 2.4). These ranges correspond to about 25–30 and 35–48 GtCO₂e yr⁻¹ in 2030, respectively, when aggregated with 100-year Global Warming Potentials from the IPCC Second Assessment Report. The limited evidence available for pathways aiming to limit warming below 1.5°C without overshoot or with limited amounts of CDR (Grubler et al., 2018; Holz et al., 2018b; van Vuuren et al., 2018) indicates that under these conditions consistent emissions in 2030 would fall at the lower end and below the above mentioned ranges. Due to the small number of 1.5°C pathways with no overshoot in the report's database (Table 2.4) and the potential for a downward bias in the selection of underlying scenario assumptions, the headline range for 1.5°C pathways with no or limited overshoot is also assessed to be of the order of 25–30 GtCO₂e yr⁻¹. Ranges for the 1.5°C-low-OS and Lower-2°C classes only overlap outside their interquartile ranges,

highlighting the more accelerated reductions in 1.5°C-consistent compared to 2°C-consistent pathways.

Appropriate emissions benchmark values also depend on the acceptable or desired portfolio of mitigation measures, representing clearly identified trade-offs and choices (Sections 2.3.4, 2.4, and 2.5.3) (Luderer et al., 2013; Rogelj et al., 2013a; Clarke et al., 2014; Krey et al., 2014a; Strefler et al., 2018b). For example, lower 2030 GHG emissions correlate with a lower dependence on the future availability and desirability of CDR (Strefler et al., 2018b). On the other hand, pathways that assume or anticipate only limited deployment of CDR during the 21st century imply lower emissions benchmarks over the coming decades, which are achieved in models through further reducing CO₂ emissions in the coming decades. The pathway archetypes used in the chapter illustrate this further (Figure 2.6). Under middle-of-the-road assumptions of technological and socioeconomic development, pathway S2 suggests emission benchmarks of 34, 12 and –8 GtCO₂e yr⁻¹ in the years 2030, 2050, and 2100, respectively. In contrast, a pathway that further limits overshoot and aims at eliminating the reliance on negative emissions technologies like BECCS as well as CCS (here labelled as the LED pathway) shows deeper emissions reductions in 2030 to limit the cumulative amount of CO₂ until net zero global CO₂ emissions (carbon neutrality). The LED pathway here suggests emission benchmarks of 25, 9 and 2 GtCO₂e yr⁻¹ in the years 2030, 2050, and 2100, respectively. However, a pathway that allows and plans for the successful large-scale deployment of BECCS by and beyond 2050 (S5) shows a shift in the opposite direction. The variation within and between the abovementioned ranges of 2030 GHG benchmarks hence depends strongly on societal choices and preferences related to the acceptability and availability of certain technologies.

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

Kyoto-GHG emission reductions are achieved by reductions in CO₂ and non-CO₂ GHGs. The AR5 identified two primary factors that influence the depth and timing of reductions in non-CO₂ Kyoto-GHG emissions: (i) the abatement potential and costs of reducing the emissions of these gases and (ii) the strategies that allow making trade-offs between them (Clarke et al., 2014). Many studies indicate low-cost, near-term mitigation options in some sectors for non-CO₂ gases compared to supply-side measures for CO₂ mitigation (Clarke et al., 2014). A large share of this potential is hence already exploited in mitigation pathways in line with 2°C. At the same time, by mid-century and beyond, estimates of further reductions of non-CO₂ Kyoto-GHGs – in particular CH₄ and N₂O – are hampered by the absence of mitigation

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

options in the current generation of IAMs, which are hence not able to reduce residual emissions of sources linked to livestock production and fertilizer use (Clarke et al., 2014; Gernaat et al., 2015) (Sections 2.3.1.2, 2.4.4, Supplementary Material 2.SM.1.2). Therefore, while net CO₂ emissions are projected to be markedly lower in 1.5°C-consistent compared to 2°C-consistent pathways, this is much less the case for methane (CH₄) and nitrous-oxide (N₂O) (Figures 2.6–2.7). This results in reductions of CO₂ being projected to take up the largest share of emissions reductions when moving between 1.5°C-consistent and 2°C-consistent pathways (Rogelj et al., 2015b, 2018; Luderer et al., 2018). If additional non-CO₂ mitigation measures are identified and adequately included in IAMs, they are expected to further contribute to mitigation efforts by lowering the floor of residual non-CO₂ emissions. However, the magnitude of these potential contributions has not been assessed as part of this report.

As a result of the interplay between residual CO₂ and non-CO₂ emissions and CDR, global GHG emissions reach net zero levels at different times in different 1.5°C-consistent pathways. Interquartile ranges of the years in which 1.5°C-low-OS and 1.5°C-high-OS reach net zero GHG emissions range from 2060 to 2080 (Table 2.4). A seesaw characteristic can be found between near-term emissions reductions and the timing of net zero GHG emissions. This is because pathways with limited emissions reductions in the next one to two decades require net negative CO₂ emissions later on (see earlier). Most 1.5°C-high-OS pathways lead to net zero GHG emissions in approximately the third quarter of this century, because all of them rely on significant amounts of annual net negative CO₂ emissions in the second half of the century to decline temperatures after overshoot (Table 2.4). However, in pathways that aim at limiting overshoot as much as possible or more slowly decline temperatures after their peak, emissions reach the point of net zero GHG emissions slightly later or at times never. Early emissions reductions in this case reduce the requirement for net negative CO₂ emissions. Estimates of 2030 GHG emissions in line with the current NDCs overlap with the highest quartile of 1.5°C-high-OS pathways (Cross-Chapter Box 9 in Chapter 4).

2.3.3.1 Emissions of long-lived climate forcers

Climate effects of long-lived climate forcers (LLCFs) are dominated by CO₂, with smaller contributions of N₂O and some fluorinated gases (Myhre et al., 2013; Blanco et al., 2014). Overall net CO₂ emissions in pathways are the result of a combination of various anthropogenic contributions (Figure 2.5) (Clarke et al., 2014): (i) CO₂ produced by fossil-fuel combustion and industrial processes, (ii) CO₂ emissions or removals from the agriculture, forestry and other land use (AFOLU) sector, (iii) CO₂ capture and sequestration (CCS) from fossil fuels or industrial activities before it is released to the atmosphere, (iv) CO₂ removal by technological means, which in current pathways is mainly achieved by BECCS and AFOLU-related CDR, although other options could be conceivable (see Chapter 4, Section 4.3.7). Pathways apply these four contributions in different configurations (Figure 2.5) depending on societal choices and preferences related to the acceptability and availability of certain technologies, the timing and stringency of near-term climate policy, and the ability to limit the demand that drives baseline emissions (Marangoni et al., 2017; Riahi et al., 2017; Grubler et al., 2018; Rogelj et al., 2018; van Vuuren et al., 2018), and come with

very different implication for sustainable development (Section 2.5.3).

All 1.5°C pathways see global CO₂ emissions embark on a steady decline to reach (near) net zero levels around 2050, with 1.5°C-low-OS pathways reaching net zero CO₂ emissions around 2045–2055 (Table 2.4; Figure 2.5). Near-term differences between the various pathway classes are apparent, however. For instance, Below-1.5°C and 1.5°C-low-OS pathways show a clear shift towards lower CO₂ emissions in 2030 relative to other 1.5°C and 2°C pathway classes, although in all 1.5°C classes reductions are clear (Figure 2.6). These lower near-term emissions levels are a direct consequence of the former two pathway classes limiting cumulative CO₂ emissions until carbon neutrality in order to aim for a higher probability of limiting peak warming to 1.5°C (Section 2.2.2 and 2.3.2.2). In some cases, 1.5°C-low-OS pathways achieve net zero CO₂ emissions one or two decades later, contingent on 2030 CO₂ emissions in the lower quartile of the literature range, that is, below about 18 GtCO₂ yr⁻¹. Median year-2030 global CO₂ emissions are of the order of 5–10 GtCO₂ yr⁻¹ lower in Below-1.5°C compared to 1.5°C-low-OS pathways, which are in turn lower than 1.5°C-high-OS pathways (Table 2.4). Below-1.5°C and 1.5°C-low-OS pathways combined show a decline in global net anthropogenic CO₂ emissions of about 45% from 2010 levels by 2030 (40–60% interquartile range). Lower-2°C pathways show CO₂ emissions declining by about 25% by 2030 in most pathways (10–30% interquartile range). The 1.5°C-high-OS pathways show emissions levels that are broadly similar to the 2°C-consistent pathways in 2030.

The development of CO₂ emissions in the second half of the century in 1.5°C pathways is characterized by the need to stay or return within a carbon budget. Figure 2.6 shows net CO₂ and N₂O emissions from various sources in 2050 and 2100 in 1.5°C pathways in the literature. Virtually all 1.5°C pathways obtain net negative CO₂ emissions at some point during the 21st century, but the extent to which net negative emissions are relied upon varies substantially (Figure 2.6, Table 2.4). This net withdrawal of CO₂ from the atmosphere compensates for residual long-lived non-CO₂ GHG emissions that also accumulate in the atmosphere (like N₂O) or cancels some of the build-up of CO₂ due to earlier emissions to achieve increasingly higher likelihoods that warming stays or returns below 1.5°C (see Section 2.3.4 for a discussion of various uses of CDR). Even non-overshoot pathways that aim at achieving temperature stabilization would hence deploy a certain amount of net negative CO₂ emissions to offset any accumulating long-lived non-CO₂ GHGs. The 1.5°C overshoot pathways display significantly larger amounts of annual net negative CO₂ emissions in the second half of the century. The larger the overshoot the more net negative CO₂ emissions are required to return temperatures to 1.5°C by the end of the century (Table 2.4, Figure 2.1).

N₂O emissions decline to a much lesser extent than CO₂ in currently available 1.5°C pathways (Figure 2.6). Current IAMs have limited emissions-reduction potentials (Gernaat et al., 2015) (Sections 2.3.1.2, 2.4.4, Supplementary Material 2.SM.1.2), reflecting the difficulty of eliminating N₂O emission from agriculture (Bodirsky et al., 2014). Moreover, the reliance of some pathways on significant amounts of bioenergy after mid-century (Section 2.4.2) coupled to a substantial use of nitrogen fertilizer (Popp et al., 2017) also makes reducing N₂O emissions harder (for example, see pathway S5 in Figure 2.6). As

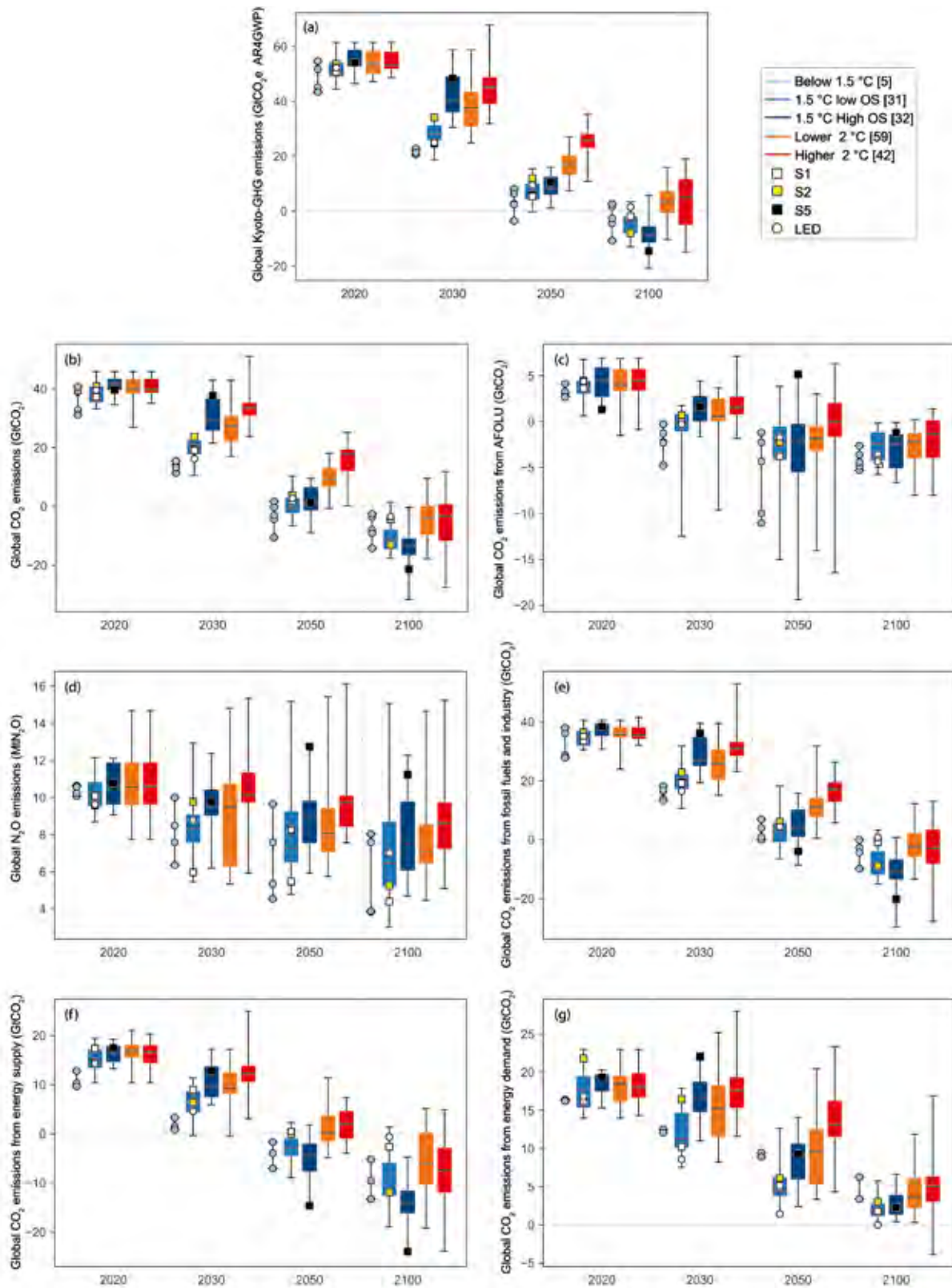


Figure 2.6 | Annual global emissions characteristics for 2020, 2030, 2050, 2100. Data are shown for (a) Kyoto-GHG emissions, and (b) global total CO₂ emissions, (c) CO₂ emissions from the agriculture, forestry and other land use (AFOLU) sector, (d) global N₂O emissions, and (e) CO₂ emissions from fossil fuel use and industrial processes. The latter is also split into (f) emissions from the energy supply sector (electricity sector and refineries) and (g) direct emissions from fossil-fuel use in energy demand sectors (industry, buildings, transport) (bottom row). Horizontal black lines show the median, boxes show the interquartile range, and whiskers the minimum–maximum range. Icons indicate the four pathway archetypes used in this chapter. In case less than seven data points are available in a class, the minimum–maximum range and single data points are shown. Kyoto-GHG emissions in the top panel are aggregated with AR4 GWP-100 and contain CO₂, CH₄, N₂O, HFCs, PFCs, and SF₆. NF₃ is typically not reported by IAMs. Scenarios with year-2010 Kyoto-GHG emissions outside the range assessed by IPCC AR5 WGIII assessed are excluded (IPCC, 2014b).

a result, sizeable residual N₂O emissions are currently projected to continue throughout the century, and measures to effectively mitigate them will be of continued relevance for 1.5°C societies. Finally, the reduction of nitrogen use and N₂O emissions from agriculture is already a present-day concern due to unsustainable levels of nitrogen pollution (Bodirsky et al., 2012). Section 2.4.4 provides a further assessment of the agricultural non-CO₂ emissions reduction potential.

2.3.3.2 Emissions of short-lived climate forcers and fluorinated gases

SLCFs include shorter-lived GHGs like CH₄ and some fluorinated gases as well as particles (aerosols), their precursors and ozone precursors. SLCFs are strongly mitigated in 1.5°C pathways, as is the case for 2°C pathways (Figure 2.7). SLCF emissions ranges of 1.5°C and 2°C pathway classes strongly overlap, indicating that the main incremental mitigation contribution between 1.5°C and 2°C pathways comes from CO₂ (Luderer et al., 2018; Rogelj et al., 2018). CO₂ and SLCF emissions reductions are connected in situations where SLCF and CO₂ are co-emitted by the same process, for example, with coal-fired power plants (Shindell and Faluvegi, 2010) or within the transport sector (Fuglestedt et al., 2010). Many CO₂-targeted mitigation measures in industry, transport and agriculture (Sections 2.4.3–4) hence also reduce non-CO₂ forcing (Rogelj et al., 2014b; Shindell et al., 2016).

Despite the fact that methane has a strong warming effect (Myhre et al., 2013; Etminan et al., 2016), current 1.5°C-consistent pathways still project significant emissions of CH₄ by 2050, indicating only a limited CH₄ mitigation potential in IAM analyses (Gernaat et al., 2015) (Sections 2.3.1.2, 2.4.4, Table 2.SM.2). The AFOLU sector contributes an important share of the residual CH₄ emissions until mid-century, with its relative share increasing from slightly below 50% in 2010 to around 55–70% in 2030, and 60–80% in 2050 in 1.5°C-consistent pathways (interquartile range across 1.5°C-consistent pathways for projections). Many of the proposed measures to target CH₄ (Shindell et al., 2012; Stohl et al., 2015) are included in 1.5°C-consistent pathways (Figure 2.7), though not all (Sections 2.3.1.2, 2.4.4, Table 2.SM.2). A detailed assessment of measures to further reduce AFOLU CH₄ emissions has not been conducted.

Overall reductions of SLCFs can have effects of either sign on temperature depending on the balance between cooling and warming agents. The reduction in SO₂ emissions is the dominant single effect as it weakens the negative total aerosol forcing. This means that reducing all SLCF emissions to zero would result in a short-term warming, although this warming is *unlikely* to be more than 0.5°C (Section 2.2 and Figure 1.5 (Samset et al., 2018)). Because of this effect, suggestions have been proposed that target the warming agents only (referred to as short-lived climate pollutants or SLCPs instead of the more general short-lived climate forcers; e.g., Shindell et al., 2012), though aerosols are often emitted in varying mixtures of warming and cooling species (Bond et al., 2013). Black carbon (BC) emissions reach similar levels across 1.5°C-consistent and 2°C-consistent pathways available in the literature, with interquartile ranges of emissions reductions across pathways of 16–34% and 48–58% in 2030 and 2050, respectively, relative to 2010 (Figure 2.7). Recent studies have identified further reduction potentials for the near term, with global reductions of about

80% being suggested (Stohl et al., 2015; Klimont et al., 2017). Because the dominant sources of certain aerosol mixtures are emitted during the combustion of fossil fuels, the rapid phase-out of unabated fossil fuels to avoid CO₂ emissions would also result in removal of these either warming or cooling SLCF air-pollutant species. Furthermore, SLCFs are also reduced by efforts to reduce particulate air pollution. For example, year-2050 SO₂ emissions (precursors of sulphate aerosol) in 1.5°C-consistent pathways are about 75–85% lower than their 2010 levels. Some caveats apply, for example, if residential biomass use would be encouraged in industrialised countries in stringent mitigation pathways without appropriate pollution control measures, aerosol concentrations could also increase (Sand et al., 2015; Stohl et al., 2015).

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

There is a general agreement across 1.5°C-consistent pathways that until 2030 forcing from the warming SLCFs is reduced less strongly than the net cooling forcing from aerosol effects, compared to 2010. As a result, the net forcing contributions from all SLCFs combined are projected to increase slightly by about 0.2–0.3 W m⁻², compared to 2010. Also, by the end of the century, about 0.1–0.3 W m⁻² of SLCF forcing is generally currently projected to remain in 1.5°C-consistent scenarios (Figure 2.8). This is similar to developments in 2°C-consistent pathways (Rose et al., 2014b; Riahi et al., 2017), which show median forcing contributions from these forcing agents that are generally no more than 0.1 W m⁻² higher. Nevertheless, there can be additional gains from targeted deeper reductions of CH₄ emissions and tropospheric ozone precursors, with some scenarios projecting less than 0.1 W m⁻² forcing from SLCFs by 2100.

2.3.4 CDR in 1.5°C Pathways

Deep mitigation pathways assessed in AR5 showed significant deployment of CDR, in particular through BECCS (Clarke et al., 2014). This has led to increased debate about the necessity, feasibility and desirability of large-scale CDR deployment, sometimes also called 'negative emissions technologies' in the literature (Fuss et al., 2014; Anderson and Peters, 2016; Williamson, 2016; van Vuuren et al.,

Table 2.4 | Emissions in 2030, 2050 and 2100 in 1.5°C and 2°C scenario classes and absolute annual rates of change between 2010–2030, 2020–2030 and 2030–2050, respectively.

Values show median and interquartile range across available scenarios (25th and 75th percentile given in brackets). If fewer than seven scenarios are available (*), the minimum–maximum range is given instead. Kyoto-GHG emissions are aggregated with GWP-100 values from IPCC AR4. Emissions in 2010 for total net CO₂, CO₂ from fossil-fuel use and industry, and AFOLU CO₂ are estimated at 38.5, 33.4, and 5 GtCO₂ yr⁻¹, respectively (Le Quéré et al., 2018). Percentage reduction numbers included in headline statement C.1 in the Summary for Policymakers are computed relative to 2010 emissions in each individual pathway, and hence differ slightly from a case where reductions are computed relative to the historical 2010 emissions reported above. A difference is reported in estimating the ‘anthropogenic’ sink by countries or the global carbon modelling community (Grassi et al., 2017), and AFOLU CO₂ estimates reported here are thus not necessarily comparable with countries’ estimates. Scenarios with year-2010 Kyoto-GHG emissions outside the range assessed by IPCC AR5 WGIII are excluded (IPCC, 2014b), as are scenario duplicates that would bias ranges towards a single study.

Name	Category	#	Annual emissions/sequestration (GtCO ₂ yr ⁻¹)			Absolute Annual Change (GtCO ₂ /yr ⁻¹)			Timing of Global Zero
			2030	2050	2100	2010–2030	2020–2030	2030–2050	Year
Total CO ₂ (net)	Below-1.5°C	5*	13.4 (15.4, 11.4)	-3.0 (1.7, -10.6)	-8.0 (-2.6, -14.2)	-1.2 (-1.0, -1.3)	-2.5 (-1.8, -2.8)	-0.8 (-0.7, -1.2)	2044 (2037, 2054)
	1.5°C-low-OS	37	20.8 (22.2, 18.0)	-0.4 (2.7, -2.0)	-10.8 (-8.1, -14.3)	-0.8 (-0.7, -1.0)	-1.7 (-1.4, -2.3)	-1.0 (-0.8, -1.2)	2050 (2047, 2055)
	1.5°C with no or limited OS	42	20.3 (22.0, 15.9)	-0.5 (2.2, -2.8)	-10.2 (-7.6, -14.2)	-0.9 (-0.7, -1.1)	-1.8 (-1.5, -2.3)	-1.0 (-0.8, -1.2)	2050 (2046, 2055)
	1.5°C-high-OS	36	29.1 (36.4, 26.0)	1.0 (6.3, -1.2)	-13.8 (-11.1, -16.4)	-0.4 (0.0, -0.6)	-1.1 (-0.5, -1.5)	-1.3 (-1.1, -1.8)	2052 (2049, 2059)
	Lower-2°C	54	28.9 (33.7, 24.5)	9.9 (13.1, 6.5)	-5.1 (-2.6, -10.3)	-0.4 (-0.2, -0.6)	-1.1 (-0.8, -1.6)	-0.9 (-0.8, -1.2)	2070 (2063, 2079)
	Higher-2°C	54	33.5 (35.0, 31.0)	17.9 (19.1, 12.2)	-3.3 (0.6, -11.5)	-0.2 (-0.0, -0.4)	-0.7 (-0.5, -0.9)	-0.8 (-0.6, -1.0)	2085 (2070, post-2100)
CO ₂ from fossil fuels and industry (gross)	Below-1.5°C	5*	18.0 (21.4, 13.8)	10.5 (20.9, 0.3)	8.3 (11.6, 0.1)	-0.7 (-0.6, -1)	-1.5 (-0.9, -2.2)	-0.4 (0, -0.7)	-
	1.5°C-low-OS	37	22.1 (24.4, 18.7)	10.3 (14.1, 7.8)	5.6 (8.1, 2.6)	-0.5 (-0.4, -0.6)	-1.3 (-0.9, -1.7)	-0.6 (-0.5, -0.7)	-
	1.5°C with no or limited OS	42	21.6 (24.2, 18.0)	10.3 (13.8, 7.7)	6.1 (8.4, 2.6)	-0.5 (-0.4, -0.7)	-1.3 (-0.9, -1.8)	-0.6 (-0.4, -0.7)	-
	1.5°C-high-OS	36	27.8 (37.1, 25.6)	13.1 (17.0, 11.6)	6.6 (8.8, 2.8)	-0.2 (0.2, -0.3)	-0.8 (-0.2, -1.1)	-0.7 (-0.6, -1.0)	-
	Lower-2°C	54	27.7 (31.5, 23.5)	15.4 (19.0, 11.1)	7.2 (10.4, 3.7)	-0.2 (-0.0, -0.4)	-0.8 (-0.5, -1.2)	-0.6 (-0.5, -0.8)	-
	Higher-2°C	54	31.3 (33.4, 28.7)	19.2 (22.6, 17.1)	8.1 (10.9, 5.0)	-0.1 (0.1, -0.2)	-0.5 (-0.2, -0.7)	-0.6 (-0.5, -0.7)	-
CO ₂ from fossil fuels and industry (net)	Below-1.5°C	5*	16.4 (18.2, 13.5)	1.0 (7.0, 0)	-2.7 (0, -9.8)	-0.8 (-0.7, -1)	-1.8 (-1.2, -2.2)	-0.6 (-0.5, -0.9)	-
	1.5°C-low-OS	37	20.6 (22.2, 17.5)	3.2 (5.6, -0.6)	-8.5 (-4.1, -11.6)	-0.6 (-0.5, -0.7)	-1.4 (-1.1, -1.8)	-0.8 (-0.7, -1.1)	-
	1.5°C with no or limited OS	42	20.1 (22.1, 16.8)	3.0 (5.6, 0.0)	-8.3 (-3.5, -10.8)	-0.6 (-0.5, -0.8)	-1.4 (-1.1, -1.9)	-0.8 (-0.7, -1.1)	-
	1.5°C-high-OS	36	26.9 (34.7, 25.3)	4.2 (10.0, 1.2)	-10.7 (-6.9, -13.2)	-0.3 (0.1, -0.3)	-0.9 (-0.3, -1.2)	-1.2 (-0.9, -1.5)	-
	Lower-2°C	54	28.2 (31.0, 23.1)	11.8 (14.1, 6.2)	-3.1 (-0.7, -6.4)	-0.2 (-0.1, -0.4)	-0.8 (-0.5, -1.2)	-0.8 (-0.7, -1.0)	-
	Higher-2°C	54	31.0 (33.0, 28.7)	17.0 (19.3, 13.1)	-2.9 (3.3, -8.0)	-0.1 (0.1, -0.2)	-0.5 (-0.2, -0.7)	-0.7 (-0.5, -1.0)	-
CO ₂ from AFOLU	Below-1.5°C	5*	-2.2 (-0.3, -4.8)	-4.4 (-1.2, -11.1)	-4.4 (-2.6, -5.3)	-0.3 (-0.2, -0.4)	-0.5 (-0.4, -0.8)	-0.1 (0, -0.4)	-
	1.5°C-low-OS	37	-0.1 (0.8, -1.0)	-2.3 (-0.6, -4.1)	-2.4 (-1.2, -4.2)	-0.2 (-0.2, -0.3)	-0.4 (-0.3, -0.5)	-0.1 (-0.1, -0.2)	-
	1.5°C with no or limited OS	42	-0.1 (0.7, -1.3)	-2.6 (-0.6, -4.5)	-2.6 (-1.3, -4.2)	-0.2 (-0.2, -0.3)	-0.4 (-0.3, -0.5)	-0.1 (-0.1, -0.2)	-
	1.5°C-high-OS	36	1.2 (2.7, 0.1)	-2.1 (-0.3, -5.4)	-2.4 (-1.5, -5.0)	-0.1 (-0.1, -0.3)	-0.2 (-0.1, -0.5)	-0.2 (-0.0, -0.3)	-
	Lower-2°C	54	1.4 (2.8, 0.3)	-1.4 (-0.5, -2.7)	-2.4 (-1.3, -4.2)	-0.2 (-0.1, -0.2)	-0.3 (-0.2, -0.4)	-0.1 (-0.1, -0.2)	-
	Higher-2°C	54	1.5 (2.7, 0.8)	-0.0 (1.9, -1.6)	-1.3 (0.1, -3.9)	-0.2 (-0.1, -0.2)	-0.2 (-0.1, -0.4)	-0.1 (-0.0, -0.1)	-
Bioenergy combined with carbon capture and storage (BECCS)	Below-1.5°C	5*	0.4 (1.1, 0)	3.4 (8.3, 0)	5.7 (13.4, 0)	0 (0.1, 0)	0 (0.1, 0)	0.2 (0.4, 0)	-
	1.5°C-low-OS	36	0.3 (1.1, 0.0)	4.6 (6.4, 3.8)	12.4 (15.6, 7.6)	0.0 (0.1, 0.0)	0.0 (0.1, 0.0)	0.2 (0.3, 0.2)	-
	1.5°C with no or limited OS	41	0.4 (1.0, 0.0)	4.5 (6.3, 3.4)	12.4 (15.0, 6.4)	0.0 (0.1, 0.0)	0.0 (0.1, 0.0)	0.2 (0.3, 0.2)	-
	1.5°C-high-OS	36	0.1 (0.4, 0.0)	6.8 (9.5, 3.7)	14.9 (16.3, 12.1)	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)	0.3 (0.4, 0.2)	-
	Lower-2°C	54	0.1 (0.3, 0.0)	3.6 (4.6, 1.8)	9.5 (12.1, 6.9)	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)	0.2 (0.2, 0.1)	-
	Higher-2°C	47	0.1 (0.2, 0.0)	3.0 (4.9, 1.6)	10.8 (15.3, 8.2) [46]	0.0 (0.0, 0.0)	0.0 (0.0, 0.0)	0.1 (0.2, 0.1)	-
Kyoto GHG (AR4) [GtCO ₂ e]	Below-1.5°C	5*	22.1 (22.8, 20.7)	2.7 (8.1, -3.5)	-2.6 (2.7, -10.7)	-1.4 (-1.3, -1.5)	-2.9 (-2.1, -3.3)	-0.9 (-0.7, -1.3)	2066 (2044, post-2100)
	1.5°C-low-OS	31	27.9 (31.1, 26.0)	7.0 (9.9, 4.5)	-3.8 (-2.1, -7.9)	-1.1 (-0.9, -1.2)	-2.3 (-1.8, -2.8)	-1.1 (-0.9, -1.2)	2068 (2061, 2080)
	1.5°C with no or limited OS	36	27.4 (30.9, 24.7)	6.5 (9.6, 4.2)	-3.7 (-1.8, -7.8)	-1.1 (-1.0, -1.3)	-2.4 (-1.9, -2.9)	-1.1 (-0.9, -1.2)	2067 (2061, 2084)
	1.5°C-high-OS	32	40.4 (48.9, 36.3)	8.4 (12.3, 6.2)	-8.5 (-5.7, -11.2)	-0.5 (-0.0, -0.7)	-1.3 (-0.6, -1.8)	-1.5 (-1.3, -2.1)	2063 (2058, 2067)
	Lower-2°C	46	39.6 (45.1, 35.7)	18.3 (20.4, 15.2)	2.1 (4.2, -2.4)	-0.5 (-0.1, -0.7)	-1.5 (-0.9, -2.2)	-1.1 (-0.9, -1.2)	post-2100 (2090 post-2100)
	Higher-2°C	42	45.3 (48.5, 39.3)	25.9 (27.9, 23.3)	5.2 (11.5, -4.8)	-0.2 (-0.0, -0.6)	-1.0 (-0.6, -1.2)	-1.0 (-0.7, -1.2)	post-2100 (2085 post-2100)

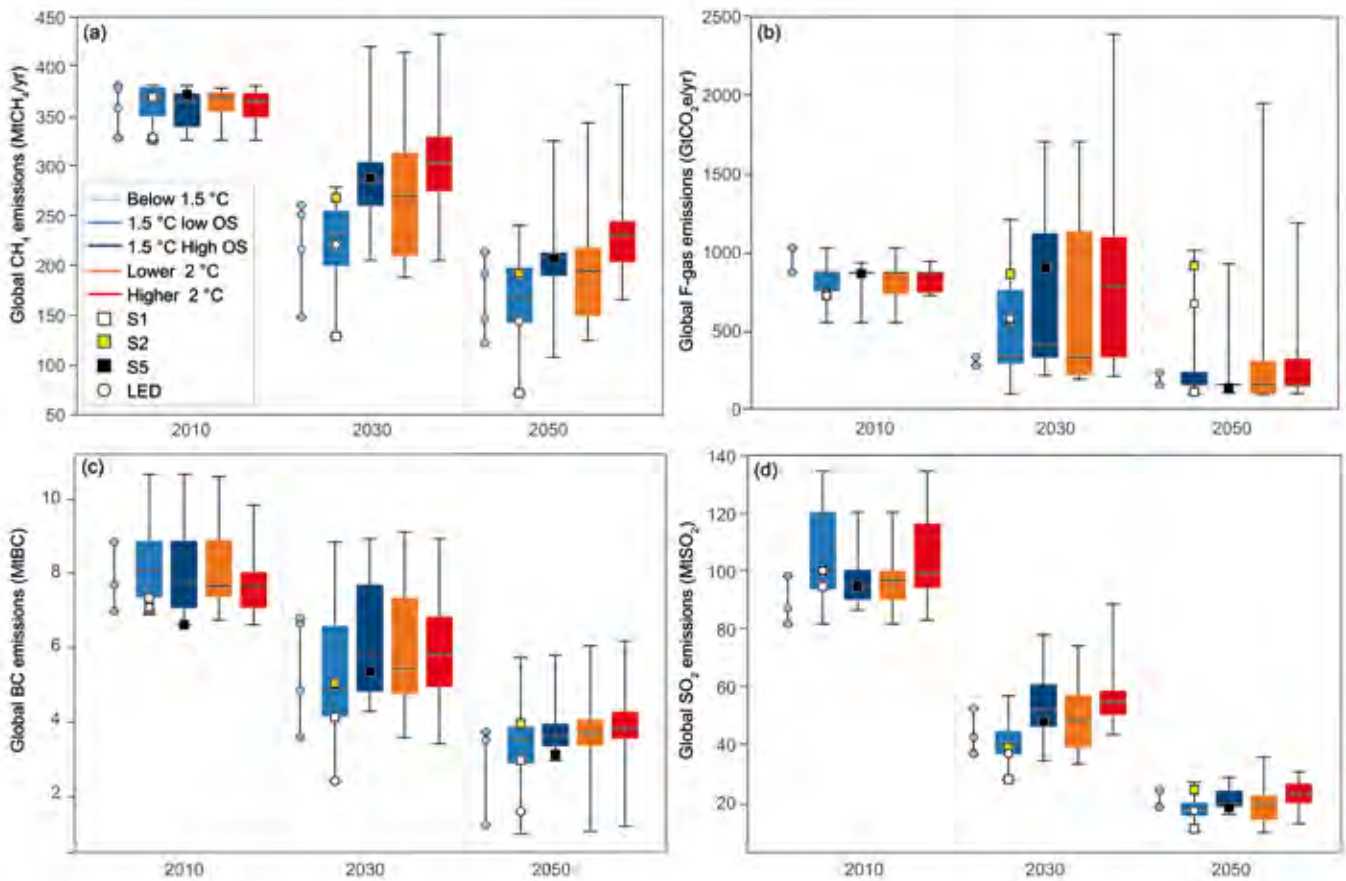


Figure 2.7 | Global characteristics of a selection of short-lived non- CO_2 emissions until mid-century for five pathway classes used in this chapter. Data are shown for (a) methane (CH_4), (b) fluorinated gases (F-gas), (c) black carbon (BC), and (d) sulphur dioxide (SO_2) emissions. Boxes with different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

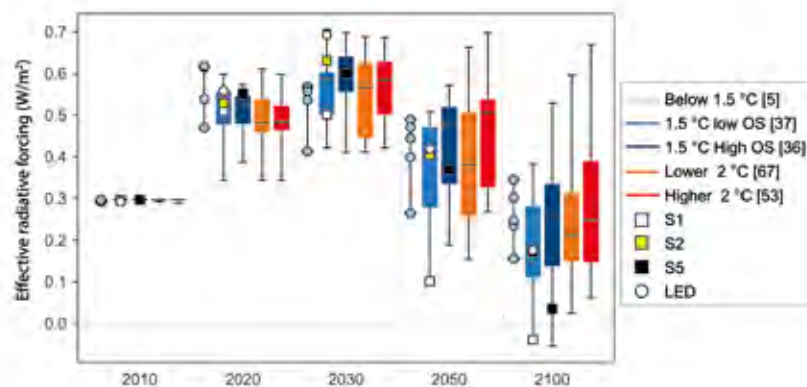


Figure 2.8 | Estimated aggregated effective radiative forcing of SLCFs for 1.5°C and 2°C pathway classes in 2010, 2020, 2030, 2050, and 2100, as estimated by the FAIR model (Smith et al., 2018). Aggregated short-lived climate forcer (SLCF) radiative forcing is estimated as the difference between total anthropogenic radiative forcing and the sum of CO_2 and N_2O radiative forcing over time, and is expressed relative to 1750. Symbols indicate the four pathways archetypes used in this chapter. Horizontal black lines indicate the median, boxes the interquartile range, and whiskers the minimum–maximum range per pathway class. Because very few pathways fall into the Below-1.5°C class, only the minimum–maximum is provided here.

2017a; Obersteiner et al., 2018). Most CDR technologies remain largely unproven to date and raise substantial concerns about adverse side-effects on environmental and social sustainability (Smith et al., 2015; Dooley and Kartha, 2018). A set of key questions emerge: how strongly do 1.5°C-consistent pathways rely on CDR deployment and what types of CDR measures are deployed at which scale? How does this vary across available 1.5°C-consistent pathways and on which factors does it depend? How does CDR deployment compare between 1.5°C- and 2°C-consistent pathways and how does it compare with the findings at the time of the AR5? How does CDR deployment in 1.5°C-consistent pathways relate to questions about availability, policy implementation and sustainable development implications that have been raised about CDR technologies? The first three questions are assessed in this section with the goal to provide an overview and assessment of CDR deployment in the 1.5°C pathway literature. The fourth question is only touched upon here and is addressed in greater depth in Chapter 4, Section 4.3.7, which assesses the rapidly growing literature on costs, potentials, availability and sustainability implications of individual CDR measures (Minx et al., 2017, 2018; Fuss et al., 2018; Nemet et al., 2018). In addition, Section 2.3.5 assesses the relationship between delayed mitigation action and increased CDR reliance. CDR deployment is intricately linked to the land-use transformation in 1.5°C-consistent pathways. This transformation is assessed in Section 2.4.4. Bioenergy and BECCS impacts on sustainable land management are further assessed in Chapter 3, Section 3.6.2 and Cross-Chapter Box 7 in Chapter 3. Ultimately, a comprehensive assessment of the land implication of land-based CDR measures will be provided in the IPCC AR6 Special Report on Climate Change and Land (SRCCL).

2.3.4.1 CDR technologies and deployment levels in 1.5°C pathways

A number of approaches to actively remove carbon-dioxide from the atmosphere are increasingly discussed in the literature (Minx et al., 2018) (see also Chapter 4, Section 4.3.7). Approaches under consideration include the enhancement of terrestrial and coastal carbon storage in plants and soils such as afforestation and reforestation (Canadell and Raupach, 2008), soil carbon enhancement (Paustian et al., 2016; Frank et al., 2017; Zomer et al., 2017), and other conservation, restoration, and management options for natural and managed land (Griscom et al., 2017) and coastal ecosystems (McLeod et al., 2011). Biochar sequestration (Woolf et al., 2010; Smith, 2016; Werner et al., 2018) provides an additional route for terrestrial carbon storage. Other approaches are concerned with storing atmospheric carbon dioxide in geological formations. They include the combination of biomass use for energy production with carbon capture and storage (BECCS) (Obersteiner et al., 2001; Keith and Rhodes, 2002; Gough and Upham, 2011) and direct air capture with storage (DACCS) using chemical solvents and sorbents (Zeman and Lackner, 2004; Keith et al., 2006; Socolow et al., 2011). Further approaches investigate the mineralization of atmospheric carbon dioxide (Mazzotti et al., 2005; Matter et al., 2016), including enhanced weathering of rocks (Schuiling and Krijgsman, 2006; Hartmann et al., 2013; Strefler et al., 2018a). A fourth group of approaches is concerned with the sequestration of carbon dioxide in the oceans, for example by means of ocean alkalization (Kheshti, 1995; Rau, 2011; Ilyina et al., 2013; Lenton et al., 2018). The costs, CDR potential and environmental side effects of

several of these measures are increasingly investigated and compared in the literature, but large uncertainties remain, in particular concerning the feasibility and impact of large-scale deployment of CDR measures (The Royal Society, 2009; Smith et al., 2015; Psarras et al., 2017; Fuss et al., 2018) (see Chapter 4.3.7). There are also proposals to remove methane, nitrous oxide and halocarbons via photocatalysis from the atmosphere (Boucher and Folberth, 2010; de Richter et al., 2017), but a broader assessment of their effectiveness, cost and sustainability impacts is lacking to date.

Only some of these approaches have so far been considered in IAMs (see Section 2.3.1.2). The mitigation scenario literature up to AR5 mostly included BECCS and, to a more limited extent, afforestation and reforestation (Clarke et al., 2014). Since then, some 2°C- and 1.5°C-consistent pathways including additional CDR measures such as DACCS (Chen and Tavoni, 2013; Marcucci et al., 2017; Lehtilä and Koljonen, 2018; Strefler et al., 2018b) and soil carbon sequestration (Frank et al., 2017) have become available. Other, more speculative approaches, in particular ocean-based CDR and removal of non-CO₂ gases, have not yet been taken up by the literature on mitigation pathways. See Supplementary Material 2.SM.1.2 for an overview on the coverage of CDR measures in models which contributed pathways to this assessment. Chapter 4.3.7 assesses the potential, costs, and sustainability implications of the full range of CDR measures.

Integrated assessment modelling has not yet explored land conservation, restoration and management options to remove carbon dioxide from the atmosphere in sufficient depth, despite land management having a potentially considerable impact on the terrestrial carbon stock (Erb et al., 2018). Moreover, associated CDR measures have low technological requirements, and come with potential environmental and social co-benefits (Griscom et al., 2017). Despite the evolving capabilities of IAMs in accounting for a wider range of CDR measures, 1.5°C-consistent pathways assessed here continue to predominantly rely on BECCS and afforestation/reforestation (see Supplementary Material 2.SM.1.2). However, IAMs with spatially explicit land-use modelling include a full accounting of land-use change emissions comprising carbon stored in the terrestrial biosphere and soils. Net CDR in the AFOLU sector, including but not restricted to afforestation and reforestation, can thus in principle be inferred by comparing AFOLU CO₂ emissions between a baseline scenario and a 1.5°C-consistent pathway from the same model and study. However, baseline AFOLU CO₂ emissions can not only be reduced by CDR in the AFOLU sector but also by measures to reduce deforestation and preserve land carbon stocks. The pathway literature and pathway data available to this assessment do not yet allow separating the two contributions. As a conservative approximation, the additional net negative AFOLU CO₂ emissions below the baseline are taken as a proxy for AFOLU CDR in this assessment. Because this does not include CDR that was deployed before reaching net zero AFOLU CO₂ emissions, this approximation is a lower-bound for terrestrial CDR in the AFOLU sector (including all mitigation-policy-related factors that lead to net negative AFOLU CO₂ emissions).

The scale and type of CDR deployment in 1.5°C-consistent pathways varies widely (Figure 2.9 and 2.10). Overall CDR deployment over the 21st century is substantial in most of the pathways, and deployment levels cover a wide range, on the order of 100–1000 Gt CO₂ in 1.5°C

pathways with no or limited overshoot (730 [260–1030] GtCO₂, for median and 5th–95th percentile range). Both BECCS (480 [0–1000] GtCO₂ in 1.5°C pathways with no or limited overshoot) and AFOLU CDR measures including afforestation and reforestation (210 [10–540] GtCO₂ in 1.5°C pathways with no or limited overshoot) can play a major role,⁴ but for both cases pathways exist where they play no role at all. This shows the flexibility in substituting between individual CDR measures, once a portfolio of options becomes available. The high end of the CDR deployment range is populated by high overshoot pathways, as illustrated by pathway archetype S5 based on SSP5 (fossil-fuelled development, see Section 2.3.1.1) and characterized by very large BECCS deployment to return warming to 1.5°C by 2100 (Kriegler et al., 2017). In contrast, the low end is populated by a few pathways with no or limited overshoot that limit CDR to on the order of 100–200 GtCO₂ over the 21st century, coming entirely from terrestrial CDR measures with no or small use of BECCS. These are pathways with very low energy demand facilitating the rapid phase-out of fossil fuels and process emissions that exclude BECCS and CCS use (Grubler et al., 2018) and/or pathways with rapid shifts to sustainable

food consumption freeing up sufficient land areas for afforestation and reforestation (Haberl et al., 2011; van Vuuren et al., 2018). Some pathways use neither BECCS nor afforestation but still rely on CDR through considerable net negative CO₂ emissions in the AFOLU sector around mid-century (Holz et al., 2018b). We conclude that the role of BECCS as a dominant CDR measure in deep mitigation pathways has been reduced since the time of the AR5. This is related to three factors: a larger variation of underlying assumptions about socio-economic drivers (Riahi et al., 2017; Rogelj et al., 2018) and associated energy (Grubler et al., 2018) and food demand (van Vuuren et al., 2018); the incorporation of a larger portfolio of mitigation and CDR options (Marcucci et al., 2017; Grubler et al., 2018; Lehtilä and Koljonen, 2018; Liu et al., 2018; van Vuuren et al., 2018); and targeted analysis of deployment limits for (specific) CDR measures (Holz et al., 2018b; Kriegler et al., 2018a; Strefler et al., 2018b), including the availability of bioenergy (Bauer et al., 2018), CCS (Krey et al., 2014a; Grubler et al., 2018) and afforestation (Popp et al., 2014b, 2017). As additional CDR measures are being built into IAMs, the prevalence of BECCS is expected to be further reduced.

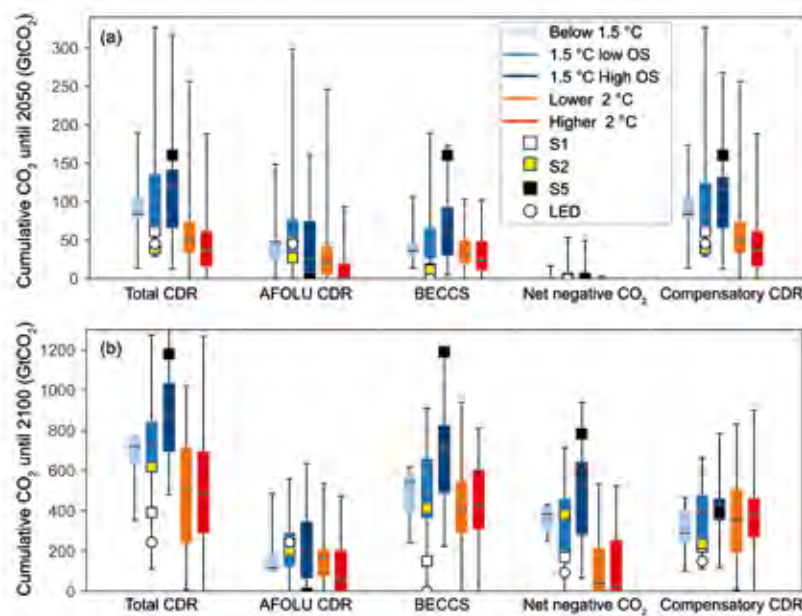


Figure 2.9 | Cumulative CDR deployment in 1.5°C-consistent pathways in the literature as reported in the database collected for this assessment until 2050 (panel a) and until 2100 (panel b). Total CDR comprises all forms of CDR, including AFOLU CDR and BECCS, and, in a few pathways, other CDR measures like DACCS. It does not include CCS combined with fossil fuels (which is not a CDR technology as it does not result in active removal of CO₂ from the atmosphere). AFOLU CDR has not been reported directly and is hence represented by means of a proxy: the additional amount of net negative CO₂ emissions in the AFOLU sector compared to a baseline scenario (see text for a discussion). ‘Compensatory CO₂’ depicts the cumulative amount of CDR that is used to neutralize concurrent residual CO₂ emissions. ‘Net negative CO₂’ describes the additional amount of CDR that is used to produce net negative CO₂ emissions, once residual CO₂ emissions are neutralized. The two quantities add up to total CDR for individual pathways (not for percentiles and medians, see Footnote 4).

As discussed in Section 2.3.2, CDR can be used in two ways in mitigation pathways: (i) to move more rapidly towards the point of carbon neutrality and maintain it afterwards in order to stabilize global mean temperature rise, and (ii) to produce net negative CO₂ emissions, drawing down anthropogenic CO₂ in the atmosphere in order to decline global mean temperature after an overshoot peak (Kriegler et al., 2018b; Obersteiner et al., 2018). Both uses are important in 1.5°C-consistent pathways (Figure 2.9 and 2.10). Because of the tighter remaining 1.5°C

carbon budget, and because many pathways in the literature do not restrict exceeding this budget prior to 2100, the relative weight of the net negative emissions component of CDR increases compared to 2°C-consistent pathways. The amount of compensatory CDR remains roughly the same over the century. This is the net effect of stronger deployment of compensatory CDR until mid-century to accelerate the approach to carbon neutrality and less compensatory CDR in the second half of the century due to deeper mitigation of end-use sectors

⁴ The median and percentiles of the sum of two quantities is in general not equal to the sum of the medians and percentiles, respectively, of the two quantities.

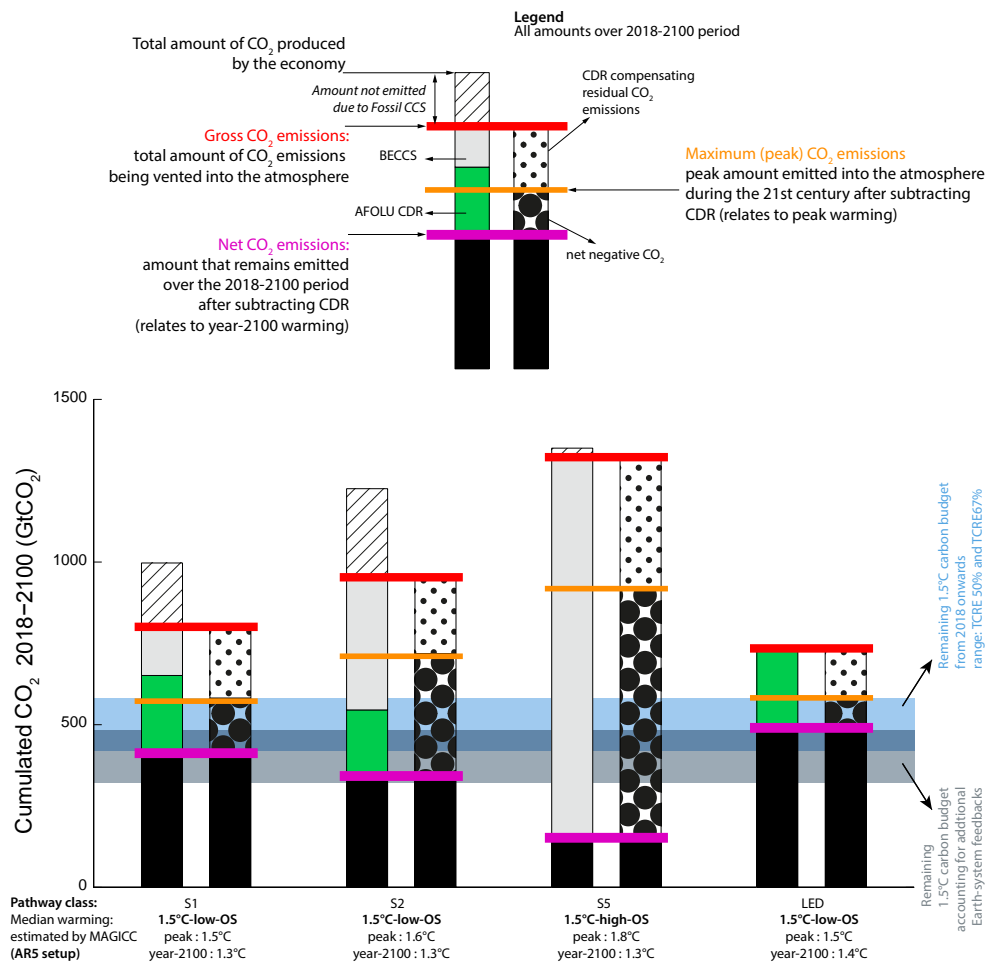


Figure 2.10 | Accounting of cumulative CO₂ emissions for the four 1.5°C-consistent pathway archetypes. See top panel for explanation of the bar plots. Total CDR is the difference between gross (red horizontal bar) and net (purple horizontal bar) cumulative CO₂ emissions over the period 2018–2100, and it is equal to the sum of the BECCS (grey) and AFOLU CDR (green) contributions. Cumulative net negative emissions are the difference between peak (orange horizontal bar) and net (purple) cumulative CO₂ emissions. The blue shaded area depicts the estimated range of the remaining carbon budget for a two-in-three to one-in-two chance of staying below 1.5°C. The grey shaded area depicts the range when accounting for additional Earth system feedbacks.

in 1.5°C-consistent pathways (Luderer et al., 2018). Comparing median levels, end-of-century net cumulative CO₂ emissions are roughly 600 GtCO₂ smaller in 1.5°C compared to 2°C-consistent pathways, with approximately two thirds coming from further reductions of gross CO₂ emissions and the remaining third from increased CDR deployment. As a result, median levels of total CDR deployment in 1.5°C-consistent pathways are larger than in 2°C-consistent pathways (Figure 2.9), but with marked variations in each pathway class.

Ramp-up rates of individual CDR measures in 1.5°C-consistent pathways are provided in Table 2.4. BECCS deployment is still limited in 2030, but ramps up to median levels of 3 (Below-1.5°C), 5 (1.5°C-low-OS) and 7 GtCO₂ yr⁻¹ (1.5°C-high-OS) in 2050, and to 6 (Below-1.5°C), 12 (1.5°C-low-OS) and 15 GtCO₂ yr⁻¹ (1.5°C-high-OS) in 2100, respectively. In 1.5°C pathways with no or limited overshoot, this amounts to 0–1, 0–8, and 0–16 GtCO₂ yr⁻¹ in 2030, 2050, and 2100, respectively (ranges refer to the union of the min-max range of the Below-1.5°C and the interquartile range of the 1.5°C-low-OS class; see Table 2.4). Net CDR in the AFOLU sector reaches slightly lower levels in 2050, and stays more constant until 2100. In 1.5°C pathways with no or limited overshoot, AFOLU CDR amounts to 0–5,

1–11, and 1–5 GtCO₂ yr⁻¹ (see above for the definition of the ranges) in 2030, 2050, and 2100, respectively. In contrast to BECCS, AFOLU CDR is more strongly deployed in non-overshoot than overshoot pathways. This indicates differences in the timing of the two CDR approaches. Afforestation is scaled up until around mid-century, when the time of carbon neutrality is reached in 1.5°C-consistent pathways, while BECCS is projected to be used predominantly in the 2nd half of the century (Figure 2.5). This reflects the fact that afforestation is a readily available CDR technology, while BECCS is more costly and much less mature a technology. As a result, the two options contribute differently to compensating concurrent CO₂ emissions (until 2050) and to producing net negative CO₂ emissions (post-2050). BECCS deployment is particularly strong in pathways with high overshoots but can also feature in pathways with low overshoot (see Figure 2.5 and 2.10). Annual deployment levels until mid-century are not found to be significantly different between 2°C-consistent pathways and 1.5°C-consistent pathways with no or low overshoot. This suggests similar implementation challenges for ramping up BECCS deployment at the rates projected in the pathways (Honegger and Reiner, 2018; Nemet et al., 2018). The feasibility and sustainability of upscaling CDR at these rates is assessed in Chapter 4.3.7.

Concerns have been raised that building expectations about large-scale CDR deployment in the future can lead to an actual reduction of near-term mitigation efforts (Geden, 2015; Anderson and Peters, 2016; Dooley and Kartha, 2018). The pathway literature confirms that CDR availability influences the shape of mitigation pathways critically (Krey et al., 2014a; Holz et al., 2018b; Kriegler et al., 2018a; Streffler et al., 2018b). Deeper near-term emissions reductions are required to reach the 1.5°C–2°C target range if CDR availability is constrained. As a result, the least-cost benchmark pathways to derive GHG emissions gap estimates (UNEP, 2017) are dependent on assumptions about CDR

availability. Using GHG benchmarks in climate policy makes implicit assumptions about CDR availability (Fuss et al., 2014; van Vuuren et al., 2017a). At the same time, the literature also shows that rapid and stringent mitigation as well as large-scale CDR deployment occur simultaneously in 1.5°C pathways due to the tight remaining carbon budget (Luderer et al., 2018). Thus, an emissions gap is identified even for high CDR availability (Streffler et al., 2018b), contradicting a wait-and-see approach. There are significant trade-offs between near-term action, overshoot and reliance on CDR deployment in the long-term which are assessed in Section 2.3.5.

Box 2.1 | Bioenergy and BECCS Deployment in Integrated Assessment Modelling

Bioenergy can be used in various parts of the energy sector of IAMs, including for electricity, liquid fuel, biogas, and hydrogen production. It is this flexibility that makes bioenergy and bioenergy technologies valuable for the decarbonization of energy use (Klein et al., 2014; Krey et al., 2014a; Rose et al., 2014a; Bauer et al., 2017, 2018). Most bioenergy technologies in IAMs are also available in combination with CCS (BECCS). Assumed capture rates differ between technologies, for example, about 90% for electricity and hydrogen production and about 40–50% for liquid fuel production. Decisions about bioenergy deployment in IAMs are based on economic considerations to stay within a carbon budget that is consistent with a long-term climate goal. IAMs consider both the value of bioenergy in the energy system and the value of BECCS in removing CO₂ from the atmosphere. Typically, if bioenergy is strongly limited, BECCS technologies with high capture rates are favoured. If bioenergy is plentiful IAMs tend to choose biofuel technologies with lower capture rates but high value for replacing fossil fuels in transport (Kriegler et al., 2013a; Bauer et al., 2018). Most bioenergy use in IAMs is combined with CCS if available (Rose et al., 2014a). If CCS is unavailable, bioenergy use remains largely unchanged or even increases due to the high value of bioenergy for the energy transformation (Bauer et al., 2018). As land impacts are tied to bioenergy use, the exclusion of BECCS from the mitigation portfolio will not automatically remove the trade-offs with food, water and other sustainability objectives due to the continued and potentially increased use of bioenergy.

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

2.3.4.2 Sustainability implications of CDR deployment in 1.5°C pathways

Strong concerns about the sustainability implications of large-scale CDR deployment in deep mitigation pathways have been raised in the literature (Williamson and Bodle, 2016; Boysen et al., 2017b; Dooley and Kartha, 2018; Heck et al., 2018), and a number of important knowledge gaps have been identified (Fuss et al., 2016). An assessment of the literature on implementation constraints and sustainable development implications of CDR measures is provided in Chapter 4, Section 4.3.7 and the Cross-chapter Box 7 in Chapter 3. An initial discussion of potential

environmental side effects of CDR deployment in 1.5°C-consistent pathways is provided in this section. Chapter 4, Section 4.3.7 then contrasts CDR deployment in 1.5°C-consistent pathways with other branches of literature on limitations of CDR. Integrated modelling aims to explore a range of developments compatible with specific climate goals and often does not include the full set of broader environmental and societal concerns beyond climate change. This has given rise to the concept of sustainable development pathways (Cross-Chapter Box 1 in Chapter 1) (van Vuuren et al., 2015), and there is an increasing body of work to extend integrated modelling to cover a broader range of sustainable development goals (Section 2.6). However, only some

of the available 1.5°C-consistent pathways were developed within a larger sustainable development context (Bertram et al., 2018; Grubler et al., 2018; Rogelj et al., 2018; van Vuuren et al., 2018). As discussed in Section 2.3.4.1, those pathways are characterized by low energy and/or food demand effectively limiting fossil-fuel substitution and alleviating land competition, respectively. They also include regulatory policies for deepening early action and ensuring environmental protection (Bertram et al., 2018). Overall sustainability implications of 1.5°C-consistent pathways are assessed in Section 2.5.3 and Chapter 5, Section 5.4.

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

Figure 2.11 shows the land requirements for BECCS and afforestation in the selected 1.5°C-consistent pathway archetypes, including the LED (Grubler et al., 2018) and S1 pathways (Fujimori, 2017; Rogelj et al., 2018) following a sustainable development paradigm. As discussed, these land-use patterns are heavily influenced by assumptions about, among other things, future population levels, crop yields, livestock production systems, and food and livestock demand, which all vary between the pathways (Popp et al., 2017) (Section 2.3.1.1). In pathways that allow for large-scale afforestation in addition to BECCS, land demand for afforestation can be larger than for BECCS (Humpenöder et al., 2014). This follows from the assumption in the modelled pathways that, unlike bioenergy crops, forests are not harvested to

allow unabated carbon storage on the same patch of land. If wood harvest and subsequent processing or burial are taken into account, this finding can change. There are also synergies between the various uses of land, which are not reflected in the depicted pathways. Trees can grow on agricultural land (Zomer et al., 2016), and harvested wood can be used with BECCS and pyrolysis systems (Werner et al., 2018). The pathways show a very substantial land demand for the two CDR measures combined, up to the magnitude of the current global cropland area. This is achieved in IAMs in particular by a conversion of pasture land freed by intensification of livestock production systems, pasture intensification and/or demand changes (Weindl et al., 2017), and to a more limited extent, cropland for food production, as well as expansion into natural land. However, pursuing such large-scale changes in land use would pose significant food supply, environmental and governance challenges, concerning both land management and tenure (Unruh, 2011; Erb et al., 2012, 2016b; Haberl et al., 2013; Haberl, 2015; Buck, 2016), particularly if synergies between land uses, the relevance of dietary changes for reducing land demand, and co-benefits with other sustainable development objectives are not fully recognized. A general discussion of the land-use transformation in 1.5°C-consistent pathways is provided in Section 2.4.4.

An important consideration for CDR which moves carbon from the atmosphere to the geological, oceanic or terrestrial carbon pools is the permanence of carbon stored in these different pools (Matthews and Caldeira, 2008; NRC, 2015; Fuss et al., 2016; Jones et al., 2016) (see also Chapter 4, Section 4.3.7 for a discussion). Terrestrial carbon can be returned to the atmosphere on decadal time scales by a variety of mechanisms, such as soil degradation, forest pest outbreaks and forest fires, and therefore requires careful consideration of policy frameworks to manage carbon storage, for example, in forests (Gren and Aklilu, 2016). There are similar concerns about outgassing of CO₂ from ocean storage (Herzog et al., 2003), unless it is transformed to a substance that does not easily exchange with the atmosphere, for example, ocean alkalinity or buried marine biomass (Rau, 2011). Understanding of the assessment and management of the potential risk of CO₂ release from geological storage of CO₂ has improved since the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005) with experience and the development of management practices in geological storage projects, including risk management to prevent sustentative leakage (Pawar et al., 2015). Estimates of leakage risk have been updated to include scenarios of unregulated drilling and limited wellbore integrity (Choi et al., 2013) and find that about 70% of stored CO₂ would still be retained after 10,000 years in these circumstances (Alcalde et al., 2018). The literature on the potential environmental impacts from the leakage of CO₂ – and approaches to minimize these impacts should a leak occur – has also grown and is reviewed by Jones et al. (2015). To the extent that non-permanence of terrestrial and geological carbon storage is driven by socio-economic and political factors, there are parallels to questions of fossil-fuel reservoirs remaining in the ground (Scott et al., 2015).

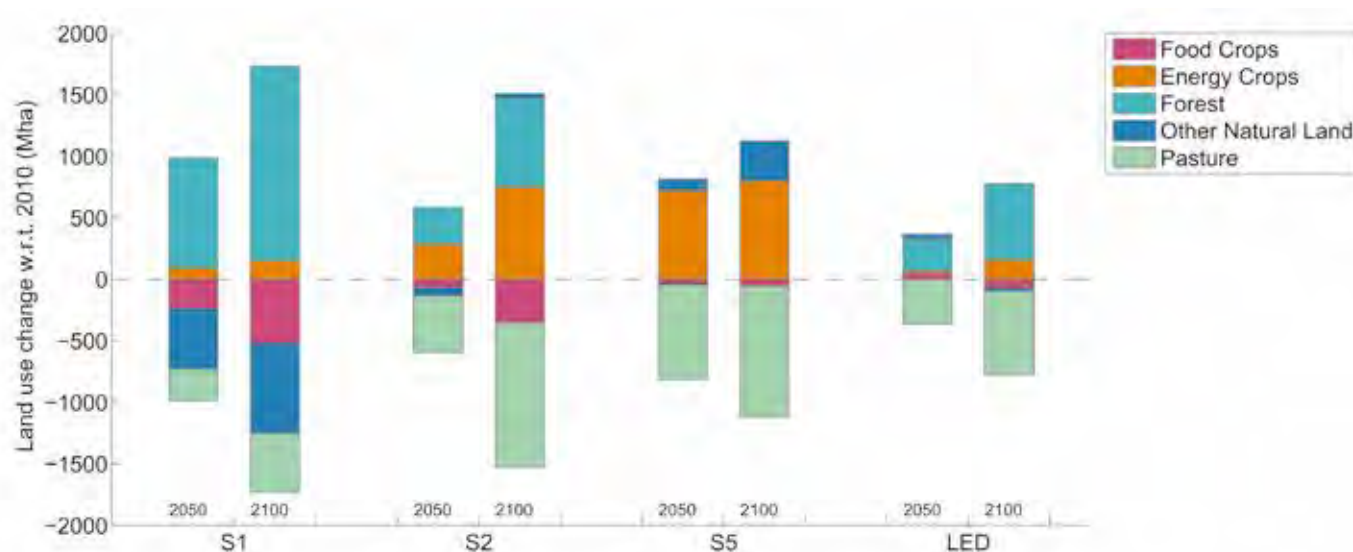


Figure 2.11 | Land-use changes in 2050 and 2100 in the illustrative 1.5°C-consistent pathway archetypes (Fricko et al., 2017; Fujimori, 2017; Kriegler et al., 2017; Grubler et al., 2018; Rogelj et al., 2018). Changes in land for food crops, energy crops, forest, pasture and other natural land are shown, compared to 2010.

2.3.5 Implications of Near-Term Action in 1.5°C Pathways

Less CO₂ emission reductions in the near term would require steeper and deeper reductions in the longer term in order to meet specific warming targets afterwards (Riahi et al., 2015; Luderer et al., 2016a). This is a direct consequence of the quasi-linear relationship between the total cumulative amount of CO₂ emitted into the atmosphere and global mean temperature rise (Matthews et al., 2009; Zickfeld et al., 2009; Collins et al., 2013; Knutti and Rogelj, 2015). Besides this clear geophysical trade-off over time, delaying GHG emissions reductions over the coming years also leads to economic and institutional lock-in into carbon-intensive infrastructure, that is, the continued investment in and use of carbon-intensive technologies that are difficult or costly to phase-out once deployed (Unruh and Carrillo-Hermosilla, 2006; Jakob et al., 2014; Erickson et al., 2015; Steckel et al., 2015; Seto et al., 2016; Michaelowa et al., 2018). Studies show that to meet stringent climate targets despite near-term delays in emissions reductions, models prematurely retire carbon-intensive infrastructure, in particular coal without CCS (Bertram et al., 2015a; Johnson et al., 2015). The AR5 reports that delaying mitigation action leads to substantially higher rates of emissions reductions afterwards, a larger reliance on CDR technologies in the long term, and higher transitional and long-term economic impacts (Clarke et al., 2014). The literature mainly focuses on delayed action until 2030 in the context of meeting a 2°C goal (den Elzen et al., 2010; van Vuuren and Riahi, 2011; Kriegler et al., 2013b; Luderer et al., 2013, 2016a; Rogelj et al., 2013b; Riahi et al., 2015; OECD/IEA and IRENA, 2017). However, because of the smaller carbon budget consistent with limiting warming to 1.5°C and the absence of a clearly declining long-term trend in global emissions to date, these general insights apply equally, or even more so, to the more stringent mitigation context of 1.5°C-consistent pathways. This

is further supported by estimates of committed emissions due to fossil fuel-based infrastructure (Seto et al., 2016; Edenhofer et al., 2018).

All available 1.5°C pathways that explore consistent mitigation action from 2020 onwards peak global Kyoto-GHG emissions in the next decade and already decline Kyoto-GHG emissions to below 2010 levels by 2030. The near-term emissions development in these pathways can be compared with estimated emissions in 2030 implied by the Nationally Determined Contributions (NDCs) submitted by Parties to the Paris Agreement (Figure 2.12). Altogether, the unconditional (conditional) NDCs are assessed to result in global Kyoto-GHG emissions on the order of 52–58 (50–54) GtCO₂e yr⁻¹ in 2030 (e.g., den Elzen et al., 2016; Fujimori et al., 2016; UNFCCC, 2016; Rogelj et al., 2017; Rose et al., 2017b; Benveniste et al., 2018; Vrontisi et al., 2018; see Cross-Chapter Box 11 in Chapter 4 for detailed assessment). In contrast, 1.5°C pathways with limited overshoot available to this assessment show an interquartile range of about 26–31 (median 28) GtCO₂e yr⁻¹ in 2030⁵ (Table 2.4, Section 2.3.3). Based on these ranges, this report assesses the emissions gap for a two-in-three chance of limiting warming to 1.5°C to be 26 (19–29) and 28 (22–33) GtCO₂e (median and interquartile ranges) for conditional and unconditional NDCs, respectively (Cross-Chapter Box 11, applying GWP-100 values from the IPCC Second Assessment Report).

The later emissions peak and decline, the more CO₂ will have accumulated in the atmosphere. Peak cumulated CO₂ emissions – and consequently peak temperatures – increase with higher 2030 emissions levels (Figure 2.12). Current NDCs (Cross-Chapter Box 11 in Chapter 4) are estimated to lead to CO₂ emissions of about 400–560 GtCO₂ from 2018 to 2030 (Rogelj et al., 2016a). Available 1.5°C- and 2°C-consistent pathways with 2030 emissions in the range estimated

⁵ Note that aggregated Kyoto-GHG emissions implied by the NDCs from Cross-Chapter Box 11 in Chapter 4 and Kyoto-GHG ranges from the pathway classes in Chapter 2 are only approximately comparable, because this chapter applies GWP-100 values from the IPCC Fourth Assessment Report while the NDC Cross-Chapter Box 11 applies GWP-100 values from the IPCC Second Assessment Report. At a global scale, switching between GWP-100 values of the Second to the Fourth IPCC Assessment Report would result in an increase in estimated aggregated Kyoto-GHG emissions of no more than about 3% in 2030 (UNFCCC, 2016).

for the NDCs rely on an assumed swift and widespread deployment of CDR after 2030, and show peak cumulative CO₂ emissions from 2018 of about 800–1000 GtCO₂, above the remaining carbon budget for a one-in-two chance of remaining below 1.5°C. These emissions reflect that no pathway is able to project a phase-out of CO₂ emissions starting from year-2030 NDC levels of about 40 GtCO₂ yr⁻¹ (Fawcett et al., 2015; Rogelj et al., 2016a) to net zero in less than about 15 years. Based on the implied emissions until 2030, the high challenges of the assumed

post-2030 transition, and the assessment of carbon budgets in Section 2.2.2, global warming is assessed to exceed 1.5°C if emissions stay at the levels implied by the NDCs until 2030 (Figure 2.12). The chances of remaining below 1.5°C in these circumstances remain conditional upon geophysical properties that are uncertain, but these Earth system response uncertainties would have to serendipitously align beyond current median estimates in order for current NDCs to become consistent with limiting warming to 1.5°C.

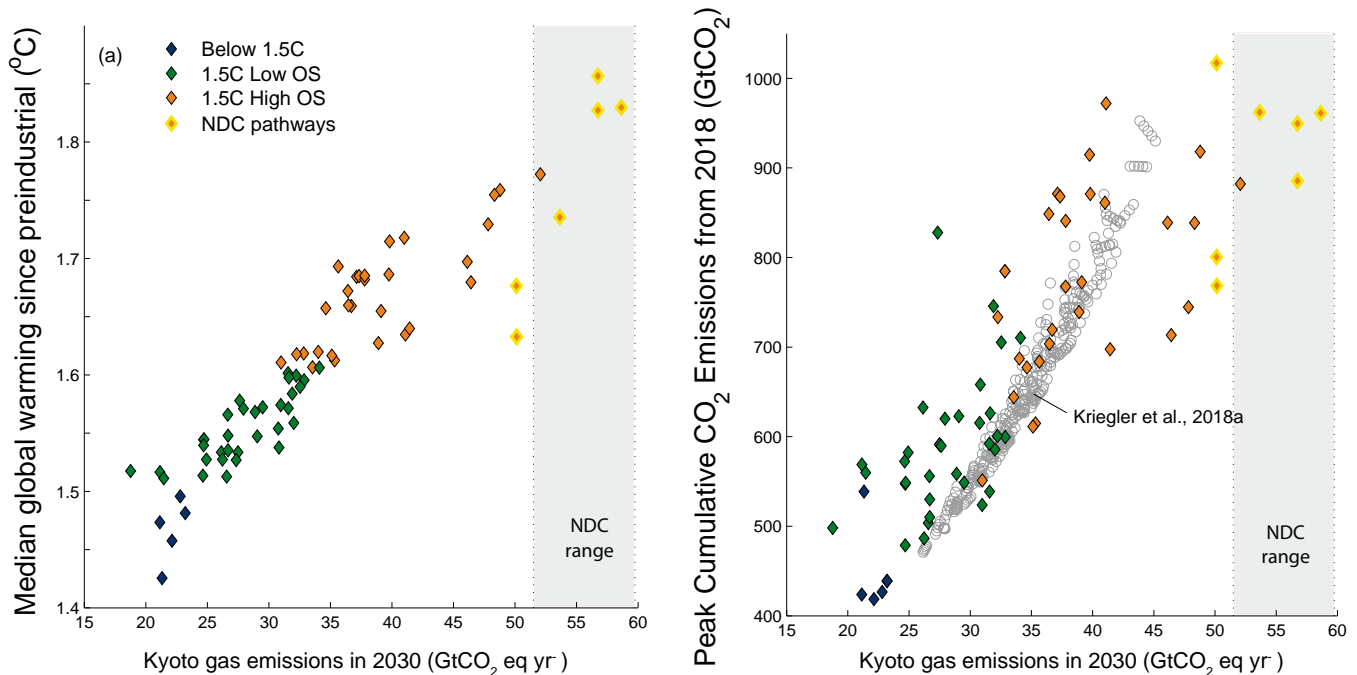


Figure 2.12 | Median global warming estimated by MAGICC (panel a) and peak cumulative CO₂ emissions (panel b) in 1.5°C-consistent pathways in the SR1.5 scenario database, as a function of CO₂-equivalent emissions (based on AR4 GWP-100) of Kyoto-GHG in 2030. Pathways that were forced to go through the NDCs or a similarly high emissions point in 2030 by design are highlighted by yellow marker edges (see caption of Figure 2.13 and text for further details on the design of these pathways). The combined range of global Kyoto-GHG emissions in 2030 for the conditional and unconditional NDCs assessed in Cross-Chapter Box 11 is shown by the grey shaded area (adjusted to AR4 GWPs for comparison). As a second line of evidence, peak cumulative CO₂ emissions derived from a 1.5°C pathway sensitivity analysis (Kriegler et al., 2018b) are shown by grey circles in the right-hand panel. Circles show gross fossil-fuel and industry emissions of the sensitivity cases, increased by assumptions about the contributions from AFOLU (5 GtCO₂ yr⁻¹ until 2020, followed by a linear phase out until 2040) and non-CO₂ Kyoto-GHGs (median non-CO₂ contribution from 1.5°C-consistent pathways available in the database: 10 GtCO₂e yr⁻¹ in 2030), and reduced by assumptions about CDR deployment until the time of net zero CO₂ emissions (limiting case for CDR deployment assumed in (Kriegler et al., 2018b) (logistic growth to 1, 4, 10 GtCO₂ yr⁻¹ in 2030, 2040, and 2050, respectively, leading to approximately 100 GtCO₂ of CDR by mid-century).

It is unclear whether following NDCs until 2030 would still allow global mean temperature to return to 1.5°C by 2100 after a temporary overshoot, due to the uncertainty associated with the Earth system response to net negative emissions after a peak (Section 2.2). Available IAM studies are working with reduced-form carbon cycle–climate models like MAGICC, which assume a largely symmetric Earth-system response to positive and net negative CO₂ emissions. The IAM findings on returning warming to 1.5°C from NDCs after a temporary temperature overshoot are hence all conditional on this assumption. Two types of pathways with 1.5°C-consistent action starting in 2030 have been considered in the literature (Luderer et al., 2018) (Figure 2.13): pathways aiming to obtain the same end-of-century carbon budget as 1.5°C-consistent pathways starting in 2020 despite higher emissions until 2030, and pathways assuming the same mitigation stringency after 2030 as in 1.5°C-consistent pathways starting in 2020 (approximated by using the same global price of emissions as

found in least-cost pathways starting from 2020). An IAM comparison study found increasing challenges to implementing pathways with the same end-of-century carbon budgets after following NDCs until 2030 (Luderer et al., 2018). The majority of model experiments (four out of seven) failed to produce NDC pathways that would return cumulative CO₂ emissions over the 2016–2100 period to 200 GtCO₂, indicating limitations to the availability and timing of CDR. The few such pathways that were identified show highly disruptive features in 2030 (including abrupt transitions from moderate to very large emissions reduction and low carbon energy deployment rates) indicating a high risk that the required post-2030 transformations are too steep and abrupt to be achieved by the mitigation measures in the models (*high confidence*). NDC pathways aiming for a cumulative 2016–2100 CO₂ emissions budget of 800 GtCO₂ were more readily obtained (Luderer et al., 2018), and some were classified as 1.5°C-high-OS pathways in this assessment (Section 2.1).

Variations in global CO₂ emissions over next decade

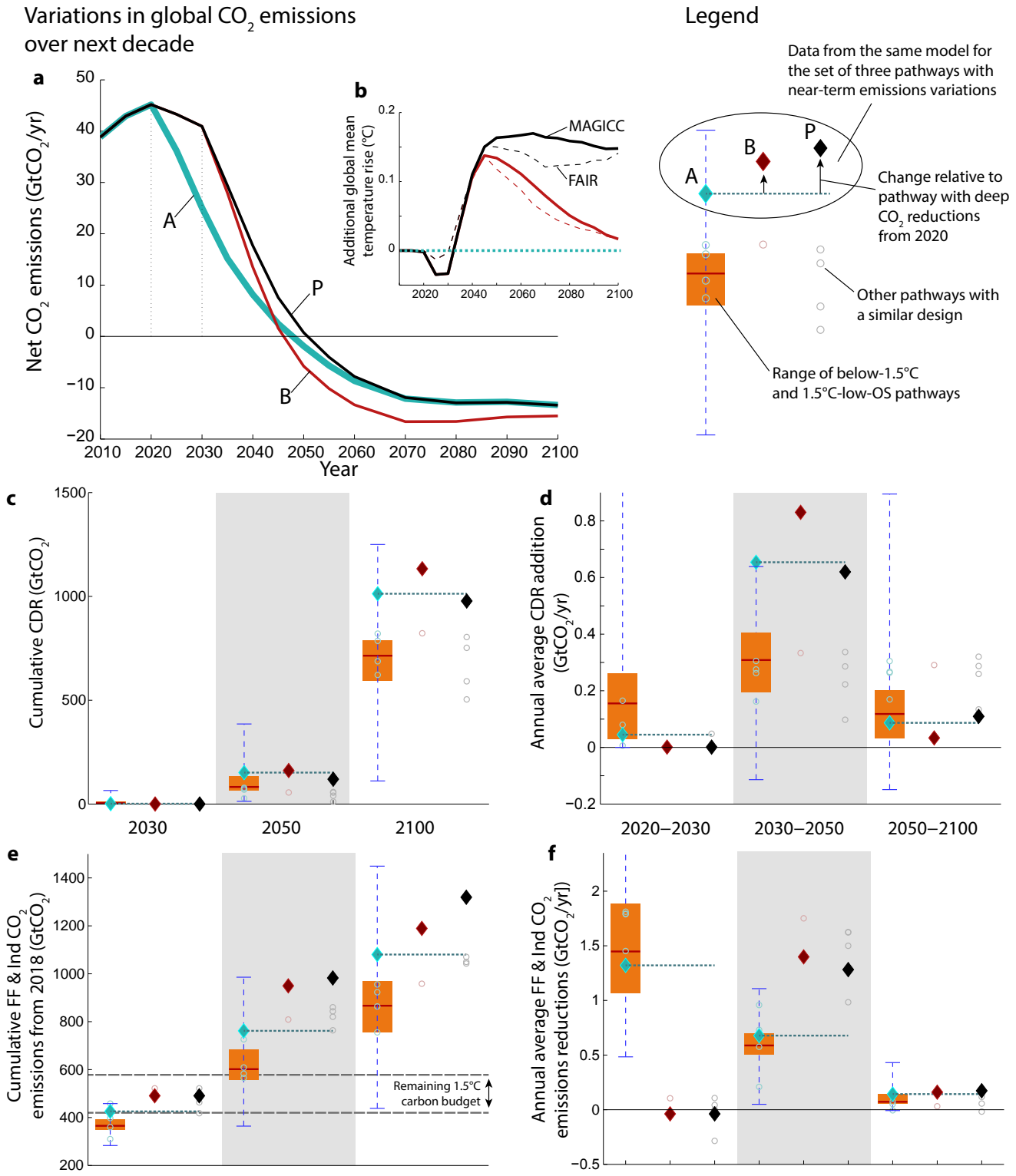


Figure 2.13 | Comparison of 1.5°C-consistent pathways starting action as of 2020 (A; light-blue diamonds) with pathways following the NDCs until 2030 and aiming to limit warming to 1.5°C thereafter. The 1.5°C pathways that follow the NDCs until 2030 either aim for the same cumulative CO₂ emissions by 2100 as the pathways that start action as of 2020 (B; red diamonds) or assume the same mitigation stringency as reflected by the price of emissions in associated least-cost 1.5°C-consistent pathways starting from 2020 (P; black diamonds). Panels show (a) the underlying emissions pathways, (b) additional warming in the delay scenarios compared to 2020 action case, (c) cumulated CDR, (d) CDR ramp-up rates, (e) cumulated gross CO₂ emissions from fossil-fuel combustion and industrial (FFI) processes over the 2018–2100 period, and (f) gross FFI CO₂ emissions reductions rates. Scenario pairs or triplets (circles and diamonds) with 2020 and 2030 action variants were calculated by six (out of seven) models in the ADVANCE study symbols (Luderer et al., 2018) and five of them (passing near-term plausibility checks) are shown by symbols. Only two of five models could identify pathways with post-2030 action leading to a 2016–2100 carbon budget of about 200 GtCO₂ (red). The range of all 1.5°C pathways with no and low overshoot is shown by the boxplots.

NDC pathways that apply a post-2030 price of emissions as found in least-cost pathways starting from 2020 show infrastructural carbon lock-in as a result of following NDCs instead of least-cost action until 2030. A key finding is that carbon lock-ins persist long after 2030, with the majority of additional CO₂ emissions occurring during the 2030–2050 period. Luderer et al. (2018) find 90 (80–120) GtCO₂ additional emissions until 2030, growing to 240 (190–260) GtCO₂ by 2050 and 290 (200–200) GtCO₂ by 2100. As a result, peak warming is about 0.2°C higher and not all of the modelled pathways return warming to 1.5°C by the end of the century. There is a four sided trade-off between (i) near-term ambition, (ii) degree of overshoot, (iii) transitional challenges during the 2030–2050 period, and (iv) the amount of CDR deployment required during the century (Figure 2.13) (Holz et al., 2018b; Strefler et al., 2018b). Transition challenges, overshoot, and CDR requirements can be significantly reduced if global emissions peak before 2030

and fall below levels in line with current NDCs by 2030. For example, Strefler et al. (2018b) find that CDR deployment levels in the second half of the century can be halved in 1.5°C-consistent pathways with similar CO₂ emissions reductions rates during the 2030–2050 period if CO₂ emissions by 2030 are reduced by an additional 30% compared to NDC levels. Kriegler et al. (2018a) investigate a global rollout of selected regulatory policies and moderate carbon pricing policies. They show that additional reductions of about 10 GtCO₂e yr⁻¹ can be achieved in 2030 compared to the current NDCs. Such a 20% reduction of year-2030 emissions compared to current NDCs would effectively lower the disruptiveness of post-2030 action. The strengthening of short-term policies in deep mitigation pathways has hence been identified as a way of bridging options to keep the Paris climate goals within reach (Bertram et al., 2015b; IEA, 2015a; Spencer et al., 2015; Kriegler et al., 2018a).

2.4 Disentangling the Whole-System Transformation

Mitigation pathways map out prospective transformations of the energy, land and economic systems over this century (Clarke et al., 2014). There is a diversity of potential pathways consistent with 1.5°C, yet they share some key characteristics summarized in Table 2.5. To explore characteristics of 1.5°C pathways in greater detail, this section focuses on changes in energy supply and demand, and changes in the AFOLU sector.

2.4.1 Energy System Transformation

The energy system links energy supply (Section 2.4.2) with energy demand (Section 2.4.3) through final energy carriers, including electricity and liquid, solid or gaseous fuels, that are tailored to their end-uses. To chart energy-system transformations in mitigation pathways, four macro-level decarbonization indicators associated with final energy are useful: limits on the increase of final energy demand, reductions in the carbon intensity of electricity, increases in the share of final energy provided by electricity, and reductions in the carbon

Table 2.5 | Overview of Key Characteristics of 1.5°C Pathways.

1.5°C Pathway Characteristic	Supporting Information	Reference
Rapid and profound near-term decarbonisation of energy supply	Strong upscaling of renewables and sustainable biomass and reduction of unabated (no CCS) fossil fuels, along with the rapid deployment of CCS, lead to a zero-emission energy supply system by mid-century.	Section 2.4.1 Section 2.4.2
Greater mitigation efforts on the demand side	All end-use sectors show marked demand reductions beyond the reductions projected for 2°C pathways. Demand reductions from IAMs for 2030 and 2050 lie within the potential assessed by detailed sectoral bottom-up assessments.	Section 2.4.3
Switching from fossil fuels to electricity in end-use sectors	Both in the transport and the residential sector, electricity covers markedly larger shares of total demand by mid-century.	Section 2.4.3.2 Section 2.4.3.3
Comprehensive emission reductions are implemented in the coming decade	Virtually all 1.5°C-consistent pathways decline net annual CO ₂ emissions between 2020 and 2030, reaching carbon neutrality around mid-century. In 2030, below-1.5°C and 1.5°C-low-OS pathways show maximum net CO ₂ emissions of 18 and 28 GtCO ₂ yr ⁻¹ , respectively. GHG emissions in these scenarios are not higher than 34 GtCO ₂ e yr ⁻¹ in 2030.	Section 2.3.4
Additional reductions, on top of reductions from both CO ₂ and non-CO ₂ required for 2°C, are mainly from CO ₂	Both CO ₂ and the non-CO ₂ GHGs and aerosols are strongly reduced by 2030 and until 2050 in 1.5°C pathways. The greatest difference to 2°C pathways, however, lies in additional reductions of CO ₂ , as the non-CO ₂ mitigation potential that is currently included in integrated pathways is mostly already fully deployed for reaching a 2°C pathway.	Section 2.3.1.2
Considerable shifts in investment patterns	Low-carbon investments in the energy supply side (energy production and refineries) are projected to average 1.6–3.8 trillion 2010USD yr ⁻¹ globally to 2050. Investments in fossil fuels decline, with investments in unabated coal halted by 2030 in most available 1.5°C-consistent projections, while the literature is less conclusive for investments in unabated gas and oil. Energy demand investments are a critical factor for which total estimates are uncertain.	Section 2.5.2
Options are available to align 1.5°C pathways with sustainable development	Synergies can be maximized, and risks of trade-offs limited or avoided through an informed choice of mitigation strategies. Particularly pathways that focus on a lowering of demand show many synergies and few trade-offs.	Section 2.5.3
CDR at scale before mid-century	By 2050, 1.5°C pathways project deployment of BECCS at a scale of 3–7 GtCO ₂ yr ⁻¹ (range of medians across 1.5°C pathway classes), depending on the level of energy demand reductions and mitigation in other sectors. Some 1.5°C pathways are available that do not use BECCS, but only focus terrestrial CDR in the AFOLU sector.	Section 2.3.3, 2.3.4.1

intensity of final energy other than electricity (referred to in this section as the carbon intensity of the residual fuel mix). Figure 2.14 shows changes of these four indicators for the pathways in the scenario database (Section 2.1.3 and Supplementary Material 2.SM.1.3) for 1.5°C and 2°C pathways (Table 2.1).

Pathways in both the 1.5°C and 2°C classes (Figure 2.14) generally show rapid transitions until mid-century, with a sustained but slower evolution thereafter. Both show an increasing share of electricity accompanied by a rapid decline in the carbon intensity of electricity. Both also show a generally slower decline in the carbon intensity of the residual fuel mix, which arises from the decarbonization of liquids, gases and solids provided to industry, residential and commercial activities, and the transport sector.

The largest differences between 1.5°C and 2°C pathways are seen in the first half of the century (Figure 2.14), where 1.5°C pathways generally show lower energy demand, a faster electrification of energy end-use, and a faster decarbonization of the carbon intensity of electricity and the residual fuel mix. There are very few pathways in the Below-1.5°C class (Figure 2.14). Those scenarios that are available, however, show a faster decline in the carbon intensity of electricity generation and residual fuel mix by 2030 than most pathways that are projected to temporarily overshoot 1.5°C and return by 2100 (or 2°C pathways). The Below-1.5°C pathways also appear to differentiate themselves from the other pathways as early as 2030 through reductions in final energy demand and increases in electricity share (Figure 2.14).

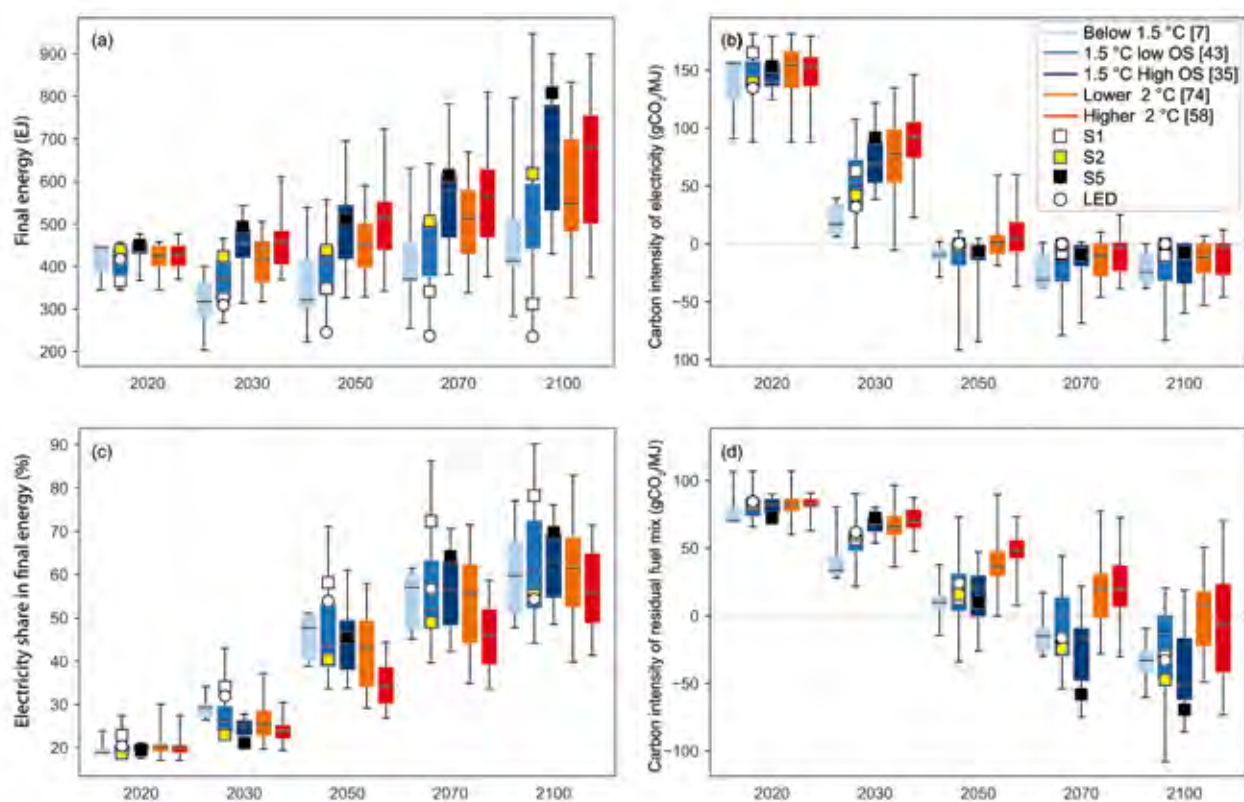


Figure 2.14 | Decomposition of transformation pathways into (a) energy demand, (b) carbon intensity of electricity, (c) the electricity share in final energy, and (d) the carbon intensity of the residual (non-electricity) fuel mix. Box plots show median, interquartile range and full range of pathways. Pathway temperature classes (Table 2.1) and illustrative pathway archetypes are indicated in the legend. Values following the class labels give the number of available pathways in each class.

2.4.2 Energy Supply

Several energy supply characteristics are evident in 1.5°C pathways assessed in this section: (i) growth in the share of energy derived from low-carbon-emitting sources (including renewables, nuclear and fossil fuel with CCS) and a decline in the overall share of fossil fuels without CCS (Section 2.4.2.1), (ii) rapid decline in the carbon intensity of electricity generation simultaneous with further electrification of energy end-use (Section 2.4.2.2), and (iii) the growth in the use of CCS applied to fossil and biomass carbon in most 1.5°C pathways (Section 2.4.2.3).

2.4.2.1 Evolution of primary energy contributions over time

By mid-century, the majority of primary energy comes from non-fossil-fuels (i.e., renewables and nuclear energy) in most 1.5°C pathways (Table 2.6). Figure 2.15 shows the evolution of primary energy supply over this century across 1.5°C pathways, and in detail for the four illustrative pathway archetypes highlighted in this chapter. Note that this section reports primary energy using the direct equivalent method on the basis of lower heating values (Bruckner et al., 2014).

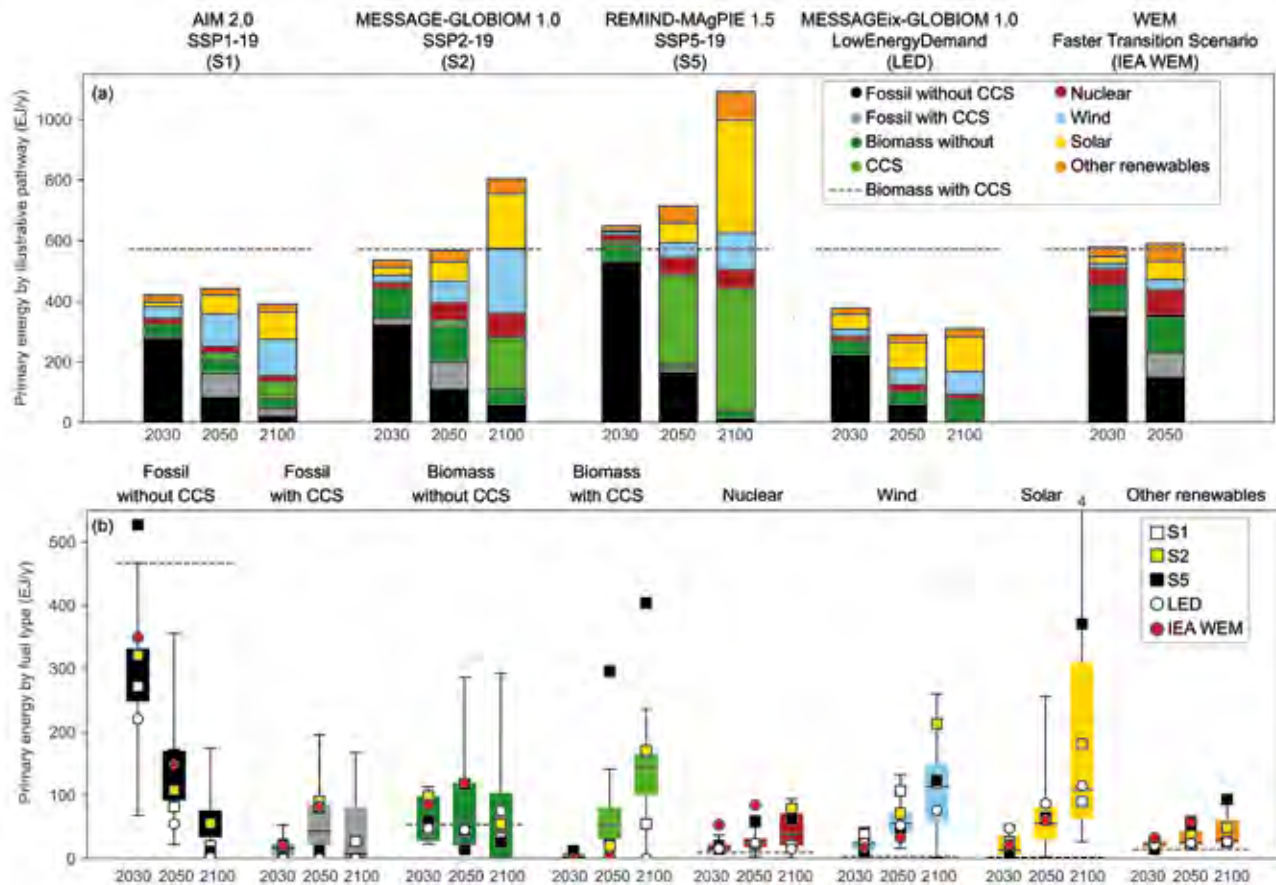


Figure 2.15 | Primary energy supply for the four illustrative pathway archetypes plus the IEA's Faster Transition Scenario (OECD/IEA and IRENA, 2017) (panel a), and their relative location in the ranges for pathways limiting warming to 1.5°C with no or limited overshoot (panel b). The category 'Other renewables' includes primary energy sources not covered by the other categories, for example, hydro and geothermal energy. The number of pathways that have higher primary energy than the scale in the bottom panel are indicated by the numbers above the whiskers. Black horizontal dashed lines indicate the level of primary energy supply in 2015 (IEA, 2017e). Box plots in the lower panel show the minimum–maximum range (whiskers), interquartile range (box), and median (vertical thin black line). Symbols in the lower panel show the four pathway archetypes S1 (white square), S2 (yellow square), S5 (black square), LED (white disc), as well as the IEA (red disc). Pathways with no or limited overshoot included the Below-1.5°C and 1.5°C-low-OS classes.

The share of energy from renewable sources (including biomass, hydro, solar, wind and geothermal) increases in all 1.5°C pathways with no or limited overshoot, with the renewable energy share of primary energy reaching 38–88% in 2050 (Table 2.6), with an interquartile range of 52–67%. The magnitude and split between bioenergy, wind, solar, and hydro differ between pathways, as can be seen in the illustrative pathway archetypes in Figure 2.15. Bioenergy is a major supplier of primary energy, contributing to both electricity and other forms of final energy such as liquid fuels for transportation (Bauer et al., 2018). In 1.5°C pathways, there is a significant growth in bioenergy used in combination with CCS for pathways where it is included (Figure 2.15).

Nuclear power increases its share in most 1.5°C pathways with no or limited overshoot by 2050, but in some pathways both the absolute capacity and share of power from nuclear generators decrease (Table 2.15). There are large differences in nuclear power between models and across pathways (Kim et al., 2014; Rogelj et al., 2018). One of the reasons for this variation is that the future deployment of nuclear can be constrained by societal preferences assumed in narratives underlying the pathways (O'Neill et al., 2017; van Vuuren et al., 2017b). Some 1.5°C pathways with no or limited overshoot no longer see a role

for nuclear fission by the end of the century, while others project about 95 EJ yr⁻¹ of nuclear power in 2100 (Figure 2.15).

The share of primary energy provided by total fossil fuels decreases from 2020 to 2050 in all 1.5°C pathways, but trends for oil, gas and coal differ (Table 2.6). By 2050, the share of primary energy from coal decreases to 0–11% across 1.5°C pathways with no or limited overshoot, with an interquartile range of 1–7%. From 2020 to 2050 the primary energy supplied by oil changes by –93 to –9% (interquartile range –77 to –39%); natural gas changes by –88 to +85% (interquartile range –62 to –13%), with varying levels of CCS. Pathways with higher use of coal and gas tend to deploy CCS to control their carbon emissions (see Section 2.4.2.3). As the energy transition is accelerated by several decades in 1.5°C pathways compared to 2°C pathways, residual fossil-fuel use (i.e., fossil fuels not used for electricity generation) without CCS is generally lower in 2050 than in 2°C pathways, while combined hydro, solar, and wind power deployment is generally higher than in 2°C pathways (Figure 2.15).

In addition to the 1.5°C pathways included in the scenario database (Supplementary Material 2.SM.1.3), there are other analyses in the

literature including, for example, sector-based analyses of energy demand and supply options. Even though they were not necessarily developed in the context of the 1.5°C target, they explore in greater detail some options for deep reductions in GHG emissions. For example, there are analyses of transitions to up to 100% renewable energy by 2050 (Creutzig et al., 2017; Jacobson et al., 2017), which describe what is entailed for a renewable energy share largely from solar and wind (and electrification) that is above the range of 1.5°C pathways available in the database, although there have been challenges to the assumptions used in high-renewable analyses (e.g., Clack et al., 2017). There are also analyses that result in a large role for nuclear energy in mitigation of GHGs (Hong et al., 2015; Berger et al., 2017a, b; Xiao and Jiang, 2018). BECCS could also contribute a larger share, but faces

challenges related to its land use and impact on food supply (Burns and Nicholson, 2017) (assessed in greater detail in Sections 2.3.4.2, 4.3.7 and 5.4). These analyses could, provided their assumptions prove plausible, expand the range of 1.5°C pathways.

In summary, the share of primary energy from renewables increases while that from coal decreases across 1.5°C pathways (*high confidence*). This statement is true for all 1.5°C pathways in the scenario database and associated literature (Supplementary Material 2.SM.1.3), and is consistent with the additional studies mentioned above, an increase in energy supply from lower-carbon-intensity energy supply, and a decrease in energy supply from higher-carbon-intensity energy supply.

Table 2.6 | Global primary energy supply of 1.5°C pathways from the scenario database (Supplementary Material 2.SM.1.3).

Values given for the median (maximum, minimum) across the full range of 85 available 1.5°C pathways. Growth Factor = [(primary energy supply in 2050)/(primary energy supply in 2020) – 1]

	Median (max, min)	Count	Primary Energy Supply (EJ)			Share in Primary Energy (%)			Growth (factor) 2020-2050
			2020	2030	2050	2020	2030	2050	
Below-1.5°C and 1.5°C-low-OS pathways	total primary	50	565.33 (619.70, 483.22)	464.50 (619.87, 237.37)	553.23 (725.40, 289.02)	NA	NA	NA	-0.05 (0.48, -0.51)
	renewables	50	87.14 (101.60, 60.16)	146.96 (203.90, 87.75)	291.33 (584.78, 176.77)	14.90 (20.39, 10.60)	29.08 (62.15, 18.24)	60.24 (87.89, 38.03)	2.37 (6.71, 0.91)
	biomass	50	60.41 (70.03, 40.54)	77.07 (113.02, 44.42)	152.30 (311.72, 40.36)	10.17 (13.66, 7.14)	17.22 (35.61, 9.08)	27.29 (54.10, 10.29)	1.71 (5.56, -0.42)
	non-biomass	50	26.35 (36.57, 17.78)	62.58 (114.41, 25.79)	146.23 (409.94, 53.79)	4.37 (7.19, 3.01)	13.67 (26.54, 5.78)	27.98 (61.61, 12.04)	4.28 (13.46, 1.45)
	wind & solar	44	10.93 (20.16, 2.61)	40.14 (82.66, 7.05)	121.82 (342.77, 27.95)	1.81 (3.66, 0.45)	9.73 (19.56, 1.54)	21.13 (51.52, 4.48)	10.00 (53.70, 3.71)
	nuclear	50	10.91 (18.55, 8.52)	16.26 (36.80, 6.80)	24.51 (66.30, 3.09)	2.10 (3.37, 1.45)	3.52 (9.61, 1.32)	4.49 (12.84, 0.44)	1.24 (5.01, -0.64)
	fossil	50	462.95 (520.41, 376.30)	310.36 (479.13, 70.14)	183.79 (394.71, 54.86)	82.53 (86.65, 77.73)	66.58 (77.30, 29.55)	32.79 (60.84, 8.58)	-0.59 (-0.21, -0.89)
	coal	50	136.89 (191.02, 83.23)	44.03 (127.98, 5.97)	24.15 (71.12, 0.92)	25.63 (30.82, 17.19)	9.62 (20.65, 1.31)	5.08 (11.43, 0.15)	-0.83 (-0.57, -0.99)
	gas	50	132.95 (152.80, 105.01)	112.51 (173.56, 17.30)	76.03 (199.18, 14.92)	23.10 (28.39, 18.09)	22.52 (35.05, 7.08)	13.23 (34.83, 3.68)	-0.40 (0.85, -0.88)
	oil	50	197.26 (245.15, 151.02)	156.16 (202.57, 38.94)	69.94 (167.52, 15.07)	34.81 (42.24, 29.00)	31.24 (39.84, 16.41)	12.89 (27.04, 2.89)	-0.66 (-0.09, -0.93)
1.5°C-high-OS	total primary	35	594.96 (636.98, 510.55)	559.04 (749.05, 419.28)	651.46 (1012.50, 415.31)	NA	NA	NA	0.13 (0.59, -0.27)
	renewables	35	89.84 (98.60, 66.57)	135.12 (159.84, 87.93)	323.21 (522.82, 177.66)	15.08 (18.58, 11.04)	23.65 (29.32, 13.78)	62.16 (86.26, 28.47)	2.68 (4.81, 1.17)
	biomass	35	62.59 (73.03, 48.42)	69.05 (98.27, 56.54)	160.16 (310.10, 71.17)	10.30 (14.23, 8.03)	13.64 (16.37, 9.03)	23.79 (45.79, 10.64)	1.71 (3.71, 0.19)
	non-biomass	35	28.46 (36.58, 17.60)	59.81 (92.12, 27.39)	164.91 (329.69, 55.72)	4.78 (6.64, 2.84)	10.23 (16.59, 4.49)	31.17 (45.86, 9.87)	6.10 (10.63, 1.38)
	wind & solar	26	11.32 (20.17, 1.91)	40.31 (65.50, 8.14)	139.20 (275.47, 30.92)	1.95 (3.66, 0.32)	7.31 (11.61, 1.83)	26.01 (38.79, 6.33)	16.06 (63.34, 3.13)
	nuclear	35	10.94 (14.27, 8.52)	16.12 (41.73, 6.80)	22.98 (115.80, 3.09)	1.86 (2.37, 1.45)	2.99 (5.57, 1.20)	4.17 (13.60, 0.43)	1.49 (7.22, -0.64)
	fossil	35	497.30 (543.29, 407.49)	397.76 (568.91, 300.63)	209.80 (608.39, 43.87)	83.17 (86.59, 79.39)	73.87 (82.94, 68.00)	33.58 (60.09, 7.70)	-0.56 (0.12, -0.91)
	coal	35	155.65 (193.55, 118.40)	70.99 (176.99, 19.15)	18.95 (134.69, 0.36)	25.94 (30.82, 19.10)	14.53 (26.35, 3.64)	4.14 (13.30, 0.05)	-0.87 (-0.30, -1.00)
	gas	35	138.01 (169.50, 107.07)	147.43 (208.55, 76.45)	97.71 (265.66, 15.96)	23.61 (27.35, 19.26)	25.79 (32.73, 14.69)	15.67 (33.80, 2.80)	-0.31 (0.99, -0.88)
	oil	35	195.02 (236.40, 154.66)	198.50 (319.80, 102.10)	126.20 (208.04, 24.68)	32.21 (38.87, 28.07)	33.27 (50.12, 24.35)	18.61 (27.30, 4.51)	-0.34 (0.06, -0.87)

Table 2.6 (continued)

	Median (max, min)	Count	Primary Energy Supply (EJ)			Share in Primary Energy (%)			Growth (factor) 2020-2050
			2020	2030	2050	2020	2030	2050	
Two above classes combined	total primary	85	582.12 (636.98, 483.22)	502.81 (749.05, 237.37)	580.78 (1012.50, 289.02)	-	-	-	0.03 (0.59, -0.51)
	renewables	85	87.70 (101.60, 60.16)	139.48 (203.90, 87.75)	293.80 (584.78, 176.77)	15.03 (20.39, 10.60)	27.90 (62.15, 13.78)	60.80 (87.89, 28.47)	2.62 (6.71, 0.91)
	biomass	85	61.35 (73.03, 40.54)	75.28 (113.02, 44.42)	154.13 (311.72, 40.36)	10.27 (14.23, 7.14)	14.38 (35.61, 9.03)	26.38 (54.10, 10.29)	1.71 (5.56, -0.42)
	non-biomass	85	26.35 (36.58, 17.60)	61.60 (114.41, 25.79)	157.37 (409.94, 53.79)	4.40 (7.19, 2.84)	11.87 (26.54, 4.49)	28.60 (61.61, 9.87)	4.63 (13.46, 1.38)
	wind & solar	70	10.93 (20.17, 1.91)	40.17 (82.66, 7.05)	125.31 (342.77, 27.95)	1.81 (3.66, 0.32)	8.24 (19.56, 1.54)	22.10 (51.52, 4.48)	11.64 (63.34, 3.13)
	nuclear	85	10.93 (18.55, 8.52)	16.22 (41.73, 6.80)	24.48 (115.80, 3.09)	1.97 (3.37, 1.45)	3.27 (9.61, 1.20)	4.22 (13.60, 0.43)	1.34 (7.22, -0.64)
	fossil	85	489.52 (543.29, 376.30)	343.48 (568.91, 70.14)	198.58 (608.39, 43.87)	83.05 (86.65, 77.73)	69.19 (82.94, 29.55)	33.06 (60.84, 7.70)	-0.58 (0.12, -0.91)
	coal	85	147.09 (193.55, 83.23)	49.46 (176.99, 5.97)	23.84 (134.69, 0.36)	25.72 (30.82, 17.19)	10.76 (26.35, 1.31)	4.99 (13.30, 0.05)	-0.85 (-0.30, -1.00)
	gas	85	135.58 (169.50, 105.01)	127.99 (208.55, 17.30)	88.97 (265.66, 14.92)	23.28 (28.39, 18.09)	24.02 (35.05, 7.08)	13.46 (34.83, 2.80)	-0.37 (0.99, -0.88)
	oil	85	195.02 (245.15, 151.02)	175.69 (319.80, 38.94)	93.48 (208.04, 15.07)	33.79 (42.24, 28.07)	32.01 (50.12, 16.41)	16.22 (27.30, 2.89)	-0.54 (0.06, -0.93)

Table 2.7 | Global electricity generation of 1.5°C pathways from the scenarios database.

(Supplementary Material 2.SM.1.3). Values given for the median (maximum, minimum) values across the full range across 89 available 1.5°C pathways. Growth Factor = [(primary energy supply in 2050)/(primary energy supply in 2020) - 1].

	Median (max, min)	Count	Electricity Generation (EJ)			Share in Electricity Generation (%)			Growth (factor) 2020-2050
			2020	2030	2050	2020	2030	2050	
TBelow -1.5°C and 1.5°C-low-OS pathways	total generation	50	98.45 (113.98, 83.53)	115.82 (152.40, 81.28)	215.58 (354.48, 126.96)	NA	NA	NA	1.15 (2.55, 0.28)
	renewables	50	26.28 (41.80, 18.50)	63.30 (111.70, 32.41)	145.50 (324.26, 90.66)	26.32 (41.84, 18.99)	53.68 (79.67, 37.30)	77.12 (96.65, 58.89)	4.48 (10.88, 2.65)
	biomass	50	2.02 (7.00, 0.76)	4.29 (11.96, 0.79)	20.35 (39.28, 0.24)	1.97 (6.87, 0.82)	3.69 (13.29, 0.73)	8.77 (30.28, 0.10)	6.42 (38.14, -0.93)
	non-biomass	50	24.21 (35.72, 17.70)	57.12 (101.90, 25.79)	135.04 (323.91, 53.79)	24.38 (40.43, 17.75)	49.88 (78.27, 29.30)	64.68 (96.46, 41.78)	4.64 (10.64, 1.45)
	wind & solar	50	1.66 (6.60, 0.38)	8.91 (48.04, 0.60)	39.04 (208.97, 2.68)	1.62 (7.90, 0.38)	8.36 (41.72, 0.53)	19.10 (60.11, 1.65)	26.31 (169.66, 5.23)
	nuclear	50	10.84 (18.55, 8.52)	15.46 (36.80, 6.80)	21.97 (64.72, 3.09)	12.09 (18.34, 8.62)	14.33 (31.63, 5.24)	8.10 (27.53, 1.02)	0.71 (4.97, -0.64)
	fossil	50	59.43 (68.75, 39.48)	36.51 (66.07, 2.25)	14.81 (57.76, 0.00)	61.32 (67.40, 47.26)	30.04 (52.86, 1.95)	8.61 (25.18, 0.00)	-0.74 (0.01, -1.00)
	coal	50	31.02 (42.00, 14.40)	8.83 (34.11, 0.00)	1.38 (17.39, 0.00)	32.32 (40.38, 17.23)	7.28 (27.29, 0.00)	0.82 (7.53, 0.00)	-0.96 (-0.56, -1.00)
	gas	50	24.70 (32.46, 13.44)	22.59 (42.08, 2.01)	12.79 (53.17, 0.00)	24.39 (35.08, 11.80)	20.18 (37.23, 1.75)	6.93 (24.87, 0.00)	-0.47 (1.27, -1.00)
	oil	50	2.48 (13.36, 1.12)	1.89 (7.56, 0.24)	0.10 (8.78, 0.00)	2.82 (11.73, 1.01)	1.95 (5.67, 0.21)	0.05 (3.80, 0.00)	-0.92 (0.36, -1.00)
1.5°C-high-OS	total generation	35	101.44 (113.96, 88.55)	125.26 (177.51, 89.60)	251.50 (363.10, 140.65)	NA	NA	NA	1.38 (2.19, 0.39)
	renewables	35	26.38 (31.83, 18.26)	53.32 (86.85, 30.06)	173.29 (273.92, 84.69)	28.37 (32.96, 17.38)	42.73 (65.73, 25.11)	82.39 (94.66, 35.58)	5.97 (8.68, 2.37)
	biomass	35	1.23 (6.47, 0.66)	2.14 (7.23, 0.86)	10.49 (40.32, 0.21)	1.22 (7.30, 0.63)	1.59 (6.73, 0.72)	3.75 (28.09, 0.08)	7.93 (33.32, -0.81)
	non-biomass	35	24.56 (30.70, 17.60)	47.96 (85.83, 27.39)	144.13 (271.17, 55.72)	26.77 (31.79, 16.75)	40.07 (64.96, 23.10)	69.72 (94.58, 27.51)	5.78 (8.70, 1.38)

Table 2.7 (continued next page)

Table 2.7 (continued)

	Median (max, min)	Count	Electricity Generation (EJ)			Share in Electricity Generation (%)			Growth (factor) 2020-2050
			2020	2030	2050	2020	2030	2050	
1.5°C-high-OS	wind & solar	35	2.24 (5.07, 0.42)	8.95 (36.52, 1.18)	65.08 (183.38, 13.79)	2.21 (5.25, 0.41)	7.48 (27.90, 0.99)	25.88 (61.24, 8.71)	30.70 (106.95, 4.87)
	nuclear	35	10.84 (14.08, 8.52)	16.12 (41.73, 6.80)	22.91 (115.80, 3.09)	10.91 (13.67, 8.62)	14.65 (23.51, 5.14)	11.19 (39.61, 1.12)	1.49 (7.22, -0.64)
	fossil	35	62.49 (76.76, 49.09)	48.08 (87.54, 30.99)	11.84 (118.12, 0.78)	61.58 (71.03, 54.01)	42.02 (59.48, 24.27)	6.33 (33.19, 0.27)	-0.80 (0.54, -0.99)
	coal	35	32.37 (46.20, 26.00)	16.22 (43.12, 1.32)	1.18 (46.72, 0.01)	32.39 (40.88, 24.41)	14.23 (29.93, 1.19)	0.55 (12.87, 0.00)	-0.96 (0.01, -1.00)
	gas	35	26.20 (41.20, 20.11)	26.45 (51.99, 16.45)	10.66 (67.94, 0.76)	26.97 (39.20, 19.58)	22.29 (43.43, 14.03)	5.29 (32.59, 0.26)	-0.57 (1.63, -0.97)
	oil	35	1.51 (6.28, 1.12)	0.61 (7.54, 0.36)	0.04 (7.47, 0.00)	1.51 (6.27, 1.01)	0.55 (6.20, 0.26)	0.02 (3.31, 0.00)	-0.99 (0.98, -1.00)
Two above classes combined	total generation	85	100.09 (113.98, 83.53)	120.01 (177.51, 81.28)	224.78 (363.10, 126.96)	NA	NA	NA	1.31 (2.55, 0.28)
	renewables	85	26.38 (41.80, 18.26)	59.50 (111.70, 30.06)	153.72 (324.26, 84.69)	27.95 (41.84, 17.38)	51.51 (79.67, 25.11)	77.52 (96.65, 35.58)	5.08 (10.88, 2.37)
	biomass	85	1.52 (7.00, 0.66)	3.55 (11.96, 0.79)	16.32 (40.32, 0.21)	1.55 (7.30, 0.63)	2.77 (13.29, 0.72)	8.02 (30.28, 0.08)	6.53 (38.14, -0.93)
	non-biomass	85	24.48 (35.72, 17.60)	55.68 (101.90, 25.79)	136.40 (323.91, 53.79)	25.00 (40.43, 16.75)	47.16 (78.27, 23.10)	66.75 (96.46, 27.51)	4.75 (10.64, 1.38)
	wind & solar	85	1.66 (6.60, 0.38)	8.95 (48.04, 0.60)	43.20 (208.97, 2.68)	1.67 (7.90, 0.38)	8.15 (41.72, 0.53)	19.70 (61.24, 1.65)	28.02 (169.66, 4.87)
	nuclear	85	10.84 (18.55, 8.52)	15.49 (41.73, 6.80)	22.64 (115.80, 3.09)	10.91 (18.34, 8.62)	14.34 (31.63, 5.14)	8.87 (39.61, 1.02)	1.21 (7.22, -0.64)
	fossil	85	61.35 (76.76, 39.48)	38.41 (87.54, 2.25)	14.10 (118.12, 0.00)	61.55 (71.03, 47.26)	33.96 (59.48, 1.95)	8.05 (33.19, 0.00)	-0.76 (0.54, -1.00)
	coal	85	32.37 (46.20, 14.40)	10.41 (43.12, 0.00)	1.29 (46.72, 0.00)	32.39 (40.88, 17.23)	8.95 (29.93, 0.00)	0.59 (12.87, 0.00)	-0.96 (0.01, -1.00)
	gas	85	24.70 (41.20, 13.44)	25.00 (51.99, 2.01)	11.92 (67.94, 0.00)	24.71 (39.20, 11.80)	21.03 (43.43, 1.75)	6.78 (32.59, 0.00)	-0.52 (1.63, -1.00)
	oil	85	1.82 (13.36, 1.12)	0.92 (7.56, 0.24)	0.08 (8.78, 0.00)	2.04 (11.73, 1.01)	0.71 (6.20, 0.21)	0.04 (3.80, 0.00)	-0.97 (0.98, -1.00)

2.4.2.2 Evolution of electricity supply over time

Electricity supplies an increasing share of final energy, reaching 34–71% in 2050, across 1.5°C pathways with no or limited overshoot (Figure 2.14), extending the historical increases in electricity share seen over the past decades (Bruckner et al., 2014). From 2020 to 2050, the quantity of electricity supplied in most 1.5°C pathways with no or limited overshoot more than doubles (Table 2.7). By 2050, the carbon intensity of electricity has fallen rapidly to -92 to +11 gCO₂ MJ⁻¹ electricity across 1.5°C pathways with no or limited overshoot from a value of around 140 gCO₂ MJ⁻¹ (range: 88–181 gCO₂ MJ⁻¹) in 2020 (Figure 2.14). A negative contribution to carbon intensity is provided by BECCS in most pathways (Figure 2.16).

By 2050, the share of electricity supplied by renewables increases from 23% in 2015 (IEA, 2017b) to 59–97% across 1.5°C pathways with no or limited overshoot. Wind, solar, and biomass together make a major contribution in 2050, although the share for each spans a wide range across 1.5°C pathways (Figure 2.16). Fossil fuels on the other hand have a decreasing role in electricity supply, with their share falling to 0–25% by 2050 (Table 2.7).

In summary, 1.5°C pathways include a rapid decline in the carbon intensity of electricity and an increase in electrification of energy end-use (*high confidence*). This is the case across all 1.5°C pathways and their associated literature (Supplementary Material 2.SM.1.3), with pathway trends that extend those seen in past decades, and results that are consistent with additional analyses (see Section 2.4.2.2).

2.4.2.3 Deployment of carbon capture and storage

Studies have shown the importance of CCS for deep mitigation pathways (Krey et al., 2014a; Krieger et al., 2014b), based on its multiple roles to limit fossil-fuel emissions in electricity generation, liquids production, and industry applications along with the projected ability to remove CO₂ from the atmosphere when combined with bioenergy. This remains a valid finding for those 1.5°C and 2°C pathways that do not radically reduce energy demand or do not offer carbon-neutral alternatives to liquids and gases that do not rely on bioenergy.

There is a wide range of CCS that is deployed across 1.5°C pathways (Figure 2.17). A few 1.5°C pathways with very low energy demand do not include CCS at all (Grubler et al., 2018). For example, the LED pathway has no CCS, whereas other pathways, such as the S5 pathway,

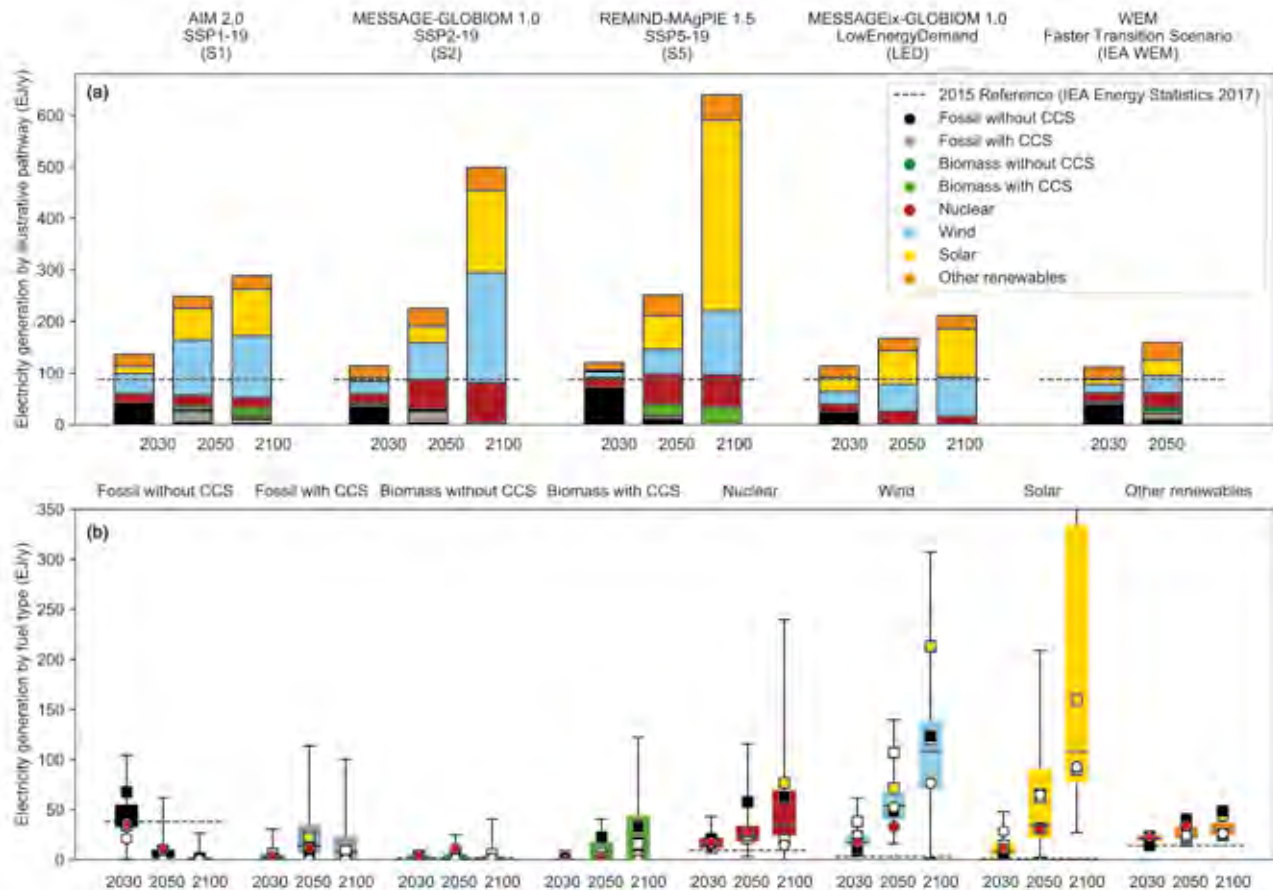


Figure 2.16 | Electricity generation for the four illustrative pathway archetypes plus the IEA's Faster Transition Scenario (IEA, 2017d) (panel a), and their relative location in the ranges for pathways limiting warming to 1.5°C with no or limited overshoot (panel b). The category 'Other renewables' includes electricity generation not covered by the other categories, for example, hydro and geothermal. The number of pathways that have higher primary energy than the scale in the bottom panel are indicated by the numbers above the whiskers. Black horizontal dashed lines indicate the level of primary energy supply in 2015 (IEA, 2017e). Box plots in the lower panel show the minimum–maximum range (whiskers), interquartile range (box), and median (vertical thin black line). Symbols in the lower panel show the four pathway archetypes – S1 (white square), S2 (yellow square), S5 (black square), LED (white disc) – as well as the IEA's Faster Transition Scenario (red disc). Pathways with no or limited overshoot included the Below-1.5°C and 1.5°C-low-OS classes.

rely on a large amount of BECCS to get to net-zero carbon emissions. The cumulative fossil and biomass CO₂ stored through 2050 ranges from zero to 300 GtCO₂ across 1.5°C pathways with no or limited overshoot, with zero up to 140 GtCO₂ from biomass captured and stored. Some pathways have very low fossil-fuel use overall, and consequently little CCS applied to fossil fuels. In 1.5°C pathways where the 2050 coal use remains above 20 EJ yr⁻¹ in 2050, 33–100% is combined with CCS. While deployment of CCS for natural gas and coal vary widely across pathways, there is greater natural gas primary energy connected to CCS than coal primary energy connected to CCS in many pathways (Figure 2.17).

CCS combined with fossil-fuel use remains limited in some 1.5°C pathways (Rogelj et al., 2018), as the limited 1.5°C carbon budget penalizes CCS if it is assumed to have incomplete capture rates or if fossil fuels are assumed to continue to have significant lifecycle GHG emissions (Pehl et al., 2017). However, high capture rates are technically achievable now at higher cost, although efforts to date have focussed on reducing the costs of capture (IEAGHG, 2006; NETL, 2013).

The quantity of CO₂ stored via CCS over this century in 1.5°C pathways with no or limited overshoot ranges from zero to more than 1,200 GtCO₂, (Figure 2.17). The IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005) found that that, worldwide, it is *likely* that there is a technical potential of at least about 2,000 GtCO₂ of storage capacity in geological formations. Furthermore, the IPCC (2005) recognized that there could be a much larger potential for geological storage in saline formations, but the upper limit estimates are uncertain due to lack of information and an agreed methodology. Since IPCC (2005), understanding has improved and there have been detailed regional surveys of storage capacity (Vangkilde-Pedersen et al., 2009; Ogawa et al., 2011; Wei et al., 2013; Bentham et al., 2014; Riis and Halland, 2014; Warwick et al., 2014; NETL, 2015) and improvement and standardization of methodologies (e.g., Bachu et al. 2007a, b). Dooley (2013) synthesized published literature on both the global geological storage resource as well as the potential demand for geologic storage in mitigation pathways, and found that the cumulative demand for CO₂ storage was small compared to a practical storage capacity estimate (as defined by Bachu et al., 2007a) of 3,900 GtCO₂ worldwide. Differences remain, however, in estimates of storage capacity due to, for example, the potential storage limitations of

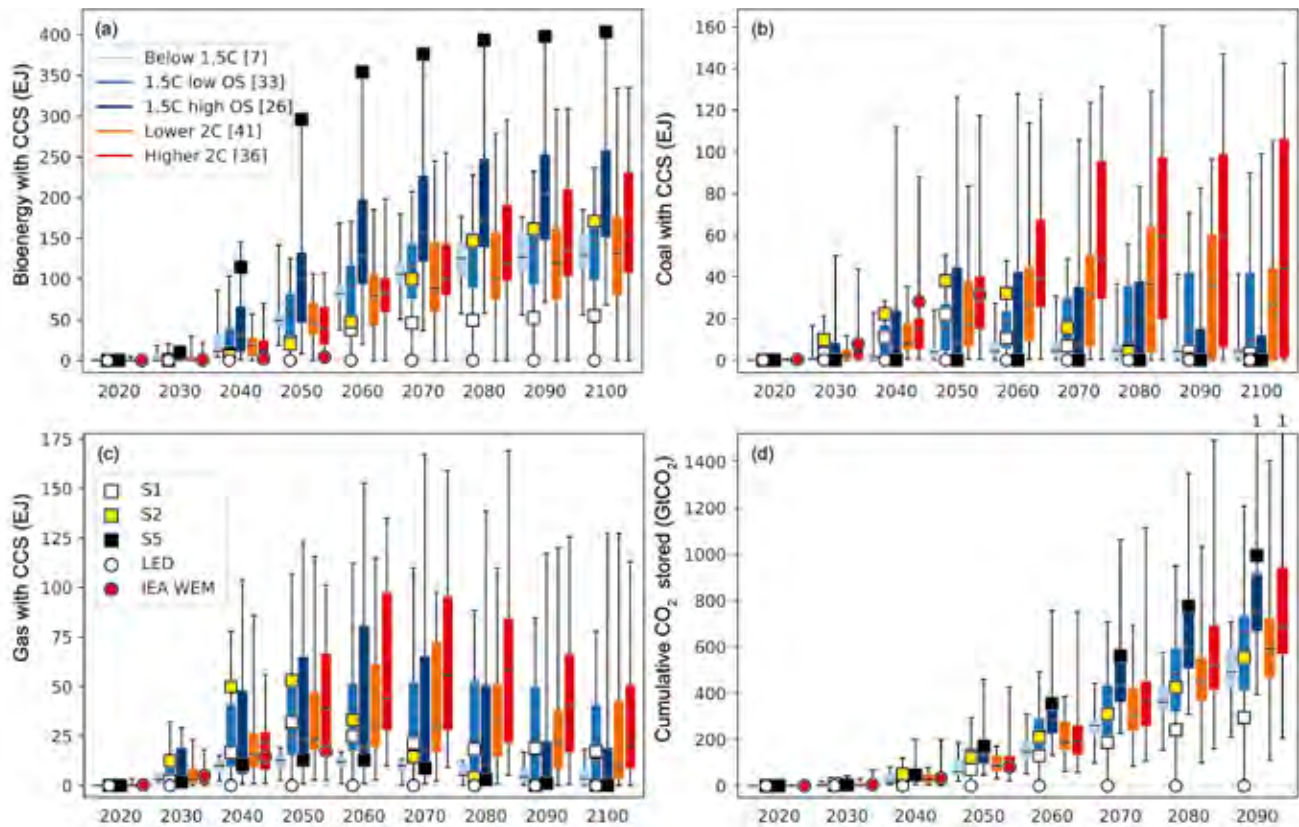


Figure 2.17 | CCS deployment in 1.5°C and 2°C pathways for (a) biomass, (b) coal and (c) natural gas (EJ of primary energy) and (d) the cumulative quantity of fossil (including from, e.g., cement production) and biomass CO₂ stored via CCS (in GtCO₂ stored). TBox plots show median, interquartile range and full range of pathways in each temperature class. Pathway temperature classes (Table 2.1), illustrative pathway archetypes, and the IEA's Faster Transition Scenario (IEA WEM) (OECD/IEA and IRENA, 2017) are indicated in the legend.

subsurface pressure build-up (Szulczewski et al., 2014) and assumptions on practices that could manage such issues (Bachu, 2015). Kearns et al. (2017) constructed estimates of global storage capacity of 8,000 to 55,000 GtCO₂ (accounting for differences in detailed regional and local estimates), which is sufficient at a global level for this century, but found that at a regional level, robust demand for CO₂ storage exceeds their lower estimate of regional storage available for some regions. However, storage capacity is not solely determined by the geological setting, and Bachu (2015) describes storage engineering practices that could further extend storage capacity estimates. In summary, the storage capacity of all of these global estimates is larger than the cumulative CO₂ stored via CCS in 1.5°C pathways over this century.

There is uncertainty in the future deployment of CCS given the limited pace of current deployment, the evolution of CCS technology that would be associated with deployment, and the current lack of incentives for large-scale implementation of CCS (Bruckner et al., 2014; Clarke et al., 2014; Riahi et al., 2017). Given the importance of CCS in most mitigation pathways and its current slow pace of improvement, the large-scale deployment of CCS as an option depends on the further development of the technology in the near term. Chapter 4 discusses how progress on CCS might be accelerated.

2.4.3 Energy End-Use Sectors

Since the power sector is almost decarbonized by mid-century in both 1.5°C and 2°C pathways, major differences come from CO₂ emission reductions in end-use sectors. Energy-demand reductions are key and common features in 1.5°C pathways, and they can be achieved by efficiency improvements and various specific demand-reduction measures. Another important feature is end-use decarbonization including by electrification, although the potential and challenges in each end-use sector vary significantly.

In the following sections, the potential and challenges of CO₂ emission reductions towards 1.5°C and 2°C-consistent pathways are discussed for each end-use energy sector (industry, buildings, and transport). For this purpose, two types of pathways are analysed and compared: IAM (integrated assessment modelling) studies and sectoral (detailed) studies. IAM data are extracted from the database that was compiled for this assessment (see Supplementary Material 2.SM.1.3), and the sectoral data are taken from a recent series of publications; 'Energy Technology Perspectives' (ETP) (IEA, 2014, 2015b, 2016a, 2017a), the IEA/IRENA report (OECD/IEA and IRENA, 2017), and the Shell Sky report (Shell International B.V., 2018). The IAM pathways are categorized according to their temperature rise in 2100 and the overshoot of temperature during the century (see Table 2.1 in Section 2.1). Since the number of Below-1.5°C pathways is small, the following analyses

focus only on the features of the 1.5°C-low-OS and 1.5°C-high-OS pathways (hereafter denoted together as 1.5°C overshoot pathways or IAM-1.5DS-OS) and 2°C-consistent pathways (IAM-2DS). In order to show the diversity of IAM pathways, we again show specific data from the four illustrative pathways archetypes used throughout this chapter (see Sections 2.1 and 2.3).

IEA ETP-B2DS ('Beyond 2 Degrees') and ETP-2DS are pathways with a 50% chance of limiting temperature rise below 1.75°C and 2°C by 2100, respectively (IEA, 2017a). The IEA-66%2DS pathway keeps global mean temperature rise below 2°C, not just in 2100 but also over the course of the 21st century, with a 66% chance of being below 2°C by 2100 (OECD/IEA and IRENA, 2017). The comparison of CO₂ emission trajectories between ETP-B2DS and IAM-1.5DS-OS show that these are consistent up to 2060 (Figure 2.18). IEA scenarios assume that only a very low level of BECCS is deployed to help offset emissions in difficult-to-decarbonize sectors, and that global energy-related CO₂ emissions do not turn net negative at any time but stay at zero from 2060 to 2100 (IEA, 2017a). Therefore, although its temperature rise in 2100 is below 1.75°C rather than below 1.5°C, this scenario can give information related to a 1.5°C overshoot pathway up to 2050. The trajectory of IEA-66%2DS (also referred to in other publications as IEA's 'Faster Transition Scenario') lies between IAM-1.5DS-OS and IAM-2DS pathway ranges, and IEA-2DS stays in the range of 2°C-consistent IAM pathways. The Shell-Sky scenario aims to hold the temperature rise to well below 2°C, but it is a delayed action pathway relative to others, as can be seen in Figure 2.18.

Energy-demand reduction measures are key to reducing CO₂ emissions from end-use sectors for low-carbon pathways. The upstream energy reductions can be from several times to an order of magnitude larger than the initial end-use demand reduction. There are interdependencies among the end-use sectors and between energy-supply and end-use sectors, which elevate the importance of a wide, systematic approach. As shown in Figure 2.19, global final energy consumption grows by 30% and 10% from 2010 to 2050 for 2°C-consistent and 1.5°C overshoot pathways from IAMs, respectively, while much higher growth of 75% is projected for reference scenarios. The ranges within a specific pathway class are due to a variety of factors as introduced in Section 2.3.1, as well as differences between modelling frameworks. The important energy efficiency and conservation improvements that facilitate many of the 1.5°C pathways raise the issue of potential rebound effects (Saunders, 2015), which, while promoting development, can make the achievement of low-energy demand futures more difficult than modelling studies anticipate (see Sections 2.5 and 2.6).

Final energy demand is driven by demand in energy services for mobility, residential and commercial activities (buildings), and manufacturing. Projections of final energy demand depend heavily on assumptions about socio-economic futures as represented by the SSPs (Bauer et al., 2017) (see Sections 2.1, 2.3 and 2.5). The structure of this demand drives the composition of final energy use in terms of energy carriers (electricity, liquids, gases, solids, hydrogen etc.).

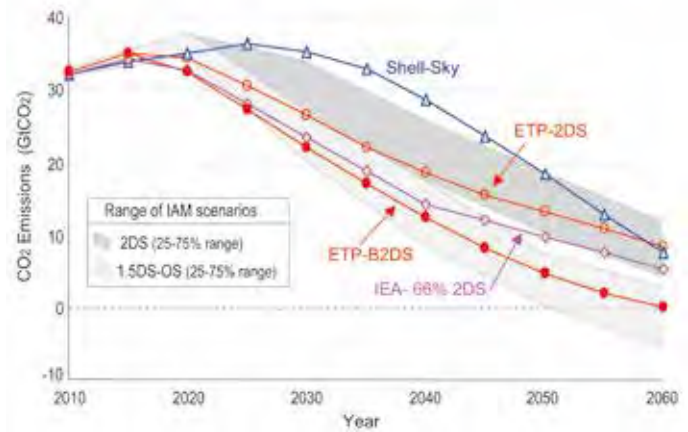


Figure 2.18 | Comparison of CO₂ emission trajectories of sectoral pathways (IEA ETP-B2DS, ETP-2DS, IEA-66%2DS, Shell-Sky) with the ranges of IAM pathway (2DS are 2°C-consistent pathways and 1.5DS-OS are 1.5°C overshoot pathways). The CO₂ emissions shown here are the energy-related emissions, including industrial process emissions.

Figure 2.19 shows the structure of global final energy demand in 2030 and 2050, indicating the trend toward electrification and fossil fuel usage reduction. This trend is more significant in 1.5°C pathways than 2°C pathways. Electrification continues throughout the second half of the century, leading to a 3.5- to 6-fold increase in electricity demand (interquartile range; median 4.5) by the end of the century relative to today (Grubler et al., 2018; Luderer et al., 2018). Since the electricity sector is completely decarbonized by mid-century in 1.5°C pathways (see Figure 2.20), electrification is the primary means to decarbonize energy end-use sectors.

The CO₂ emissions⁶ of end-use sectors and carbon intensity are shown in Figure 2.20. The projections of IAMs and IEA studies show rather different trends, especially in the carbon intensity. These differences come from various factors, including the deployment of CCS, the level of fuel switching and efficiency improvements, and the effect of structural and behavioural changes. IAM projections are generally optimistic for the industry sectors, but not for buildings and transport sectors. Although GDP increases by a factor of 3.4 from 2010 to 2050, the total energy consumption of end-use sectors grows by only about 30% and 20% in 1.5°C overshoot and 2°C-consistent pathways, respectively. However, CO₂ emissions would need to be reduced further to achieve the stringent temperature limits. Figure 2.20 shows that the reduction in CO₂ emissions of end-use sectors is larger and more rapid in 1.5°C overshoot than 2°C-consistent pathways, while emissions from the power sector are already almost zero in 2050 in both sets of pathways, indicating that supply-side emissions reductions are almost fully exploited already in 2°C-consistent pathways (see Figure 2.20) (Rogelj et al., 2015b, 2018; Luderer et al., 2016b). The emission reductions in end-use sectors are largely made possible by efficiency improvements, demand reduction measures and electrification, but the level of emissions reductions varies across end-use sectors. While the carbon intensity of the industry and buildings sectors decreases

⁶ This section reports 'direct' CO₂ emissions as reported for pathways in the database for the report. As shown below, the emissions from electricity are nearly zero around 2050, so the impact of indirect emissions on the whole emission contributions of each sector is very small in 2050.

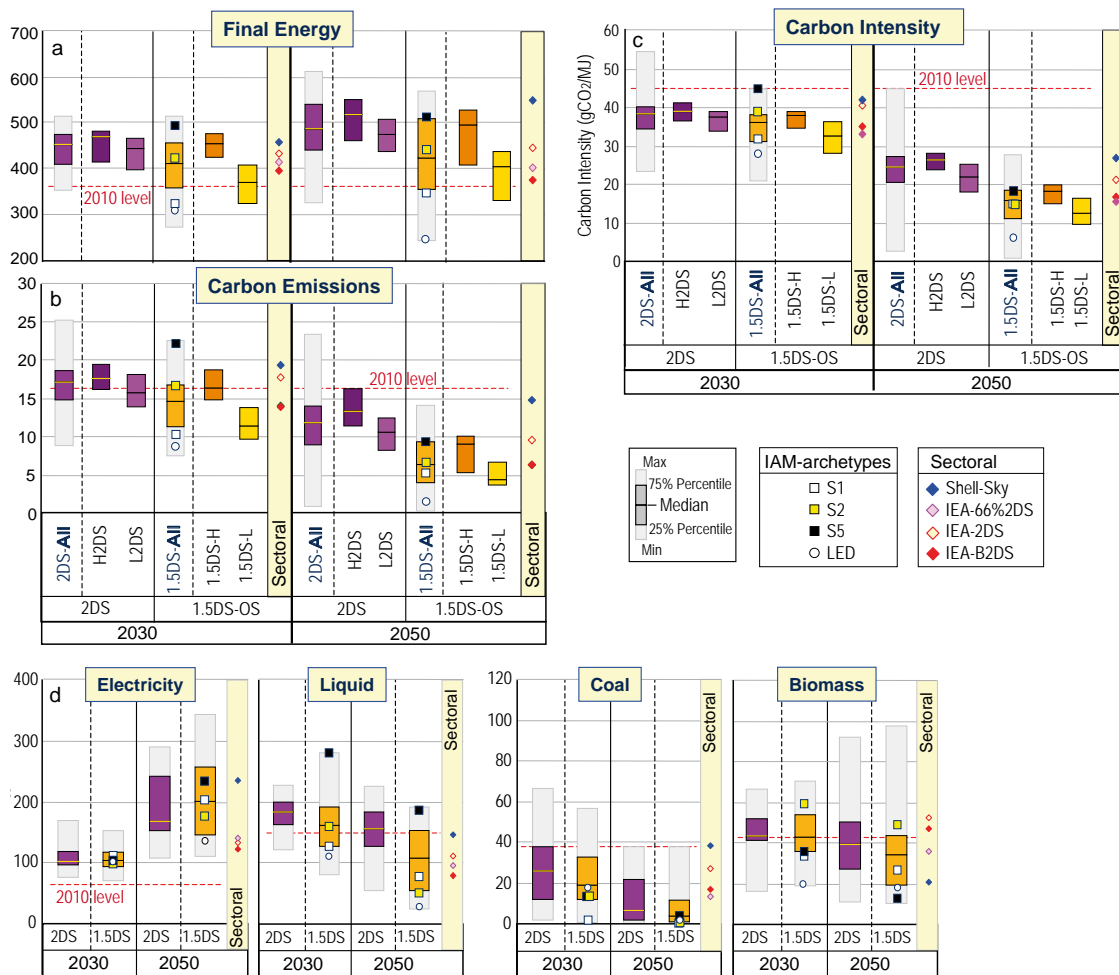


Figure 2.19 | (a) Global final energy, (b) direct CO₂ emissions from the all energy demand sectors, (c) carbon intensity, and (d) structure of final energy (electricity, liquid fuel, coal, and biomass). The squares and circles indicate the IAM archetype pathways and diamonds indicate the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS = Higher-2°C, L2DS = Lower-2°C, 1.5DS-H = 1.5°C-high-OS, 1.5DS-L = 1.5°C-low-OS. The label 1.5DS combines both high and low overshoot 1.5°C-consistent pathway. See Section 2.1 for descriptions.

to a very low level of around 10 gCO₂ MJ⁻¹, the carbon intensity of transport becomes the highest of any sector by 2040 due to its higher reliance on oil-based fuels. In the following subsections, the potential and challenges of CO₂ emission reduction in each end-use sector are discussed in detail.

2.4.3.1 Industry

The industry sector is the largest end-use sector, both in terms of final energy demand and GHG emissions. Its direct CO₂ emissions currently account for about 25% of total energy-related and process CO₂ emissions, and emissions have increased at an average annual rate of 3.4% between 2000 and 2014, significantly faster than total CO₂ emissions (Hoesly et al., 2018). In addition to emissions from the combustion of fossil fuels, non-energy uses of fossil fuels in the petrochemical industry and metal smelting, as well as non-fossil fuel process emissions (e.g., from cement production) contribute a small amount (~5%) to the sector's CO₂ emissions inventory. Material industries are particularly energy and emissions intensive: together, the steel, non-ferrous metals, chemicals, non-metallic minerals, and

pulp and paper industries accounted for close to 66% of final energy demand and 72% of direct industry-sector emissions in 2014 (IEA, 2017a). In terms of end-uses, the bulk of energy in manufacturing industries is required for process heating and steam generation, while most electricity (but smaller shares of total final energy) is used for mechanical work (Banerjee et al., 2012; IEA, 2017a).

As shown in Figure 2.21, a major share of the additional emission reductions required for 1.5°C-overshoot pathways compared to those in 2°C-consistent pathways comes from industry. Final energy, CO₂ emissions, and carbon intensity are consistent in IAM and sectoral studies, but in IAM-1.5°C-overshoot pathways the share of electricity is higher than IEA-B2DS (40% vs. 25%) and hydrogen is also considered to have a share of about 5% versus 0%. In 2050, final energy is increased by 30% and 5% compared with the 2010 level (red dotted line) for 1.5°C-overshoot and 2°C-consistent pathways, respectively, but CO₂ emissions are decreased by 80% and 50% and carbon intensity by 80% and 60%, respectively. This additional decarbonization is brought by switching to low-carbon fuels and CCS deployment.

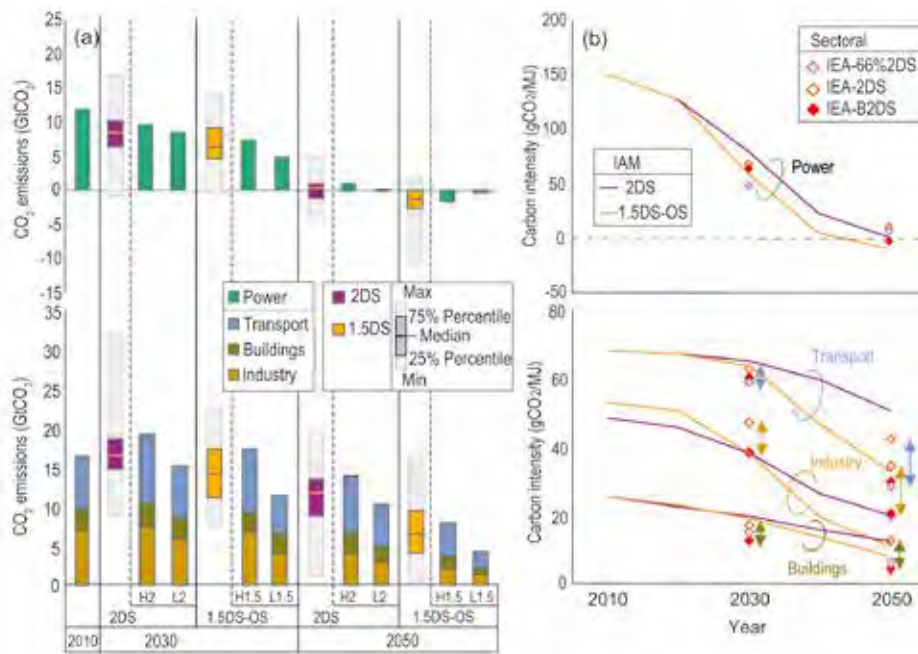


Figure 2.20 | Comparison of (a) direct CO₂ emissions and (b) carbon intensity of the power and energy end-use sectors (industry, buildings, and transport sectors) between IAMs and sectoral studies (IEA-ETP and IEA/IRENA). Diamond markers in panel (b) show data for IEA-ETP scenarios (2DS and B2DS), and IEA/IRENA scenario (66%2DS). Note: for the data from IAM studies, there is rather large variation of projections for each indicator. Please see the details in the following figures in each end-use sector section.

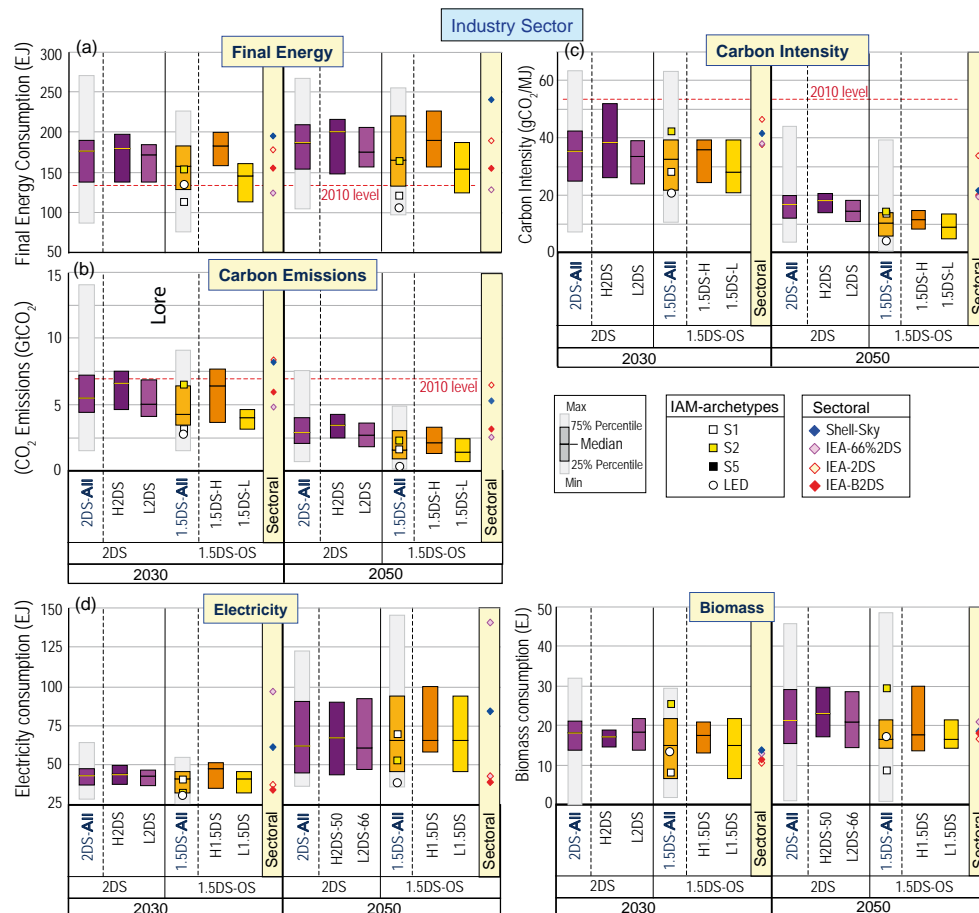


Figure 2.21 | Comparison of (a) final energy, (b) direct CO₂ emissions, (c) carbon intensity, (d) electricity and biomass consumption in the industry sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS = Higher-2°C, L2DS = Lower-2°C, 1.5DS-H = 1.5°C-high-OS, 1.5DS-L = 1.5°C-low-OS. The label 1.5DS combines both high and low overshoot 1.5°C-consistent pathways. Section 2.1 for descriptions.

Broadly speaking, the industry sector's mitigation measures can be categorized in terms of the following five strategies: (i) reducing demand, (ii) energy efficiency, (iii) increasing electrification of energy demand, (iv) reducing the carbon content of non-electric fuels, and (v) deploying innovative processes and application of CCS. IEA ETP estimates the relative contribution of different measures for CO₂ emission reduction in their B2DS scenario compared with their reference scenario in 2050 as follows: energy efficiency 42%, innovative process and CCS 37%, switching to low-carbon fuels and feedstocks 13% and material efficiency (include efficient production and use to contribute to demand reduction) 8%. The remainder of this section delves more deeply into the potential mitigation contributions of these strategies as well as their limitations.

Reduction in the use of industrial materials, while delivering similar services, or improving the quality of products could help to reduce energy demand and overall system-level CO₂ emissions. Strategies include using materials more intensively, extending product lifetimes, increasing recycling, and increasing inter-industry material synergies, such as clinker substitution in cement production (Allwood et al., 2013; IEA, 2017a). Related to material efficiency, use of fossil-fuel feedstocks could shift to lower-carbon feedstocks, such as from oil to natural gas and biomass, and end-uses could shift to more sustainable materials, such as biomass-based materials, reducing the demand for energy-intensive materials (IEA, 2017a).

Reaping energy efficiency potentials hinges critically on advanced management practices, such as energy management systems, in industrial facilities as well as targeted policies to accelerate adoption of the best available technology (see Section 2.5). Although excess energy, usually as waste heat, is inevitable, recovering and reusing this waste heat under economically and technically viable conditions benefits the overall energy system. Furthermore, demand-side management strategies could modulate the level of industrial activity in line with the availability of resources in the power system. This could imply a shift away from peak demand and as power supply decarbonizes, this demand-shaping potential could shift some load to times with high portions of low-carbon electricity generation (IEA, 2017a).

In the industry sector, energy demand increases more than 40% between 2010 and 2050 in baseline scenarios. However, in the 1.5°C-overshoot and 2°C-consistent pathways from IAMs, the increase is only 30% and 5%, respectively (Figure 2.21). These energy-demand reductions encompass both efficiency improvements in production and reductions in material demand, as most IAMs do not discern these two factors.

CO₂ emissions from industry increase by 30% in 2050 compared to 2010 in baseline scenarios. By contrast, these emissions are reduced by 80% and 50% relative to 2010 levels in 1.5°C-overshoot and 2°C-consistent pathways from IAMs, respectively (Figure 2.21). By mid-

century, CO₂ emissions per unit of electricity are projected to decrease to near zero in both sets of pathways (see Figure 2.20). An accelerated electrification of the industry sector thus becomes an increasingly powerful mitigation option. In the IAM pathways, the share of electricity increases up to 30% by 2050 in 1.5°C-overshoot pathways (Figure 2.21) from 20% in 2010. Some industrial fuel uses are substantially more difficult to electrify than others, and electrification would have other effects on the process, including impacts on plant design, cost and available process integration options (IEA, 2017a).⁷

In 1.5°C-overshoot pathways, the carbon intensity of non-electric fuels consumed by industry decreases to 16 gCO₂ MJ⁻¹ by 2050, compared to 25 gCO₂ MJ⁻¹ in 2°C-consistent pathways. Considerable carbon intensity reductions are already achieved by 2030, largely via a rapid phase-out of coal. Biomass becomes an increasingly important energy carrier in the industry sector in deep-decarbonization pathways, but primarily in the longer term (in 2050, biomass accounts for only 10% of final energy consumption even in 1.5°C-overshoot pathways). In addition, hydrogen plays a considerable role as a substitute for fossil-based non-electric energy demands in some pathways.

Without major deployment of new sustainability-oriented low-carbon industrial processes, the 1.5°C-overshoot target is difficult to achieve. Bringing such technologies and processes to commercial deployment requires significant investment in research and development. Some examples of innovative low-carbon process routes include: new steelmaking processes such as upgraded smelt reduction and upgraded direct reduced iron, inert anodes for aluminium smelting, and full oxy-fuelling kilns for clinker production in cement manufacturing (IEA, 2017a).

CCS plays a major role in decarbonizing the industry sector in the context of 1.5°C and 2°C pathways, especially in industries with higher process emissions, such as cement, iron and steel industries. In 1.5°C-overshoot pathways, CCS in industry reaches 3 GtCO₂ yr⁻¹ by 2050, albeit with strong variations across pathways. Given the projected long-lead times and need for technological innovation, early scale-up of industry-sector CCS is essential to achieving the stringent temperature target. Development and demonstration of such projects has been slow, however. Currently, only two large-scale industrial CCS projects outside of oil and gas processing are in operation (Global CCS Institute, 2016). The estimated current cost⁸ of CO₂ avoided (in USD2015) ranges from \$20–27 tCO₂⁻¹ for gas processing and bio-ethanol production, and \$60–138 tCO₂⁻¹ for fossil fuel-fired power generation up to \$104–188 tCO₂⁻¹ for cement production (Irlam, 2017).

2.4.3.2 Buildings

In 2014, the buildings sector accounted for 31% of total global final energy use, 54% of final electricity demand, and 8% of energy-related CO₂ emissions (excluding indirect emissions due to electricity). When

⁷ Electrification can be linked with the heating and drying process by electric boilers and electro-thermal processes, and also with low-temperature heat demand by heat pumps. In the iron and steel industry, hydrogen produced by electrolysis can be used as a reduction agent of iron instead of coke. Excess resources, such as black liquor, will provide the opportunity to increase the systematic efficiency to use for electricity generation.

⁸ These are first-of-a-kind (FOAK) cost data.

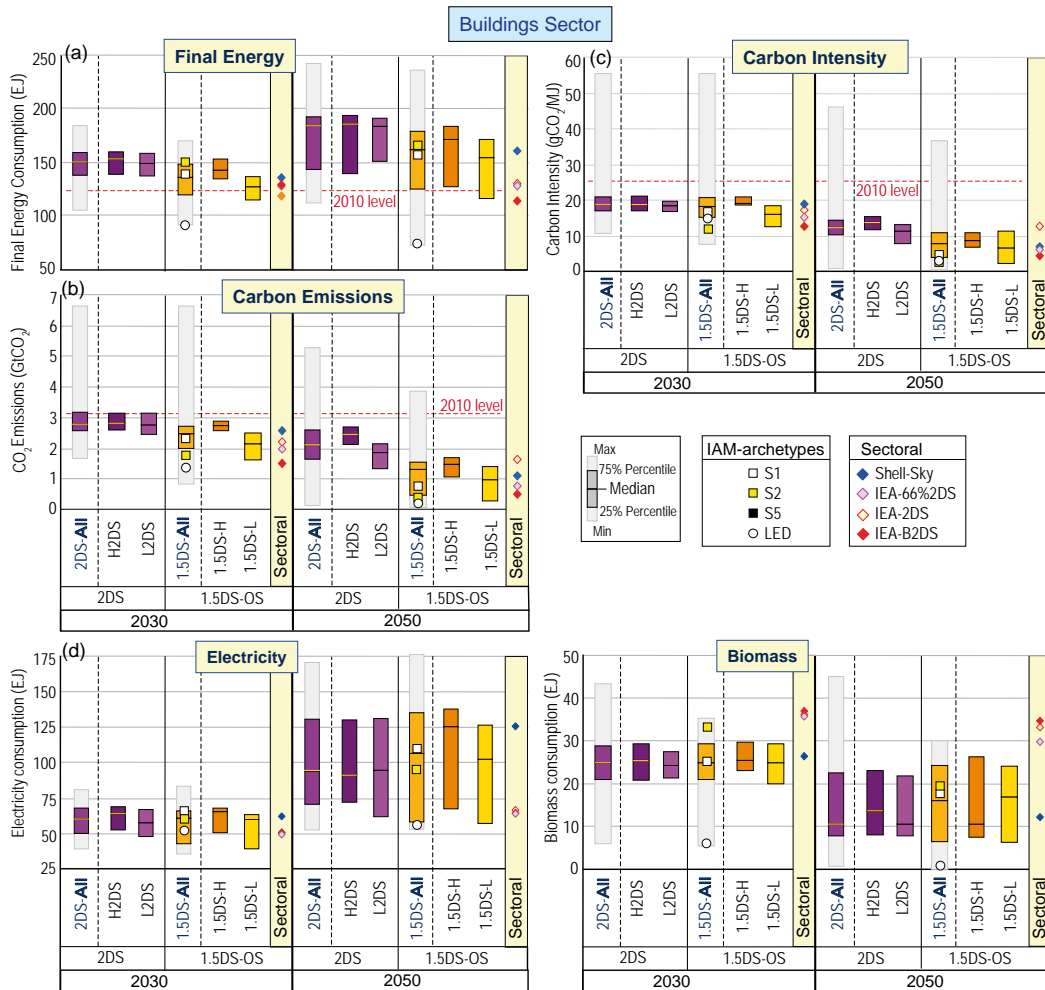


Figure 2.22 | Comparison of (a) final energy, (b) direct CO₂ emissions, (c) carbon intensity, (d) electricity and biomass consumption in the buildings sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS = Higher-2°C, L2DS = Lower-2°C, 1.5DS-H = 1.5°C-high-OS, 1.5DS-L = 1.5°C-low-OS. The label 1.5DS combines both high and low overshoot 1.5°C-consistent pathways. Section 2.1 for descriptions.

upstream electricity generation is taken into account, buildings were responsible for 23% of global energy-related CO₂ emissions, with one-third of those from direct fossil fuel consumption (IEA, 2017a).

Past growth of energy consumption has been mainly driven by population and economic growth, with improved access to electricity, and higher use of electrical appliances and space cooling resulting from increasing living standards, especially in developing countries (Lucon et al., 2014). These trends will continue in the future and in 2050, energy consumption is projected to increase by 20% and 50% compared to 2010 in the IAM-1.5°C-overshoot and 2°C-consistent pathways, respectively (Figure 2.22). However, sectoral studies (IEA-ETP scenarios) show different trends. Energy consumption in 2050 decreases compared to 2010 in ETP-B2DS, and the reduction rate of CO₂ emissions is higher than in IAM pathways (Figure 2.22). Mitigation options are often more widely covered in sectoral studies (Lucon et al., 2014), leading to greater reductions in energy consumption and CO₂ emissions.

Emissions reductions are driven by a clear tempering of energy demand and a strong electrification of the buildings sector. The share of electricity in 2050 is 60% in 1.5°C-overshoot pathways, compared

with 50% in 2°C-consistent pathways (Figure 2.22). Electrification contributes to the reduction of direct CO₂ emissions by replacing carbon-intensive fuels, like oil and coal. Furthermore, when combined with a rapid decarbonization of the power system (see Section 2.4.1) it also enables further reduction of indirect CO₂ emissions from electricity. Sectoral bottom-up models generally estimate lower electrification potentials for the buildings sector in comparison to global IAMs (see Figure 2.22). Besides CO₂ emissions, increasing global demand for air conditioning in buildings may also lead to increased emissions of HFCs in this sector over the next few decades. Although these gases are currently a relatively small proportion of annual GHG emissions, their use in the air conditioning sector is expected to grow rapidly over the next few decades if alternatives are not adopted. However, their projected future impact can be significantly mitigated through better servicing and maintenance of equipment and switching of cooling gases (Shah et al., 2015; Purohit and Höglund-Isaksson, 2017).

IEA-ETP (IEA, 2017a) analysed the relative importance of various technology measures toward the reduction of energy and CO₂ emissions in the buildings sector. The largest energy savings potential is in heating and cooling demand, largely due to building envelope improvements and high efficiency and renewable equipment. In the

ETP-B2DS, energy demand for space heating and cooling is 33% lower in 2050 than in the reference scenario, and these reductions account for 54% of total reductions from the reference scenario. Energy savings from shifts to high-performance lighting, appliances, and water heating equipment account for a further 24% of the total reduction. The long-term, strategic shift away from fossil-fuel use in buildings, alongside the rapid uptake of energy efficient, integrated and renewable energy technologies (with clean power generation), leads to a drastic reduction of CO₂ emissions. In ETP-B2DS, the direct CO₂ emissions are 79% lower than the reference scenario in 2050, and the remaining emissions come mainly from the continued use of natural gas.

The buildings sector is characterized by very long-living infrastructure, and immediate steps are hence important to avoid lock-in of inefficient carbon and energy-intensive buildings. This applies both to new buildings in developing countries where substantial new construction is expected in the near future and to retrofits of existing building stock in developed regions. This represents both a significant risk and opportunity for mitigation.⁹ A recent study highlights the benefits of deploying the most advanced renovation technologies, which would avoid lock-in into less efficient measures (Güneralp et al., 2017). Aside from the effect of building envelope measures, adoption of energy-efficient technologies such as heat pumps and, more recently, light-emitting diodes is also important for the reduction of energy and CO₂ emissions (IEA, 2017a). Consumer choices, behaviour and building operation can also significantly affect energy consumption (see Chapter 4, Section 4.3).

2.4.3.3 Transport

Transport accounted for 28% of global final energy demand and 23% of global energy-related CO₂ emissions in 2014. Emissions increased by 2.5% annually between 2010 and 2015, and over the past half century the sector has witnessed faster emissions growth than any other. The transport sector is the least diversified energy end-use sector; the sector consumed 65% of global oil final energy demand, with 92% of transport final energy demand consisting of oil products (IEA, 2017a), suggesting major challenges for deep decarbonization.

Final energy, CO₂ emissions, and carbon intensity for the transport sector are shown in Figure 2.23. The projections of IAMs are more pessimistic than IEA-ETP scenarios, though both clearly project deep cuts in energy consumption and CO₂ emissions by 2050. For example, 1.5°C-overshoot pathways from IAMs project a reduction of 15% in energy consumption between 2015 and 2050, while ETP-B2DS projects a reduction of 30% (Figure 2.23). Furthermore, IAM pathways are generally more pessimistic in the projections of CO₂ emissions and carbon intensity reductions. In AR5 (Clarke et al., 2014; Sims et al., 2014), similar comparisons between IAMs and sectoral studies were performed and these were in good agreement with each other. Since the AR5, two important changes can be identified: rapid growth of electric vehicle sales in passenger cars, and more attention towards

structural changes in this sector. The former contributes to reduction of CO₂ emissions and the latter to reduction of energy consumption.

Deep emissions reductions in the transport sector would be achieved by several means. Technology-focused measures such as energy efficiency and fuel-switching are two of these. Structural changes that avoid or shift transport activity are also important. While the former solutions (technologies) always tend to figure into deep decarbonization pathways in a major way, this is not always the case with the latter, especially in IAM pathways. Comparing different types of global transport models, Yeh et al. (2016) find that sectoral (intensive) studies generally envision greater mitigation potential from structural changes in transport activity and modal choice. Though, even there, it is primarily the switching of passengers and freight from less- to more-efficient travel modes (e.g., cars, trucks and airplanes to buses and trains) that is the main strategy; other actions, such as increasing vehicle load factors (occupancy rates) and outright reductions in travel demand (e.g., as a result of integrated transport, land-use and urban planning), figure much less prominently. Whether these dynamics accurately reflect the actual mitigation potential of structural changes in transport activity and modal choice is a point of investigation. According to the recent IEA-ETP scenarios, the share of avoid (reduction of mobility demand) and shift (shifting to more efficient modes) measures in the reduction of CO₂ emissions from the reference to B2DS scenarios in 2050 amounts to 20% (IEA, 2017a).

The potential and strategies to reduce energy consumption and CO₂ emissions differ significantly among transport modes. In ETP-B2DS, the shares of energy consumption and CO₂ emissions in 2050 for each mode are rather different (see Table 2.8), indicating the challenge of decarbonizing heavy-duty vehicles (HDV, trucks), aviation, and shipping. The reduction of CO₂ emissions in the whole sector from the reference scenario to ETP-B2DS is 60% in 2050, with varying contributions per mode (Table 2.8). Since there is no silver bullet for this deep decarbonization, every possible measure would be required to achieve this stringent emissions outcome. The contribution of various measures for the CO₂ emission reduction from the reference scenario to the IEA-B2DS in 2050 can be decomposed to efficiency improvement (29%), biofuels (36%), electrification (15%), and avoid/shift (20%) (IEA, 2017a). It is noted that the share of electrification becomes larger compared with older studies, reflected by the recent growth of electric vehicle sales worldwide. Another new trend is the allocation of biofuels to each mode of transport. In IEA-B2DS, the total amount of biofuels consumed in the transport sector is 24EJ¹⁰ in 2060, and allocated to LDV (light-duty vehicles, 17%), HDV (35%), aviation (28%), and shipping (21%), that is, more biofuels is allocated to the difficult-to-decarbonize modes (see Table 2.8).

In road transport, incremental vehicle improvements (including engines) are relevant, especially in the short to medium term. Hybrid electric vehicles are also instrumental to enabling the transition from

⁹ In this section, we only discuss the direct emissions from the sector, but the selection of building materials has a significant impact on the reduction of energy and emissions during production, such as shift from the steel and concrete to wood-based materials.

¹⁰ This is estimated for the biofuels produced in a “sustainable manner” from non-food crop feedstocks, which are capable of delivering significant lifecycle GHG emissions savings compared with fossil fuel alternatives, and which do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts.

Table 2.8 | Transport sector indicators by mode in 2050 (IEA, 2017a).

Share of energy consumption, biofuel consumption, CO₂ emissions, and reduction of energy consumption and CO₂ emissions from 2014. (CO₂ emissions are well-to-wheel emissions, including the emission during the fuel production.), LDV: light duty vehicle, HDV: heavy duty vehicle.

	Share of Each Mode (%)			Reduction from 2014 (%)	
	Energy	Biofuel	CO ₂	Energy	CO ₂
LDV	36	17	30	51	81
HDV	33	35	36	8	56
Rail	6	-	-1	-136	107
Aviation	12	28	14	14	56
Shipping	17	21	21	26	29

internal combustion engine vehicles to electric vehicles, especially plug-in hybrid electric vehicles. Electrification is a powerful measure to decarbonize short-distance vehicles (passenger cars and two and three wheelers) and the rail sector. In road freight transport (trucks), systemic improvements (e.g., in supply chains, logistics, and routing) would be effective measures in conjunction with efficiency improvement of vehicles. Shipping and aviation are more challenging to decarbonize, while their demand growth is projected to be higher than other

transport modes. Both modes would need to pursue highly ambitious efficiency improvements and use of low-carbon fuels. In the near and medium term, this would be advanced biofuels while in the long term it could be hydrogen as direct use for shipping or an intermediate product for synthetic fuels for both modes (IEA, 2017a).

The share of low-carbon fuels in the total transport fuel mix increases to 10% and 16% by 2030 and to 40% and 58% by 2050

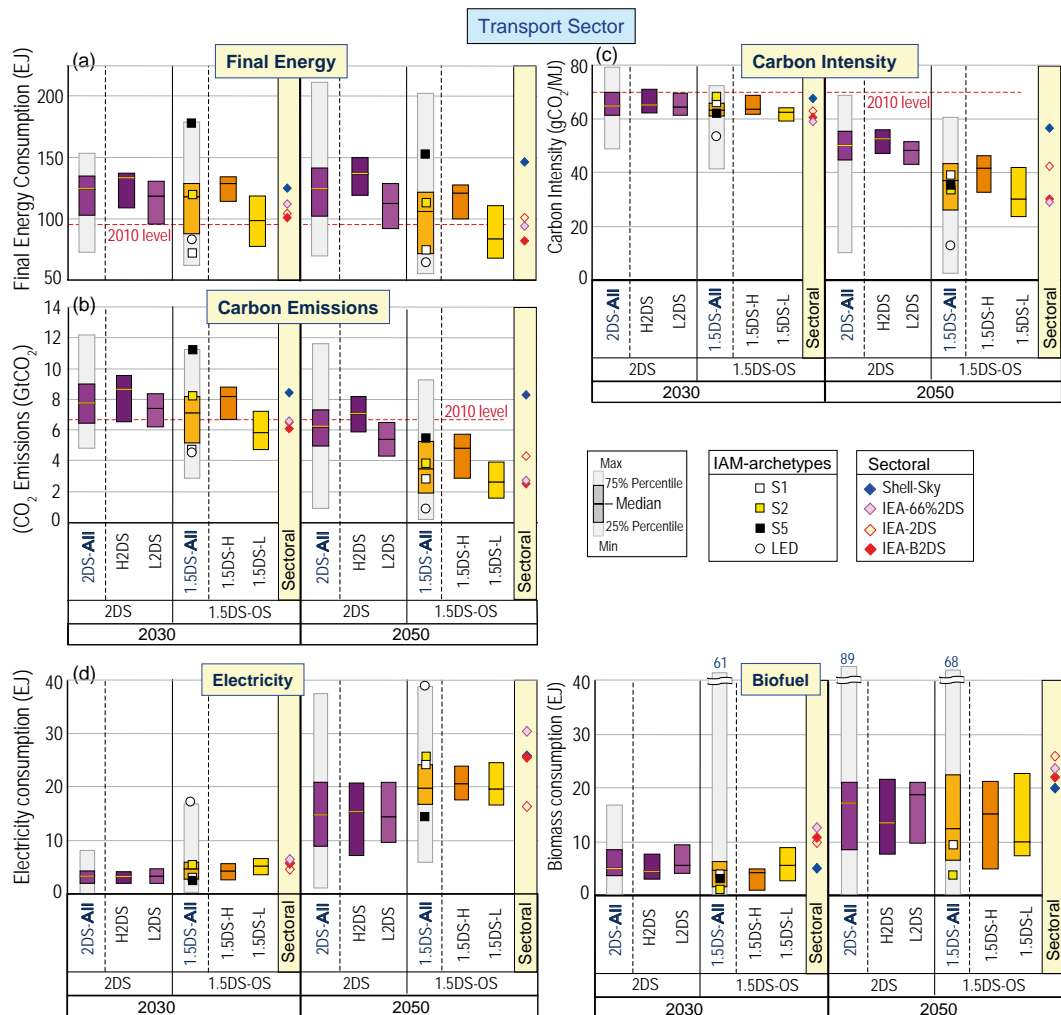


Figure 2.23 | Comparison of (a) final energy, (b) direct CO₂ emissions, (c) carbon intensity, (d) electricity and biofuel consumption in the transport sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS = Higher-2°C, L2DS = Lower-2°C, 1.5DS-H = 1.5°C-high-OS, 1.5DS-L = 1.5°C-low-OS. The label 1.5DS combines both high and low overshoot 1.5°C-consistent pathways. Section 2.1 for descriptions.

in 1.5°C-overshoot pathways from IAMs and the IEA-B2DS pathway, respectively. The IEA-B2DS scenario is on the more ambitious side, especially in the share of electricity. Hence, there is wide variation among scenarios, including the IAM pathways, regarding changes in the transport fuel mix over the first half of the century. As seen in Figure 2.23, the projections of energy consumption, CO₂ emissions and carbon intensity are quite different between IAM and ETP scenarios. These differences can be explained by more weight on efficiency improvements and avoid/shift decreasing energy consumption, and the higher share of biofuels and electricity accelerating the speed of decarbonization in ETP scenarios. Although biofuel consumption and electric vehicle sales have increased significantly in recent years, the growth rates projected in these pathways would be unprecedented and far higher than has been experienced to date.

The 1.5°C pathways require an acceleration of the mitigation solutions already featured in 2°C-consistent pathways (e.g., more efficient vehicle technologies operating on lower-carbon fuels), as well as those having received lesser attention in most global transport decarbonization pathways up to now (e.g., mode-shifting and travel demand management). Current-generation, global pathways generally do not include these newer transport sector developments, whereby technological solutions are related to shifts in traveller's behaviour.

2.4.4 Land-Use Transitions and Changes in the Agricultural Sector

The agricultural and land system described together under the umbrella of the AFOLU (agriculture, forestry, and other land use) sector plays an important role in 1.5°C pathways (Clarke et al., 2014; Smith and Bustamante, 2014; Popp et al., 2017). On the one hand, its emissions need to be limited over the course of this century to be in line with pathways limiting warming to 1.5°C (see Sections 2.2-3). On the other hand, the AFOLU system is responsible for food and feed production; for wood production for pulp and construction; for the production of biomass that is used for energy, CDR or other uses; and for the supply of non-provisioning (ecosystem) services (Smith and Bustamante, 2014). Meeting all demands together requires changes in land use, as well as in agricultural and forestry practices, for which a multitude of potential options have been identified (Smith and Bustamante, 2014; Popp et al., 2017) (see also Supplementary Material 2.SM.1.2 and Chapter 4, Section 4.3.1, 4.3.2 and 4.3.7).

This section assesses the transformation of the AFOLU system, mainly making use of pathways from IAMs (see Section 2.1) that are based on quantifications of the SSPs and that report distinct land-use evolutions in line with limiting warming to 1.5°C (Calvin et al., 2017; Fricko et al., 2017; Fujimori, 2017; Kriegler et al., 2017; Popp et al., 2017; Riahi et al., 2017; van Vuuren et al., 2017b; Doelman et al., 2018; Rogelj et al., 2018). The SSPs were designed to vary mitigation challenges (O'Neill et al., 2014) (Cross-Chapter Box 1 in Chapter 1), including for the AFOLU sector (Popp et al., 2017; Riahi et al., 2017). The SSP pathway ensemble hence allows for a structured exploration of AFOLU transitions in the context of climate change mitigation in line with 1.5°C, taking into account technological and socio-economic aspects. Other considerations, like food security, livelihoods and biodiversity, are also of importance when identifying AFOLU strategies. These are

at present only tangentially explored by the SSPs. Further assessments of AFOLU mitigation options are provided in other parts of this report and in the IPCC Special Report on Climate Change and Land (SRCL). Chapter 4 provides an assessment of bioenergy (including feedstocks, see Section 4.3.1), livestock management (Section 4.3.1), reducing rates of deforestation and other land-based mitigation options (as mitigation and adaptation option, see Section 4.3.2), and BECCS, afforestation and reforestation options (including the bottom-up literature of their sustainable potential, mitigation cost and side effects, Section 4.3.7). Chapter 3 discusses impacts land-based CDR (Cross-Chapter Box 7 in Chapter 3). Chapter 5 assesses the sustainable development implications of AFOLU mitigation, including impacts on biodiversity (Section 5.4). Finally, the SRCL will undertake a more comprehensive assessment of land and climate change aspects. For the sake of complementarity, this section focusses on the magnitude and pace of land transitions in 1.5°C pathways, as well as on the implications of different AFOLU mitigation strategies for different land types. The interactions with other societal objectives and potential limitations of identified AFOLU measures link to these large-scale evolutions, but these are assessed elsewhere (see above).

Land-use changes until mid-century occur in the large majority of SSP pathways, both under stringent mitigation and in absence of mitigation (Figure 2.24). In the latter case, changes are mainly due to socio-economic drivers like growing demands for food, feed and wood products. General transition trends can be identified for many land types in 1.5°C pathways, which differ from those in baseline scenarios and depend on the interplay with mitigation in other sectors (Figure 2.24) (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Mitigation that demands land mainly occurs at the expense of agricultural land for food and feed production. Additionally, some biomass is projected to be grown on marginal land or supplied from residues and waste, but at lower shares. Land for second-generation energy crops (such as *Miscanthus* or poplar) expands by 2030 and 2050 in all available pathways that assume a cost-effective achievement of a 1.5°C temperature goal in 2100 (Figure 2.24), but the scale depends strongly on underlying socio-economic assumptions (see later discussion of land pathway archetypes). Reducing rates of deforestation restricts agricultural expansion, and forest cover can expand strongly in 1.5°C and 2°C pathways alike compared to its extent in no-climate-policy baselines due to reduced deforestation and afforestation and reforestation measures. However, the extent to which forest cover expands varies highly across models in the literature, with some models projecting forest cover to stay virtually constant or decline slightly. This is due to whether afforestation and reforestation is included as a mitigation technology in these pathways and interactions with other sectors.

As a consequence of other land-use changes, pasture land is generally projected to be reduced compared to both baselines in which no climate change mitigation action is undertaken and 2°C-consistent pathways. Furthermore, cropland for food and feed production decreases in most 1.5°C pathways, both compared to a no-climate baseline and relative to 2010. These reductions in agricultural land for food and feed production are facilitated by intensification on agricultural land and in livestock production systems (Popp et al., 2017), as well as changes in consumption patterns (Frank et al., 2017; Fujimori, 2017) (see

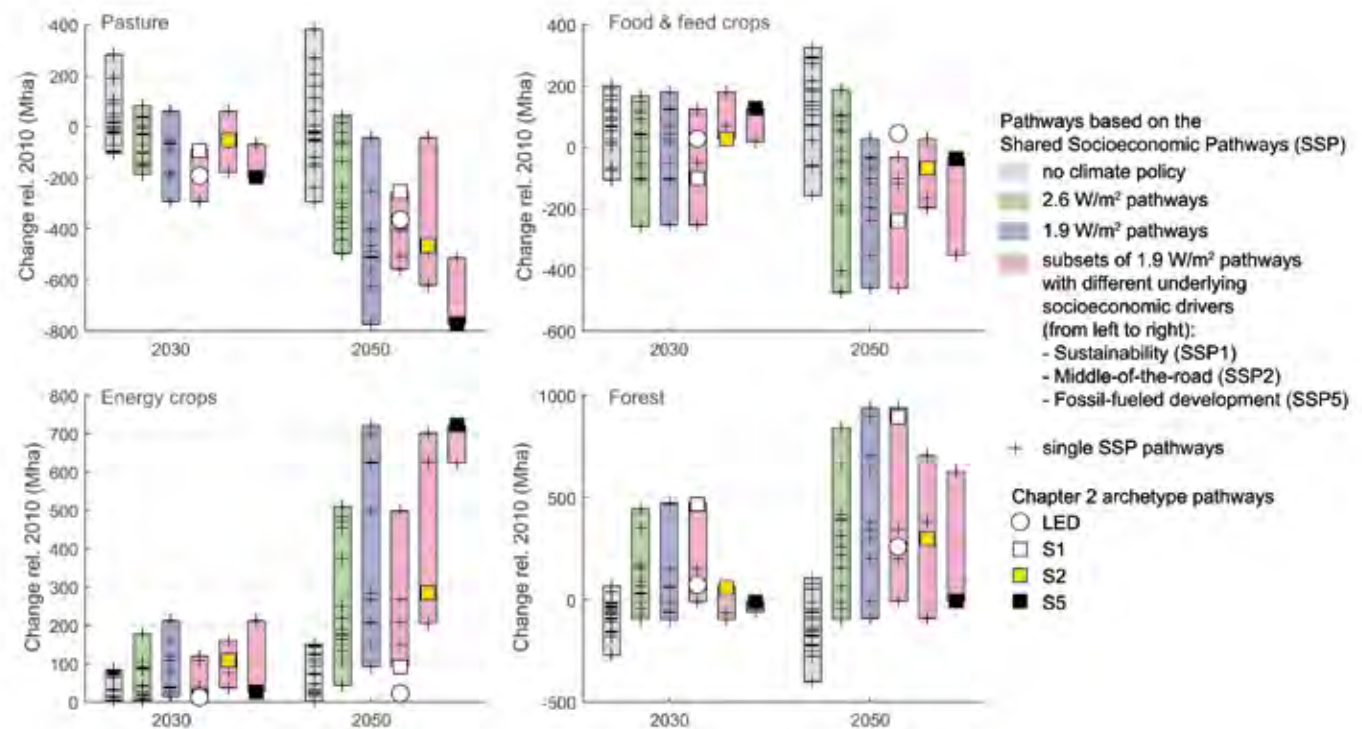


Figure 2.24 | Overview of land-use change transitions in 2030 and 2050, relative to 2010 based on pathways based on the Shared Socio-Economic Pathways (SSPs) (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Grey: no-climate-policy baseline; green: 2.6 W m^{-2} pathways; blue: 1.9 W m^{-2} pathways. Pink: 1.9 W m^{-2} pathways grouped per underlying socio-economic assumption (from left to right: SSP1 sustainability, SSP2 middle-of-the-road, SSP5 fossil-fueled development). Ranges show the minimum–maximum range across the SSPs. Single pathways are shown with plus signs. Illustrative archetype pathways are highlighted with distinct icons. Each panel shows the changes for a different land type. The 1.9 and 2.6 W m^{-2} pathways are taken as proxies for 1.5°C and 2°C pathways, respectively. The 2.6 W m^{-2} pathways are mostly consistent with the Lower- 2°C and Higher- 2°C pathway classes. The 1.9 W m^{-2} pathways are consistent with the 1.5°C -low-OS (mostly SSP1 and SSP2) and 1.5°C -high-OS (SSP5) pathway classes. In 2010, pasture was estimated to cover about 3–3.5 103 Mha, food and feed crops about 1.5–1.6 103 Mha, energy crops about 0–14 Mha and forest about 3.7–4.2 103 Mha, across the models that reported SSP pathways (Popp et al., 2017). When considering pathways limiting warming to 1.5°C with no or limited overshoot, the full set of scenarios shows a conversion of 50–1100 Mha of pasture into 0–600 Mha for energy crops, a 200 Mha reduction to 950 Mha increase forest, and a 400 Mha decrease to a 250 Mha increase in non-pasture agricultural land for food and feed crops by 2050 relative to 2010. The large range across the literature and the understanding of the variations across models and assumptions leads to *medium confidence* in the size of these ranges.

also Chapter 4, Section 4.3.2 for an assessment of these mitigation options). For example, in a scenario based on rapid technological progress (Kriegler et al., 2017), global average cereal crop yields in 2100 are assumed to be above $5 \text{ tDM ha}^{-1} \text{ yr}^{-1}$ in mitigation scenarios aiming at limiting end-of-century radiative forcing to 4.5 or 2.6 W m^{-2} , compared to $4 \text{ tDM ha}^{-1} \text{ yr}^{-1}$ in the SSP5 baseline to ensure the same food production. Similar improvements are present in 1.5°C variants of such scenarios. Historically, cereal crop yields are estimated at $1 \text{ tDM ha}^{-1} \text{ yr}^{-1}$ and about $3 \text{ tDM ha}^{-1} \text{ yr}^{-1}$ in 1965 and 2010, respectively (calculations based on FAOSTAT, 2018). For aggregate energy crops, models assume 4.2 – $8.9 \text{ tDM ha}^{-1} \text{ yr}^{-1}$ in 2010, increasing to about 6.9 – $17.4 \text{ tDM ha}^{-1} \text{ yr}^{-1}$ in 2050, which fall within the range found in the bottom-up literature yet depend on crop, climatic zone, land quality and plot size (Searle and Malins, 2014).

The pace of projected land transitions over the coming decades can differ strongly between 1.5°C and baseline scenarios without climate change mitigation and from historical trends (Table 2.9). However, there is uncertainty in the sign and magnitude of these future land-use changes (Prestele et al., 2016; Popp et al., 2017; Doelman et al., 2018). The pace of projected cropland changes overlaps with historical trends over the past four decades, but in several cases also goes well beyond this range. By the 2030–2050 period, the projected reductions

in pasture and potentially strong increases in forest cover imply a reversed dynamic compared to historical and baseline trends. This suggests that distinct policy and government measures would be needed to achieve forest increases, particularly in a context of projected increased bioenergy use.

Changes in the AFOLU sector are driven by three main factors: demand changes, efficiency of production, and policy assumptions (Smith et al., 2013; Popp et al., 2017). Demand for agricultural products and other land-based commodities is influenced by consumption patterns (including dietary preferences and food waste affecting demand for food and feed) (Smith et al., 2013; van Vuuren et al., 2018), demand for forest products for pulp and construction (including less wood waste), and demand for biomass for energy production (Lambin and Meyfroidt, 2011; Smith and Bustamante, 2014). Efficiency of agricultural and forestry production relates to improvements in agricultural and forestry practices (including product cascades, by-products and more waste- and residue-based biomass for energy production), agricultural and forestry yield increases, and intensification of livestock production systems leading to higher feed efficiency and changes in feed composition (Havlik et al., 2014; Weindl et al., 2015). Policy assumptions relate to the level of land protection, the treatment of food waste, policy choices about the timing of mitigation action (early vs late), the choice and

Table 2.9 | Annual pace of land-use change in baseline, 2°C and 1.5°C pathways.

All values in Mha yr⁻¹. The 2.6 W m⁻² pathways are mostly consistent with the Lower-2°C and Higher-2°C pathway classes. The 1.9 W m⁻² pathways are broadly consistent with the 1.5°C-low-OS (mostly SSP1 and SSP2) and 1.5°C-high-OS (SSP5) pathway classes. Baseline projections reflect land-use developments projected by integrated assessment models under the assumptions of the Shared Socio-Economic Pathways (SSPs) in absence of climate policies (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Values give the full range across SSP scenarios. According to the Food and Agriculture Organization of the United Nations (FAOSTAT, 2018), 4.9 billion hectares (approximately 40% of the land surface) was under agricultural use in 2005, either as cropland (1.5 billion hectares) or pasture (3.4 billion hectares). FAO data in the table are equally from FAOSTAT (2018).

Annual Pace of Land-Use Change [Mha yr ⁻¹]					
Land Type	Pathway	Time Window		Historical	
		2010–2030	2030–2050	1970–1990	1990–2010
Pasture	1.9 W m ⁻²	[-14.6/3.0]	[-28.7/-5.2]	8.7 Permanent meadows and pastures (FAO)	0.9 Permanent meadows and pastures (FAO)
	2.6 W m ⁻²	[-9.3/4.1]	[-21.6/0.4]		
	Baseline	[-5.1/14.1]	[-9.6/9.0]		
Cropland for food, feed and material	1.9 W m ⁻²	[-12.7/9.0]	[-18.5/0.1]		
	2.6 W m ⁻²	[-12.9/8.3]	[-16.8/2.3]		
	Baseline	[-5.3/9.9]	[-2.7/6.7]		
Cropland for energy	1.9 W m ⁻²	[0.7/10.5]	[3.9/34.8]		
	2.6 W m ⁻²	[0.2/8.8]	[2.0/22.9]		
	Baseline	[0.2/4.2]	[-0.2/6.1]		
Total cropland (Sum of cropland for food and feed & energy)	1.9 W m ⁻²	[-6.8/12.8]	[-5.8/26.7]	4.6 Arable land and Permanent crops	0.9 Arable land and Permanent crops
	2.6 W m ⁻²	[-8.4/9.3]	[-7.1/17.8]		
	Baseline	[-3.0/11.3]	[0.6/11.0]		
Forest	1.9 W m ⁻²	[-4.8/23.7]	[0.0/34.3]	N.A. Forest (FAO)	-5.6 Forest (FAO)
	2.6 W m ⁻²	[-4.7/22.2]	[-2.4/31.7]		
	Baseline	[-13.6/3.3]	[-6.5/4.3]		

preference of land-based mitigation options (for example, the inclusion of afforestation and reforestation as mitigation options), interactions with other sectors (Popp et al., 2017), and trade (Schmitz et al., 2012; Wiebe et al., 2015).

A global study (Stevanović et al., 2017) reported similar GHG reduction potentials for both production-side (agricultural production measures in combination with reduced deforestation) and consumption-side (diet change in combination with lower shares of food waste) measures on the order of 40% in 2100¹¹ (compared to a baseline scenario without land-based mitigation). Lower consumption of livestock products by 2050 could also substantially reduce deforestation and cumulative carbon losses (Weindl et al., 2017). On the supply side, minor productivity growth in extensive livestock production systems is projected to lead to substantial CO₂ emission abatement, but the emission-saving potential of productivity gains in intensive systems is limited, mainly due to trade-offs with soil carbon stocks (Weindl et al., 2017). In addition, even within existing livestock production systems, a transition from extensive to more productive systems bears substantial GHG abatement potential, while improving food availability (Gerber et al., 2013; Havlik et al., 2014). Many studies highlight the capability of agricultural intensification for reducing GHG emissions in the AFOLU sector or even enhancing terrestrial carbon stocks (Valin et al., 2013; Popp et al., 2014a; Wise et al., 2014). Also the importance of immediate and global land-use regulations for a comprehensive reduction of

land-related GHG emissions (especially related to deforestation) has been shown by several studies (Calvin et al., 2017; Fricko et al., 2017; Fujimori, 2017). Ultimately, there are also interactions between these three factors and the wider society and economy, for example, if CDR technologies that are not land-based are deployed (like direct air capture – DACCS, see Chapter 4, Section 4.3.7) or if other sectors over- or underachieve their projected mitigation contributions (Clarke et al., 2014). Variations in these drivers can lead to drastically different land-use implications (Popp et al., 2014b) (Figure 2.24).

Stringent mitigation pathways inform general GHG dynamics in the AFOLU sector. First, CO₂ emissions from deforestation can be abated at relatively low carbon prices if displacement effects in other regions (Calvin et al., 2017) or other land-use types with high carbon density (Calvin et al., 2014; Popp et al., 2014a; Kriegler et al., 2017) can be avoided. However, efficiency and costs of reducing rates of deforestation strongly depend on governance performance, institutions and macroeconomic factors (Wang et al., 2016). Secondly, besides CO₂ reductions, the land system can play an important role for overall CDR efforts (Rogelj et al., 2018) via BECCS, afforestation and reforestation, or a combination of options. The AFOLU sector also provides further potential for active terrestrial carbon sequestration, for example, via land restoration, improved management of forest and agricultural land (Griscom et al., 2017), or biochar applications (Smith, 2016) (see also Chapter 4, Section 4.3.7). These options have so far

¹¹ Land-based mitigation options on the supply and the demand side are assessed in 4.3.2, and CDR options with a land component in 4.3.7. Chapter 5 (Section 5.4) assesses the implications of land-based mitigation for related SDGs, e.g., food security.

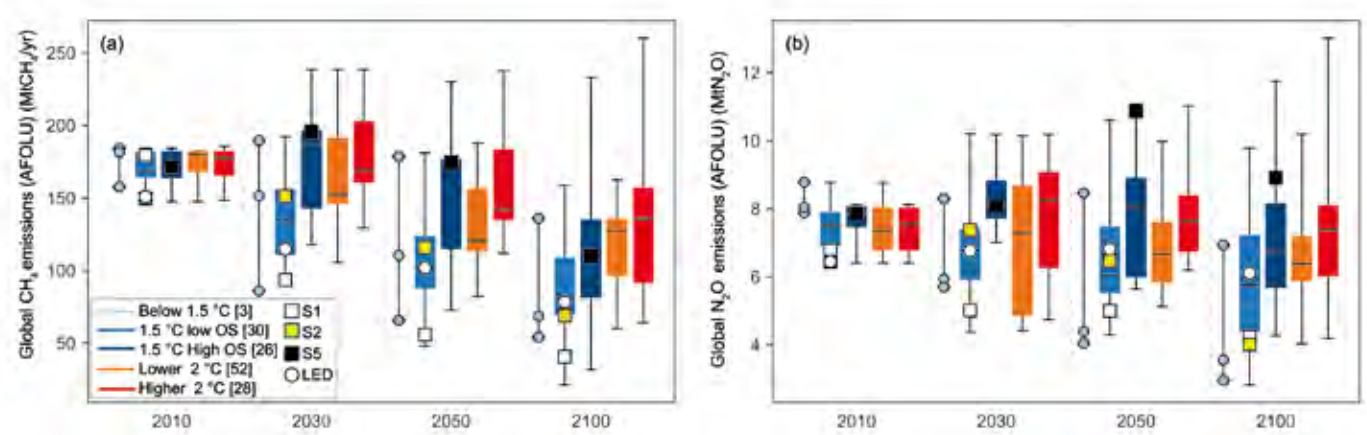


Figure 2.25 | Agricultural emissions in transformation pathways. Global agricultural (a) CH₄ and (b) N₂O emissions. Box plots show median, interquartile range and full range. Classes are defined in Section 2.1.

not been extensively integrated in the mitigation pathway literature (see Supplementary Material 2.SM.1.2), but in theory their availability would impact the deployment of other CDR technologies, like BECCS (Section 2.3.4) (Strefler et al., 2018a). These interactions will be discussed further in the SRCCL.

Residual agricultural non-CO₂ emissions of CH₄ and N₂O play an important role for temperature stabilization pathways, and their relative importance increases in stringent mitigation pathways in which CO₂ is reduced to net zero emissions globally (Gernaat et al., 2015; Popp et al., 2017; Stevanović et al., 2017; Rogelj et al., 2018), for example, through their impact on the remaining carbon budget (Section 2.2). Although agricultural non-CO₂ emissions show marked reduction potentials in 2°C-consistent pathways, complete elimination of these emission sources does not occur in IAMs based on the evolution of agricultural practice assumed in integrated models (Figure 2.25) (Gernaat et al., 2015). Methane emissions in 1.5°C pathways are reduced through improved agricultural management (e.g., improved management of water in rice production, manure and herds, and better livestock quality through breeding and improved feeding practices) as well as dietary shifts away from emissions-intensive livestock products. Similarly, N₂O emissions decrease due to improved N-efficiency and manure management (Frank et al., 2018). However, high levels of bioenergy production can also result in increased N₂O emissions (Kriegler et al., 2017), highlighting the importance of appropriate management approaches (Davis et al., 2013). Residual agricultural emissions can be further reduced by limiting demand for GHG-intensive foods through shifts to healthier and more sustainable diets (Tilman and Clark, 2014; Erb et al., 2016b; Springmann et al., 2016) and reductions in food waste (Bajželj et al., 2014; Muller et al., 2017; Popp et al., 2017) (see also Chapter 4 and SRCCL). Finally, several mitigation measures that could affect these agricultural non-CO₂ emissions are not, or only to a limited degree, considered in the current integrated pathway literature (see Supplementary Material 2.SM.1.2). Such measures (like plant-based and synthetic proteins, methane inhibitors and vaccines in livestock, alternate wetting and drying in paddy rice, or nitrification inhibitors) are very diverse and differ in their development or deployment stages. Their potentials have not been explicitly assessed here.

Pathways consistent with 1.5°C rely on one or more of the three strategies highlighted above (demand changes, efficiency gains, and

policy assumptions), and can apply these in different configurations. For example, among the four illustrative archetypes used in this chapter (Section 2.1), the LED and S1 pathways focus on generally low resource and energy consumption (including healthy diets with low animal-calorie shares and low food waste) as well as significant agricultural intensification in combination with high levels of nature protection. Under such assumptions, comparably small amounts of land are needed for land-demanding mitigation activities such as BECCS and afforestation and reforestation, leaving the land footprint for energy crops in 2050 virtually the same compared to 2010 levels for the LED pathway. In contrast, future land-use developments can look very different under the resource- and energy-intensive S5 pathway that includes less healthy diets with high animal shares and high shares of food waste (Tilman and Clark, 2014; Springmann et al., 2016) combined with a strong orientation towards technology solutions to compensate for high reliance on fossil-fuel resources and associated high levels of GHG emissions in the baseline. In such pathways, climate change mitigation strategies strongly depend on the availability of CDR through BECCS (Humpeöder et al., 2014). As a consequence, the S5 pathway sources significant amounts of biomass through bioenergy crop expansion in combination with agricultural intensification. Also, further policy assumptions can strongly affect land-use developments, highlighting the importance for land use of making appropriate policy choices. For example, within the SSP set, some pathways rely strongly on a policy to incentivize afforestation and reforestation for CDR together with BECCS, which results in an expansion of forest area and a corresponding increase in terrestrial carbon stock. Finally, the variety of pathways illustrates how policy choices in the AFOLU and other sectors strongly affect land-use developments and associated sustainable development interactions (Chapter 5, Section 5.4) in 1.5°C pathways.

The choice of strategy or mitigation portfolio impacts the GHG dynamics of the land system and other sectors (see Section 2.3), as well as the synergies and trade-offs with other environmental and societal objectives (see Section 2.5.3 and Chapter 5, Section 5.4). For example, AFOLU developments in 1.5°C pathways range from strategies that differ by almost an order of magnitude in their projected land requirements for bioenergy (Figure 2.24), and some strategies would allow an increase in forest cover over the 21st century compared to strategies under which forest cover remains approximately constant.

High agricultural yields and application of intensified animal husbandry, implementation of best-available technologies for reducing non-CO₂ emissions, or lifestyle changes including a less-meat-intensive diet and less CO₂-intensive transport modes, have been identified as allowing for such a forest expansion and reduced footprints from bioenergy without compromising food security (Frank et al., 2017; Doelman et al., 2018; van Vuuren et al., 2018).

The IAMs used in the pathways underlying this assessment (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018) do not include all potential land-based mitigation options and side-effects, and their results are hence subject to uncertainty. For example, recent research has highlighted the potential impact of forest management practices on land carbon content (Erb et al., 2016a; Naudts et al., 2016) and the uncertainty surrounding future crop yields (Haberl et al., 2013; Searle and Malins, 2014) and water availability (Liu et al., 2014). These aspects are included in IAMs in varying degrees but were not assessed in this report. Furthermore, land-use modules of some IAMs can depict spatially resolved climate damages to agriculture (Nelson et al., 2014), but this option was not used in the SSP quantifications (Riahi et al., 2017). Damages (e.g., due to ozone exposure or varying indirect fertilization due to atmospheric N and Fe deposition (e.g., Shindell et al., 2012; Mahowald et al., 2017) are also not included. Finally, this assessment did not look into the literature of agricultural sector models which could provide important additional detail and granularity to the discussion presented here.¹² This limits their ability to capture the full mitigation potentials and benefits between scenarios. An in-depth assessment of these aspects lies outside the scope of this Special Report. However, their existence affects the confidence assessment of the AFOLU transition in 1.5°C pathways.

Despite the limitations of current modelling approaches, there is *high agreement* and *robust evidence* across models and studies that the AFOLU sector plays an important role in stringent mitigation pathways. The findings from these multiple lines of evidence also result in *high confidence* that AFOLU mitigation strategies can vary significantly based on preferences and policy choices, facilitating the exploration of strategies that can achieve multiple societal objectives simultaneously (see also Section 2.5.3). At the same time, given the many uncertainties and limitations, only *low to medium confidence* can be attributed by this assessment to the more extreme AFOLU developments found in the pathway literature, and *low to medium confidence* to the level of residual non-CO₂ emissions.

2.5 Challenges, Opportunities and Co-Impacts of Transformative Mitigation Pathways

This section examines aspects other than climate outcomes of 1.5°C mitigation pathways. Focus is given to challenges and opportunities related to policy regimes, price of carbon and co-impacts, including sustainable development issues, which can be derived from the existing integrated pathway literature. Attention is also given to uncertainties and critical assumptions underpinning mitigation pathways. The

challenges and opportunities identified in this section are further elaborated Chapter 4 (e.g., policy choice and implementation) and Chapter 5 (e.g., sustainable development). The assessment indicates unprecedented policy and geopolitical challenges.

2.5.1 Policy Frameworks and Enabling Conditions

Moving from a 2°C to a 1.5°C pathway implies bold integrated policies that enable higher socio-technical transition speeds, larger deployment scales, and the phase-out of existing systems that may lock in emissions for decades (*high confidence*) (Geels et al., 2017; Kuramochi et al., 2017; Rockström et al., 2017; Vogt-Schilb and Hallegatte, 2017; Kriegler et al., 2018a; Michaelowa et al., 2018). This requires higher levels of transformative policy regimes in the near term, which allow deep decarbonization pathways to emerge and a net zero carbon energy–economy system to emerge in the 2040–2060 period (Rogelj et al., 2015b; Bataille et al., 2016b). This enables accelerated levels of technological deployment and innovation (Geels et al., 2017; IEA, 2017a; Grubler et al., 2018) and assumes more profound behavioural, economic and political transformation (Sections 2.3, 2.4 and 4.4). Despite inherent levels of uncertainty attached to modelling studies (e.g., related to climate and carbon cycle response), studies stress the urgency for transformative policy efforts to reduce emissions in the short term (Riahi et al., 2015; Kuramochi et al., 2017; Rogelj et al., 2018).

The available literature indicates that mitigation pathways in line with 1.5°C pathways would require stringent and integrated policy interventions (*very high confidence*). Higher policy ambition often takes the form of stringent economy-wide emission targets (and resulting peak-and-decline of emissions), larger coverage of NDCs to more gases and sectors (e.g., land-use, international aviation), much lower energy and carbon intensity rates than historically seen, carbon prices much higher than the ones observed in real markets, increased climate finance, global coordinated policy action, and implementation of additional initiatives (e.g., by non-state actors) (Sections 2.3, 2.4 and 2.5.2). The diversity (beyond explicit carbon pricing) and effectiveness of policy portfolios are of prime importance, particularly in the short-term (Mundaca and Markandya, 2016; Kuramochi et al., 2017; OECD, 2017; Kriegler et al., 2018a; Michaelowa et al., 2018). For instance, deep decarbonization pathways in line with a 2°C target (covering 74% of global energy-system emissions) include a mix of stringent regulation (e.g., building codes, minimum performance standards), carbon pricing mechanisms and R&D (research and development) innovation policies (Bataille et al., 2016a). Explicit carbon pricing, direct regulation and public investment to enable innovation are critical for deep decarbonization pathways (Grubb et al., 2014). Effective planning (including compact city measures) and integrated regulatory frameworks are also key drivers in the IEA-ETP B2DS study for the transport sector (IEA, 2017a). Effective urban planning can reduce GHG emissions from urban transport between 20% and 50% (Creutzig, 2016). Comprehensive policy frameworks would be needed if the decarbonization of the power system is pursued while increasing end-use electrification (including transport) (IEA, 2017a). Technology policies (e.g., feed-in-tariffs), financing instruments, carbon pricing

¹² For example, the GLEAM (<http://www.fao.org/gleam/en/>) model from the UN Food and Agricultural Organisation (FAO).

and system integration management driving the rapid adoption of renewable energy technologies are critical for the decarbonization of electricity generation (Bruckner et al., 2014; Luderer et al., 2014; Creutzig et al., 2017; Pietzcker et al., 2017). Likewise, low-carbon and resilient investments are facilitated by a mix of coherent policies, including fiscal and structural reforms (e.g., labour markets), public procurement, carbon pricing, stringent standards, information schemes, technology policies, fossil-fuel subsidy removal, climate risk disclosure, and land-use and transport planning (OECD, 2017). Pathways in which CDR options are restricted emphasize the strengthening of near-term policy mixes (Luderer et al., 2013; Kriegler et al., 2018a). Together with the decarbonization of the supply side, ambitious policies targeting fuel switching and energy efficiency improvements on the demand side play a major role across mitigation pathways (Clarke et al., 2014; Kriegler et al., 2014b; Riahi et al., 2015; Kuramochi et al., 2017; Brown and Li, 2018; Rogelj et al., 2018; Wachsmuth and Duscha, 2018).

The combined evidence suggests that aggressive policies addressing energy efficiency are central in keeping 1.5°C within reach and lowering energy system and mitigation costs (*high confidence*) (Luderer et al., 2013; Rogelj et al., 2013b, 2015b; Grubler et al., 2018). Demand-side policies that increase energy efficiency or limit energy demand at a higher rate than historically observed are critical enabling factors for reducing mitigation costs in stringent mitigation pathways across the board (Luderer et al., 2013; Rogelj et al., 2013b, 2015b; Clarke et al., 2014; Bertram et al., 2015a; Bataille et al., 2016b). Ambitious sector-specific mitigation policies in industry, transportation and residential sectors are needed in the short run for emissions to peak in 2030 (Méjean et al., 2018). Stringent demand-side policies (e.g., tightened efficiency standards for buildings and appliances) driving the expansion, efficiency and provision of high-quality energy services are essential to meet a 1.5°C mitigation target while reducing the reliance on CDR (Grubler et al., 2018). A 1.5°C pathway for the transport sector is possible using a mix of additional and stringent policy actions preventing (or reducing) the need for transport, encouraging shifts towards efficient modes of transport, and improving vehicle-fuel efficiency (Gota et al., 2018). Stringent demand-side policies also reduce the need for CCS (Wachsmuth and Duscha, 2018). Even in the presence of weak near term policy frameworks, increased energy efficiency lowers mitigation costs noticeably compared to pathways with reference energy intensity (Bertram et al., 2015a). Common issues in the literature relate to the rebound effect, the potential overestimation of the effectiveness of energy efficiency policy, and policies to counteract the rebound (Saunders, 2015; van den Bergh, 2017; Grubler et al., 2018) (Sections 2.4 and 4.4).

SSP-based modelling studies underline that socio-economic and climate policy assumptions strongly influence mitigation pathway characteristics and the economics of achieving a specific climate target (*very high confidence*) (Bauer et al., 2017; Guivarch and Rogelj, 2017; Riahi et al., 2017; Rogelj et al., 2018). SSP assumptions related to economic growth and energy intensity are critical determinants of projected CO₂ emissions (Marangoni et al., 2017). A multimodel inter-comparison study found that mitigation challenges in line with a 1.5°C target vary substantially across SSPs and policy assumptions (Rogelj et al., 2018). Under SSP1-SPA1 (sustainability) and SSP2-SPA2 (middle-of-the-road), the majority of IAMs were capable of producing

1.5°C pathways. On the contrary, none of the IAMs contained in the SR1.5 database could produce a 1.5°C pathway under SSP3-SPA3 assumptions. Preventing elements include, for instance, climate policy fragmentation, limited control of land-use emissions, heavy reliance on fossil fuels, unsustainable consumption and marked inequalities (Rogelj et al., 2018). Dietary aspects of the SSPs are also critical: climate-friendly diets were contained in 'sustainability' (SSP1) and meat-intensive diets in SSP3 and SSP5 (Popp et al., 2017). CDR requirements are reduced under 'sustainability' related assumptions (Strefler et al., 2018b). These are major policy-related reasons for why SSP1-SPA1 translates into relatively low mitigation challenges whereas SSP3-SPA3 and SSP5-SPA5 entail futures that pose the highest socio-technical and economic challenges. SSPs/SPAs assumptions indicate that policy-driven pathways that encompass accelerated change away from fossil fuels, large-scale deployment of low-carbon energy supplies, improved energy efficiency and sustainable consumption lifestyles reduce the risks of climate targets becoming unreachable (Clarke et al., 2014; Riahi et al., 2015, 2017; Marangoni et al., 2017; Rogelj et al., 2017, 2018; Strefler et al., 2018b).

Policy assumptions that lead to weak or delayed mitigation action from what would be possible in a fully cooperative world strongly influence the achievability of mitigation targets (*high confidence*) (Luderer et al., 2013; Rogelj et al., 2013b; OECD, 2017; Holz et al., 2018a; Strefler et al., 2018b). Such regimes also include current NDCs (Fawcett et al., 2015; Aldy et al., 2016; Rogelj et al., 2016a, 2017; Hof et al., 2017; van Soest et al., 2017), which have been reported to make achieving a 2°C pathway unattainable without CDR (Strefler et al., 2018b). Not strengthening NDCs would make it very challenging to keep 1.5°C within reach (see Section 2.3 and Cross-Chapter Box 11 in Chapter 4). One multimodel inter-comparison study (Luderer et al., 2016b, 2018) explored the effects on 1.5°C pathways assuming the implementation of current NDCs until 2030 and stringent reductions thereafter. It finds that delays in globally coordinated actions lead to various models reaching no 1.5°C pathways during the 21st century. Transnational emission reduction initiatives (TERIs) outside the UNFCCC have also been assessed and found to overlap (70–80%) with NDCs and be inadequate to bridge the gap between NDCs and a 2°C pathway (Roelfsema et al., 2018). Weak and fragmented short-term policy efforts use up a large share of the long-term carbon budget before 2030–2050 (Bertram et al., 2015a; van Vuuren et al., 2016) and increase the need for the full portfolio of mitigation measures, including CDR (Clarke et al., 2014; Riahi et al., 2015; Xu and Ramanathan, 2017). Furthermore, fragmented policy scenarios also exhibit 'carbon leakage' via energy and capital markets (Arroyo-Currás et al., 2015; Kriegler et al., 2015b). A lack of integrated policy portfolios can increase the risks of trade-offs between mitigation approaches and sustainable development objectives (see Sections 2.5.3 and 5.4). However, more detailed analysis is needed about realistic (less disruptive) policy trajectories until 2030 that can strengthen near-term mitigation action and meaningfully decrease post-2030 challenges (see Chapter 4, Section 4.4).

Whereas the policy frameworks and enabling conditions identified above pertain to the 'idealized' dimension of mitigation pathways, aspects related to 1.5°C mitigation pathways in practice are of prime importance. For example, issues related to second-best stringency levels, international cooperation, public acceptance, distributional

consequences, multilevel governance, non-state actions, compliance levels, capacity building, rebound effects, linkages across highly heterogeneous policies, sustained behavioural change, finance and intra- and inter-generational issues need to be considered (see Chapter 4, Section 4.4) (Bataille et al., 2016a; Mundaca and Markandya, 2016; Baranzini et al., 2017; MacDougall et al., 2017; van den Bergh, 2017; Vogt-Schilb and Hallegatte, 2017; Chan et al., 2018; Holz et al., 2018a; Klinsky and Winkler, 2018; Michaelowa et al., 2018; Patterson et al., 2018). Furthermore, policies interact with a wide portfolio of pre-existing policy instruments that address multiple areas (e.g., technology markets, economic growth, poverty alleviation, climate adaptation) and deal with various market failures (e.g., information asymmetries) and behavioural aspects (e.g., heuristics) that prevent or hinder mitigation actions (Kolstad et al., 2014; Mehling and Tvinneim, 2018). The socio-technical transition literature points to multiple complexities in real-world settings that prevent reaching 'idealized' policy conditions but at the same time can still accelerate transformative change through other co-evolutionary processes of technology and society (Geels et

al., 2017; Rockström et al., 2017). Such co-processes are complex and go beyond the role of policy (including carbon pricing) and comprise the role of citizens, businesses, stakeholder groups or governments, as well as the interplay of institutional and socio-political dimensions (Michaelowa et al., 2018; Veland et al., 2018). It is argued that large system transformations, similar to those in 1.5°C pathways, require prioritizing an evolutionary and behavioural framework in economic theory rather than an optimization or equilibrium framework as is common in current IAMs (Grubb et al., 2014; Patt, 2017). Accumulated know-how, accelerated innovation and public investment play a key role in (rapid) transitions (see Sections 4.2 and 4.4) (Geels et al., 2017; Michaelowa et al., 2018).

In summary, the emerging literature supports the AR5 on the need for integrated, robust and stringent policy frameworks targeting both the supply and demand-side of energy-economy systems (*high confidence*). Continuous ex-ante policy assessments provide learning opportunities for both policy makers and stakeholders.

Cross-Chapter Box 5 | Economics of 1.5°C Pathways and the Social Cost of Carbon

Contributing Authors:

Luis Mundaca (Sweden/Chile), Mustafa Babiker (Sudan), Johannes Emmerling (Italy/Germany), Sabine Fuss (Germany), Jean-Charles Hourcade (France), Elmar Kriegler (Germany), Anil Markandya (Spain/UK), Joyashree Roy (India), Drew Shindell (USA)

Two approaches have been commonly used to assess alternative emissions pathways: **cost-effectiveness analysis (CEA)** and **cost-benefit analysis (CBA)**. **CEA** aims at identifying emissions pathways minimising the total mitigation costs of achieving a given warming or GHG limit (Clarke et al., 2014). **CBA** has the goal to identify the optimal emissions trajectory minimising the discounted flows of abatement expenditures and monetized climate change damages (Boardman et al., 2006; Stern, 2007). A third concept, the **Social Cost of Carbon (SCC)** measures the total net damages of an extra metric ton of CO₂ emissions due to the associated climate change (Nordhaus, 2014; Pizer et al., 2014; Rose et al., 2017a). Negative and positive impacts are monetized, discounted and the net value is expressed as an equivalent loss of consumption today. The SCC can be evaluated for any emissions pathway under policy consideration (Rose, 2012; NASEM, 2016, 2017).

Along the optimal trajectory determined by CBA, the SCC equals the discounted value of the marginal abatement cost of a metric ton of CO₂ emissions. Equating the present value of future damages and marginal abatement costs includes a number of critical value judgements in the formulation of the social welfare function (SWF), particularly in how non-market damages and the distribution of damages across countries and individuals and between current and future generations are valued (Kolstad et al., 2014). For example, since climate damages accrue to a larger extent farther in the future and can persist for many years, assumptions and approaches to determine the social discount rate (normative 'prescriptive' vs. positive 'descriptive') and social welfare function (e.g., discounted utilitarian SWF vs. undiscounted prioritarian SWF) can heavily influence CBA outcomes and associated estimates of SCC (Kolstad et al., 2014; Pizer et al., 2014; Adler and Treich, 2015; Adler et al., 2017; NASEM, 2017; Nordhaus, 2017; Rose et al., 2017a).

In CEA, the marginal abatement cost of carbon is determined by the climate goal under consideration. It equals the shadow price of carbon associated with the goal which in turn can be interpreted as the willingness to pay for imposing the goal as a political constraint. Emissions prices are usually expressed in carbon (equivalent) prices using the GWP-100 metric as the exchange rate for pricing emissions of non-CO₂ GHGs controlled under internationally climate agreements (like CH₄, N₂O and fluorinated gases, see Cross-Chapter Box 2 in Chapter 1).¹³ Since policy goals like the goals of limiting warming to 1.5°C or well below 2°C do not directly result from a money metric trade-off between mitigation and damages, associated shadow prices can differ from the SCC in a CBA. In CEA, value judgments are to a large extent concentrated in the choice of climate goal and related implications, while more explicit assumptions about social values are required to perform CBA. For example, in CEA assumptions about the social discount rate no longer affect the overall abatement levels now set by the climate goal, but the choice and timing of investments in individual measures to reach these levels.

¹³ Also other metrics to compare emissions have been suggested and adopted by governments nationally (Kandlikar, 1995; Marten et al., 2015; Shindell, 2015; IWG, 2016).

Cross Chapter Box 5 (continued)

Although CBA-based and CEA-based assessment are both subject to large uncertainty about socio-techno-economic trends, policy developments and climate response, the range of estimates for the SCC along an optimal trajectory determined by CBA is far wider than for estimates of the shadow price of carbon in CEA-based approaches. In CBA, the value judgments about inter- and intra-generational equity combined with uncertainties in the climate damage functions assumed, including their empirical basis, are important (Pindyck, 2013; Stern, 2013; Revesz et al., 2014). In a CEA-based approach, the value judgments about the aggregate welfare function matter less, and uncertainty about climate response and impacts can be tied into various climate targets and related emissions budgets (Clarke et al., 2014).

The CEA- and CBA-based carbon cost estimates are derived with a different set of tools. They are all summarised as integrated assessment models (IAMs) but in fact are of very different nature (Weyant, 2017). Detailed process IAMs such as AIM (Fujimori, 2017), GCAM (Thomson et al., 2011; Calvin et al., 2017), IMAGE (van Vuuren et al., 2011b, 2017b), MESSAGE-GLOBIOM (Riahi et al., 2011; Havlik et al., 2014; Fricko et al., 2017), REMIND-MAGPIE (Popp et al., 2010; Luderer et al., 2013; Kriegler et al., 2017) and WITCH (Bosetti et al., 2006, 2008, 2009) include a process-based representation of energy and land systems, but in most cases lack a comprehensive representation of climate damages, and are typically used for CEA. Diagnostic analyses across CBA-IAMs indicate important dissimilarities in modelling assembly, implementation issues and behaviour (e.g., parametric uncertainty, damage responses, income sensitivity) that need to be recognized to better understand SCC estimates (Rose et al., 2017a).

CBA-IAMs such as DICE (Nordhaus and Boyer, 2000; Nordhaus, 2013, 2017), PAGE (Hope, 2006) and FUND (Tol, 1999; Anthoff and Tol, 2009) attempt to capture the full feedback from climate response to socio-economic damages in an aggregated manner, but are usually much more stylised than detailed process IAMs. In a nutshell, the methodological framework for estimating SCC involves projections of population growth, economic activity and resulting emissions; computations of atmospheric composition and global mean temperatures as a result of emissions; estimations of physical impacts of climate changes; monetization of impacts (positive and negative) on human welfare; and the discounting of the future monetary value of impacts to year of emission (Kolstad et al., 2014; Revesz et al., 2014; NASEM, 2017; Rose et al., 2017a). There has been a discussion in the literature to what extent CBA-IAMs underestimate the SCC due to, for example, a limited treatment or difficulties in addressing damages to human well-being, labour productivity, value of capital stock, ecosystem services and the risks of catastrophic climate change for future generations (Ackerman and Stanton, 2012; Revesz et al., 2014; Moore and Diaz, 2015; Stern, 2016). However, there has been progress in 'bottom-up' empirical analyses of climate damages (Hsiang et al., 2017), the insights of which could be integrated into these models (Dell et al., 2014). Most of the models used in Chapter 2 on 1.5°C mitigation pathways are detailed process IAMs and thus deal with CEA.

An important question is how results from CEA- and CBA-type approaches can be compared and synthesized. Such synthesis needs to be done with care, since estimates of the shadow price of carbon under the climate goal and SCC estimates from CBA might not be directly comparable due to different tools, approaches and assumptions used to derive them. Acknowledging this caveat, the SCC literature has identified a range of factors, assumptions and value judgements that support SCC values above \$100 tCO₂⁻¹ that are also found as net present values of the shadow price of carbon in 1.5°C pathways. These factors include accounting for tipping points in the climate system (Lemoine and Traeger, 2014; Cai et al., 2015; Lontzek et al., 2015), a low social discount rate (Nordhaus, 2007a; Stern, 2007) and inequality aversion (Schmidt et al., 2013; Dennig et al., 2015; Adler et al., 2017).

The SCC and the shadow price of carbon are not merely theoretical concepts but used in regulation (Pizer et al., 2014; Revesz et al., 2014; Stiglitz et al., 2017). As stated by the report of the High-Level Commission on Carbon Pricing (Stiglitz et al., 2017), in the real world there is a distinction to be made between the implementable and efficient explicit carbon prices and the implicit (notional) carbon prices to be retained for policy appraisal and the evaluation of public investments, as is already done in some jurisdictions such as the USA, UK and France. Since 2008, the U.S. government has used SCC estimates to assess the benefits and costs related to CO₂ emissions resulting from federal policymaking (NASEM, 2017; Rose et al., 2017a).

The use of the SCC for policy appraisals is, however, not straightforward in an SDG context. There are suggestions that a broader range of polluting activities than only CO₂ emissions, for example emissions of air pollutants, and a broader range of impacts than only climate change, such as impacts on air quality, health and sustainable development in general (see Chapter 5 for a detailed discussion), would need to be included in social costs (Sarofim et al., 2017; Shindell et al., 2017a). Most importantly, a consistent valuation of the SCC in a sustainable development framework would require accounting for the SDGs in the social welfare formulation (see Chapter 5).

2.5.2 Economic and Investment Implications of 1.5°C Pathways

2.5.2.1 Price of carbon emissions

The price of carbon assessed here is fundamentally different from the concepts of optimal carbon price in a cost–benefit analysis, or the social cost of carbon (see Cross-Chapter Box 5 in this chapter and Chapter 3, Section 3.5.2). Under a cost-effectiveness analysis (CEA) modelling framework, prices for carbon (mitigation costs) reflect the stringency of mitigation requirements at the margin (i.e., cost of mitigating one extra unit of emission). Explicit carbon pricing is briefly addressed here to the extent it pertains to the scope of Chapter 2. For detailed policy issues about carbon pricing see Section 4.4.5.

Based on data available for this special report, the price of carbon varies substantially across models and scenarios, and their values increase with mitigation efforts (see Figure 2.26) (*high confidence*). For instance, undiscounted values under a Higher-2°C pathway range from 15–220 USD₂₀₁₀ tCO_{2-eq}⁻¹ in 2030, 45–1050 USD₂₀₁₀ tCO_{2-eq}⁻¹ in 2050, 120–1100 USD₂₀₁₀ tCO_{2-eq}⁻¹ in 2070 and 175–2340 USD₂₀₁₀ tCO_{2-eq}⁻¹ in 2100. On the contrary, estimates for a Below-1.5°C pathway range from 135–6050 USD₂₀₁₀ tCO_{2-eq}⁻¹ in 2030, 245–14300 USD₂₀₁₀ tCO_{2-eq}⁻¹ in 2050, 420–19300 USD₂₀₁₀ tCO_{2-eq}⁻¹ in 2070 and 690–30100 USD₂₀₁₀ tCO_{2-eq}⁻¹ in 2100. Values for 1.5°C-low-OS pathway are relatively higher than 1.5°C-high-OS pathway in 2030, but the difference decreases over time, particularly between 2050 and 2070. This is because in 1.5°C-high-OS pathways there is relatively less mitigation activity in the first half of the century, but more in the second half. The low energy demand (LED, P1 in the Summary for Policymakers) scenario exhibits the lowest values across the illustrative pathway archetypes. As a whole, the global average discounted price of emissions across 1.5°C- and 2°C pathways differs by a factor of four across models (assuming a 5% annual discount rate, comparing to Below-1.5°C and 1.5°C-low-OS pathways). If 1.5°C-high-OS pathways (with peak warming 0.1–0.4°C higher than 1.5°C) or pathways with very large land-use sinks are also considered, the differential value is reduced to a limited degree, from a factor 4 to a factor 3. The increase in mitigation costs between 1.5°C and 2°C pathways is based on a direct comparison of pathway pairs from the same model and the same study in which the 1.5°C pathway assumes a significantly smaller carbon budget compared to the 2°C pathway (e.g., 600 GtCO₂ smaller in the CD-LINKS and ADVANCE studies). This assumption is the main driver behind the increase in the price of carbon (Luderer et al., 2018; McCollum et al., 2018).¹⁴

The wide range of values depends on numerous aspects, including methodologies, projected energy service demands, mitigation targets, fuel prices and technology availability (*high confidence*) (Clarke et al., 2014; Kriegler et al., 2015b; Rogelj et al., 2015c; Riahi et al., 2017; Stiglitz et al., 2017). The characteristics of the technology portfolio, particularly in terms of investment costs and deployment rates, play a key role (Luderer et al., 2013, 2016a; Clarke et al., 2014; Bertram et al., 2015a; Riahi et al., 2015; Rogelj et al., 2015c). Models that encompass

a higher degree of technology granularity and that entail more flexibility regarding mitigation response often produce relatively lower mitigation costs than those that show less flexibility from a technology perspective (Bertram et al., 2015a; Kriegler et al., 2015a). Pathways providing high estimates often have limited flexibility of substituting fossil fuels with low-carbon technologies and the associated need to compensate fossil-fuel emissions with CDR. The price of carbon is also sensitive to the non-availability of BECCS (Bauer et al., 2018). Furthermore, and due to the treatment of future price anticipation, recursive-dynamic modelling approaches (with ‘myopic anticipation’) exhibit higher prices in the short term but modest increases in the long term compared to optimization modelling frameworks with ‘perfect foresight’ that show exponential pricing trajectories (Guivarch and Rogelj, 2017). The chosen social discount rate in CEA studies (range of 2–8% per year in the reported data, varying over time and sectors) can also affect the choice and timing of investments in mitigation measures (Clarke et al., 2014; Kriegler et al., 2015b; Weyant, 2017). However, the impacts of varying discount rates on 1.5°C (and 2°C) mitigation strategies can only be assessed to a limited degree. The above highlights the importance of sampling bias in pathway analysis ensembles towards outcomes derived from models which are more flexible, have more mitigation options and cheaper cost assumptions and thus can provide feasible pathways in contrast to other who are unable to do so (Tavoni and Tol, 2010; Clarke et al., 2014; Bertram et al., 2015a; Kriegler et al., 2015a; Guivarch and Rogelj, 2017). All CEA-based IAM studies reveal no unique path for the price of emissions (Bertram et al., 2015a; Kriegler et al., 2015b; Akimoto et al., 2017; Riahi et al., 2017).

Socio-economic conditions and policy assumptions also influence the price of carbon (*very high confidence*) (Bauer et al., 2017; Guivarch and Rogelj, 2017; Hof et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). A multimodel study (Riahi et al., 2017) estimated the average discounted price of carbon (2010–2100, 5% discount rate) for a 2°C target to be nearly three times higher in the SSP5 marker than in the SSP1 marker. Another multimodel study (Rogelj et al., 2018) estimated the average discounted price of carbon (2020–2100, 5%) to be 35–65% lower in SSP1 compared to SSP2 in 1.5°C pathways. Delayed near-term mitigation policies and measures, including the limited extent of international global cooperation, result in increases in total economic mitigation costs and corresponding prices of carbon (Luderer et al., 2013; Clarke et al., 2014). This is because stronger efforts are required in the period after the delay to counterbalance the higher emissions in the near term. Staged accession scenarios also produce higher mitigation costs than immediate action mitigation scenarios under the same stringency level of emissions (Kriegler et al., 2015b).

It has been long argued that an explicit carbon pricing mechanism (whether via a tax or cap-and-trade scheme) can theoretically achieve cost-effective emission reductions (Nordhaus, 2007b; Stern, 2007; Aldy and Stavins, 2012; Goulder and Schein, 2013; Somanthan et al., 2014; Weitzman, 2014; Tol, 2017). Whereas the integrated assessment literature is mostly focused on the role of carbon pricing to reduce emissions (Clarke et al., 2014; Riahi et al., 2017; Weyant, 2017), there

¹⁴ Unlike AR5, which only included cost-effective scenarios for estimating discounted average carbon prices for 2015–2100 (also using a 5% discount rate) (see Clarke et al., 2014, p.450), please note that values shown in Figure 2.26b include delays or technology constraint cases (see Sections 2.1 and 2.3).

is an emerging body of studies (including bottom-up approaches) that focuses on the interaction and performance of various policy mixes (e.g., regulation, subsidies, standards). Assuming global implementation of a mix of regionally existing best-practice policies (mostly regulatory policies in the electricity, industry, buildings, transport and agricultural sectors) and moderate carbon pricing (between 5–20 USD₂₀₁₀ tCO₂⁻¹ in 2025 in most world regions and average prices around 25 USD₂₀₁₀ tCO₂⁻¹ in 2030), early action mitigation pathways are generated that reduce global CO₂ emissions by an additional 10 GtCO₂e in 2030 compared to the NDCs (Kriegler et al., 2018a) (see Section 2.3.5). Furthermore, a mix of stringent energy efficiency policies (e.g., minimum performance standards, building codes) combined with a carbon tax (rising from 10 USD₂₀₁₀ tCO₂⁻¹ in 2020 to 27 USD₂₀₁₀ tCO₂⁻¹ in 2040) is more cost-effective than a carbon tax alone (from 20 to 53 USD₂₀₁₀ tCO₂⁻¹) to generate a 1.5°C pathway for the U.S. electric sector (Brown and Li, 2018). Likewise, a policy mix encompassing a moderate carbon price (7 USD₂₀₁₀ tCO₂⁻¹ in 2015) combined with a ban on new coal-based power plants and dedicated policies addressing renewable electricity generation capacity and electric vehicles reduces efficiency losses compared with an optimal carbon pricing in 2030 (Bertram et al., 2015b). One study estimates the carbon prices in high energy-intensive pathways to be 25–50% higher than in low energy-intensive pathways that assume ambitious regulatory instruments, economic incentives (in addition to a carbon price) and voluntary initiatives (Méjean et al., 2018). A bottom-up approach shows that stringent minimum performance standards (MEPS) for appliances (e.g., refrigerators) can effectively complement explicit carbon pricing, as tightened MEPS can achieve ambitious efficiency improvements that cannot be assured by carbon prices of 100 USD₂₀₁₀ tCO₂⁻¹ or higher (Sonnenschein et al., 2018). In addition, the revenue recycling effect of carbon pricing can reduce mitigation costs by displacing distortionary taxes (Baranzini et al., 2017; OECD, 2017; McFarland et al., 2018; Sands, 2018; Siegmeier et al., 2018), and the reduction of capital tax (compared to a labour tax) can yield greater savings in welfare costs (Sands, 2018). The effect on public budgets is particularly important in the near term; however, it can decline in the long term as carbon neutrality is achieved (Sands, 2018). The literature indicates that explicit carbon pricing is relevant but needs to be complemented with other policies to drive the required changes in line with 1.5°C cost-effective pathways (*low to medium evidence, high agreement*) (see Chapter 4, Section 4.4.5) (Stiglitz et al., 2017; Mehling and Tvinnereim, 2018; Méjean et al., 2018; Michaelowa et al., 2018).

In summary, new analyses are consistent with AR5 and show that the price of carbon increases significantly if a higher level of stringency is pursued (*high confidence*). Values vary substantially across models, scenarios and socio-economic, technology and policy assumptions. While an explicit carbon pricing mechanism is central to prompt mitigation scenarios compatible with 1.5°C pathways, a complementary mix of stringent policies is required.

2.5.2.2 Investments

Realizing the transformations towards a 1.5°C world would require a major shift in investment patterns (McCollum et al., 2018). Literature on global climate change mitigation investments is relatively sparse, with most detailed literature having focused on 2°C pathways (McCollum

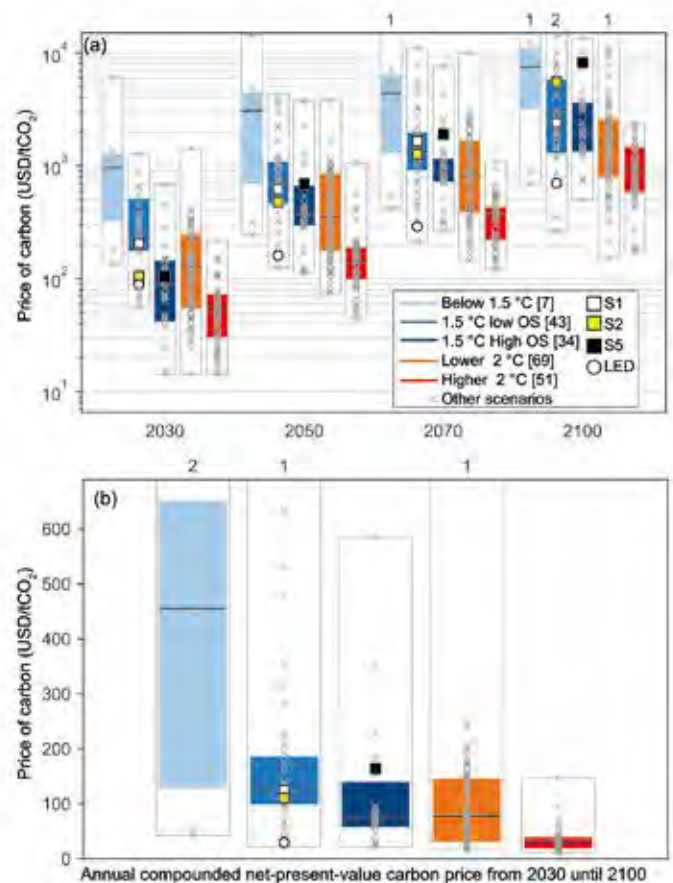


Figure 2.26 | Global price of carbon emissions consistent with mitigation pathways. Panels show (a) undiscounted price of carbon (2030–2100) and (b) average price of carbon (2030–2100) discounted at a 5% discount rate to 2020 in USD₂₀₁₀. AC: Annually compounded. NPV: Net present value. Median values in floating black line. The number of pathways included in box plots is indicated in the legend. Number of pathways outside the figure range is noted at the top.

et al., 2013; Bowen et al., 2014; Gupta and Harnisch, 2014; Marangoni and Tavoni, 2014; OECD/IEA and IRENA, 2017).

Global energy-system investments in the year 2016 are estimated at approximately 1.7 trillion USD₂₀₁₀ (approximately 2.2% of global GDP and 10% of gross capital formation), of which 0.23 trillion USD₂₀₁₀ was for incremental end-use energy efficiency and the remainder for supply-side capacity installations (IEA, 2017c). There is some uncertainty surrounding this number because not all entities making investments report them publicly, and model-based estimates show an uncertainty range of about ±15% (McCollum et al., 2018). Notwithstanding, the trend for global energy investments has been generally upward over the last two decades: increasing about threefold between 2000 and 2012, then levelling off for three years before declining in both 2015 and 2016 as a result of the oil price collapse and simultaneous capital cost reductions for renewables (IEA, 2017c).

Estimates of demand-side investments, either in total or for incremental efficiency efforts, are more uncertain, mainly due to a lack of reliable statistics and definitional issues about what exactly is counted towards a demand-side investment and what the reference should be for estimating incremental efficiency (McCollum et al., 2013). Grubler and

Wilson (2014) use two working definitions (a broader and a narrower one) to provide a first-order estimate of historical end-use technology investments in total. The broad definition defines end-use technologies as the technological systems purchasable by final consumers in order to provide a useful service, for example, heating and air conditioning systems, cars, freezers, or aircraft. The narrow definition sets the boundary at the specific energy-using components or subsystems of the larger end-use technologies (e.g., compressor, car engine, heating element). Based on these two definitions, demand-side energy investments for the year 2005 were estimated about 1–3.5 trillion USD₂₀₁₀ (central estimate 1.7 trillion USD₂₀₁₀) using the broad definition and 0.1–0.6 trillion USD₂₀₁₀ (central estimate 0.3 trillion USD₂₀₁₀) using the narrower definition. Due to these definitional issues, demand-side investment projections are uncertain, often underreported, and difficult to compare. Global IAMs often do not fully and explicitly represent all the various measures that could improve end-use efficiency.

Research carried out by six global IAM teams found that 1.5°C-consistent climate policies would require a marked upscaling of energy system supply-side investments (resource extraction, power generation, fuel conversion, pipelines/transmission, and energy storage) between now and mid-century, reaching levels of between 1.6–3.8 trillion USD₂₀₁₀ yr⁻¹ globally on average over the 2016–2050 timeframe (McCollum et al., 2018) (Figure 2.27). How these investment needs compare to those in a policy baseline scenario is uncertain: they could be higher, much higher, or lower. Investments in the policy baselines from these same models are 1.6–2.7 trillion USD₂₀₁₀ yr⁻¹. Much hinges on the reductions in energy demand growth embodied in the 1.5°C pathways, which require investing in energy efficiency. Studies suggest that annual supply-side investments by mid-century could be lowered by around 10% (McCollum et al., 2018) and in some cases up to 50% (Grubler et al., 2018) if strong policies to limit energy demand growth are successfully implemented. However, the degree to which these supply-side reductions would be partially offset by an increase in demand-side investments is unclear.

Some trends are robust across scenarios (Figure 2.27). First, pursuing 1.5°C mitigation efforts requires a major reallocation of the investment portfolio, implying a financial system aligned to mitigation challenges. The path laid out by countries' current NDCs until 2030 will not drive these structural changes; and despite increasing low-carbon investments in recent years (IEA, 2016b; Frankfurt School-UNEP Centre/BNEF, 2017), these are not yet aligned with 1.5°C. Second, additional annual average energy-related investments for the period 2016 to 2050 in pathways limiting warming to 1.5°C compared to the baseline (i.e., pathways without new climate policies beyond those in place today) are estimated by the models employed in McCollum et al. (2018) to be around 830 billion USD₂₀₁₀ (range of 150 billion to 1700 billion USD₂₀₁₀ across six models). This compares to total annual average energy *supply* investments in 1.5°C pathways of 1460 to 3510 billion USD₂₀₁₀ and total annual average energy *demand* investments of 640 to 910 billion USD₂₀₁₀ for the period 2016 to 2050. Total energy-related investments increase by about 12% (range of 3% to 24%) in 1.5°C pathways relative to 2°C pathways. Average annual investment in low-carbon energy technologies and energy efficiency are upscaled by roughly a factor of six (range of factor of 4 to 10) by 2050 compared to 2015. Specifically, annual investments in low-carbon energy are

projected to average 0.8–2.9 trillion USD₂₀₁₀ yr⁻¹ globally to 2050 in 1.5°C pathways, overtaking fossil investments globally already by around 2025 (McCollum et al., 2018). The bulk of these investments are projected to be for clean electricity generation, particularly solar and wind power (0.09–1.0 trillion USD₂₀₁₀ yr⁻¹ and 0.1–0.35 trillion USD₂₀₁₀ yr⁻¹, respectively) as well as nuclear power (0.1–0.25 trillion USD₂₀₁₀ yr⁻¹). Third, the precise apportioning of these investments depends on model assumptions and societal preferences related to mitigation strategies and policy choices (see Sections 2.1 and 2.3). Investments for electricity transmission and distribution and storage are also scaled up in 1.5°C pathways (0.3–1.3 trillion USD₂₀₁₀ yr⁻¹), given their widespread electrification of the end-use sectors (see Section 2.4). Meanwhile, 1.5°C pathways see a reduction in annual investments for fossil-fuel extraction and unabated fossil electricity generation (to 0.3–0.85 trillion USD₂₀₁₀ yr⁻¹ on average over the 2016–2050 period). Investments in unabated coal are halted by 2030 in most 1.5°C projections, while the literature is less conclusive for investments in unabated gas (McCollum et al., 2018). This illustrates how mitigation strategies vary between models, but in the real world should be considered in terms of their societal desirability (see Section 2.5.3). Furthermore, some fossil investments made over the next few years – or those made in the last few – will *likely* need to be retired prior to fully recovering their capital investment or before the end of their operational lifetime (Bertram et al., 2015a; Johnson et al., 2015; OECD/IEA and IRENA, 2017). How the pace of the energy transition will be affected by such dynamics, namely with respect to politics and society, is not well captured by global IAMs at present. Modelling studies have, however, shown how the reliability of institutions influences investment risks and hence climate mitigation investment decisions (Iyer et al., 2015), finding that a lack of regulatory credibility or policy commitment fails to stimulate low-carbon investments (Bosetti and Victor, 2011; Faehn and Isaksen, 2016).

Low-carbon supply-side investment needs are projected to be largest in OECD countries and those of developing Asia. The regional distribution of investments in 1.5°C pathways estimated by the multiple models in (McCollum et al., 2018) are the following (average over 2016–2050 timeframe): 0.30–1.3 trillion USD₂₀₁₀ yr⁻¹ (ASIA), 0.35–0.85 trillion USD₂₀₁₀ yr⁻¹ (OECD), 0.08–0.55 trillion USD₂₀₁₀ yr⁻¹ (MAF), 0.07–0.25 trillion USD₂₀₁₀ yr⁻¹ (LAM), and 0.05–0.15 trillion USD₂₀₁₀ yr⁻¹ (REF) (regions are defined consistent with their use in AR5 WGIII, see Table A.II.8 in Krey et al., 2014b).

Until now, IAM investment analyses of 1.5°C pathways have focused on middle-of-the-road socio-economic and technological development futures (SSP2) (Fricko et al., 2017). Consideration of a broader range of development futures would yield different outcomes in terms of the magnitudes of the projected investment levels. Sensitivity analyses indicate that the magnitude of supply-side investments as well as the investment portfolio do not change strongly across the SSPs for a given level of climate policy stringency (McCollum et al., 2018). With only one dedicated multimodel comparison study published, there is *limited to medium evidence* available. For some features, there is *high agreement* across modelling frameworks leading, for example, to *medium to high confidence* that limiting global temperature increase to 1.5°C would require a major reallocation of the investment portfolio. Given the limited amount of sensitivity cases available compared to the default SSP2

assumptions, *medium confidence* can be assigned to the specific energy and climate mitigation investment estimates reported here.

Assumptions in modelling studies indicate a number of challenges. For instance, access to finance and mobilization of funds are critical (Fankhauser et al., 2016; OECD, 2017). In turn, policy efforts need to be effective in redirecting financial resources (UNEP, 2015; OECD, 2017) and reducing transaction costs for bankable mitigation projects (i.e. projects that have adequate future cash flow, collateral, etc. so lenders are willing to finance it), particularly on the demand side (Mundaca et al., 2013; Brunner and Enting, 2014; Grubler et al., 2018). Assumptions also imply that policy certainty, regulatory oversight mechanisms and fiduciary duty need to be robust and effective to safeguard credible and stable financial

markets and de-risk mitigation investments in the long term (Clarke et al., 2014; Mundaca et al., 2016; EC, 2017; OECD, 2017). Importantly, the different time horizons that actors have in the competitive finance industry are typically not explicitly captured by modelling assumptions (Harmes, 2011). See Chapter 4, Section 4.4.5 for details of climate finance in practice.

In summary and despite inherent uncertainties, the emerging literature indicates a gap between current investment patterns and those compatible with 1.5°C (or 2°C) pathways (*limited to medium evidence, high agreement*). Estimates and assumptions from modelling frameworks suggest a major shift in investment patterns and entail a financial system effectively aligned with mitigation challenges (*high confidence*).

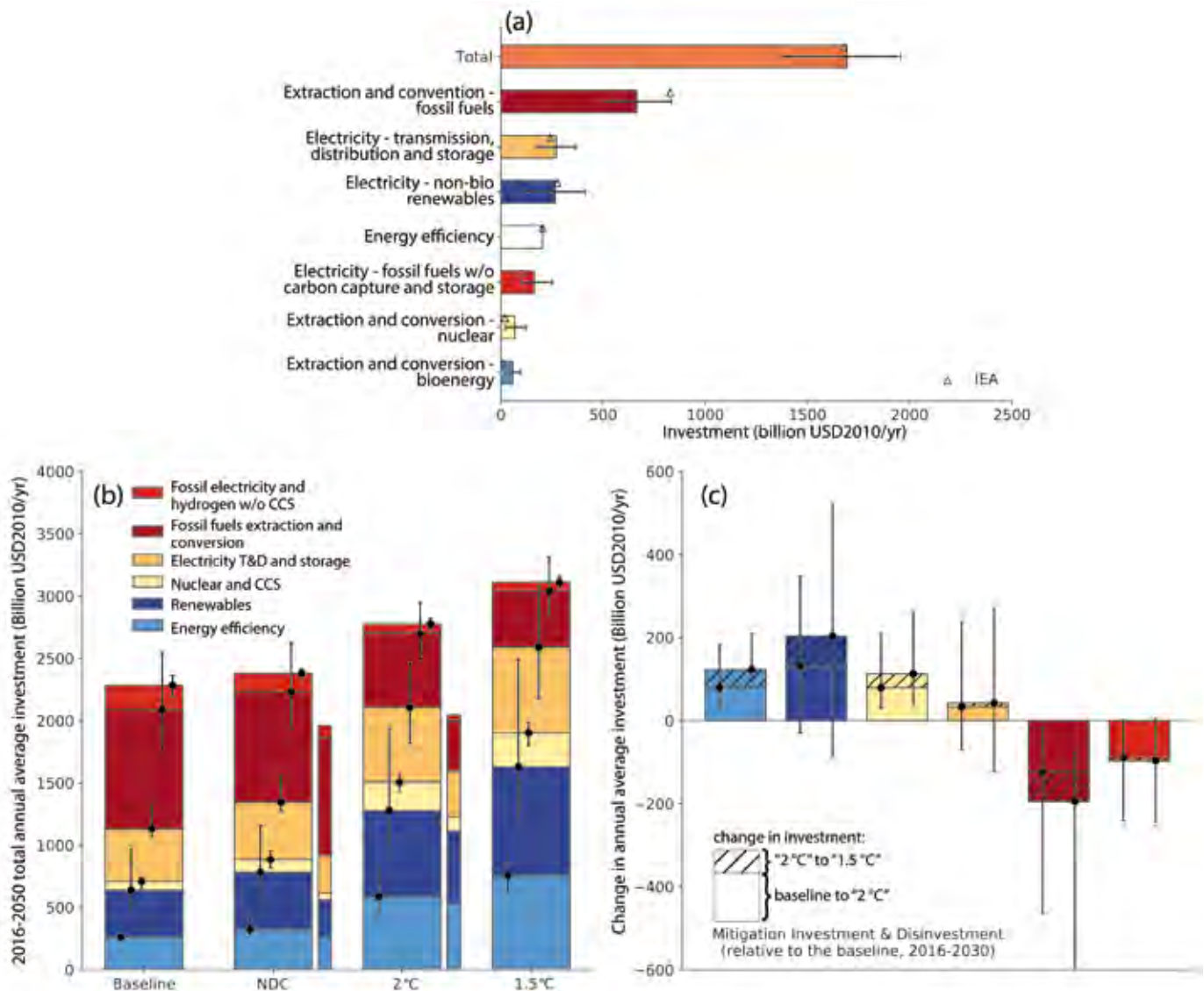


Figure 2.27 | Historical and projected global energy investments. (a) Historical investment estimates across six global models from (McCollum et al., 2018) (bars = model means, whiskers full model range) compared to historical estimates from IEA (International Energy Agency (IEA) 2016) (triangles). (b) Average annual investments over the 2016–2050 period in the “baselines” (i.e., pathways without new climate policies beyond those in place today), scenarios which implement the NDCs (‘NDC’, including conditional NDCs), scenarios consistent with the Lower-2°C pathway class (‘2°C’), and scenarios in line with the 1.5°C-low-OS pathway class (‘1.5°C’). Whiskers show the range of models; wide bars show the multimodel means; narrow bars represent analogous values from individual IEA scenarios (OECD/IEA and IRENA, 2017). (c) Average annual mitigation investments and disinvestments for the 2016–2030 periods relative to the baseline. The solid bars show the values for ‘2°C’ pathways, while the hatched areas show the additional investments for the pathways labelled with ‘1.5°C’. Whiskers show the full range around the multimodel means. T&D stands for transmission and distribution, and CCS stands for carbon capture and storage. Global cumulative carbon dioxide emissions, from fossil fuels and industrial processes (FF&I) but excluding land use, over the 2016–2100 timeframe range from 880 to 1074 GtCO₂ (multimodel mean: 952 GtCO₂) in the ‘2°C’ pathway and from 206 to 525 GtCO₂ (mean: 390 GtCO₂) in the ‘1.5°C’ pathway.

2.5.3 Sustainable Development Features of 1.5°C Pathways

Potential synergies and trade-offs between 1.5°C mitigation pathways and different sustainable development (SD) dimensions (see Cross-Chapter Box 4 in Chapter 1) are an emerging field of research. Chapter 5, Section 5.4 assesses interactions between individual mitigation measures with other societal objectives, as well as the Sustainable

Development Goals (SDGs) (Table 5.1). This section synthesized the Chapter 5 insights to assess how these interactions play out in integrated 1.5°C pathways, and the four illustrative pathway archetypes of this chapter in particular (see Section 2.1). Information from integrated pathways is combined with the interactions assessed in Chapter 5 and aggregated for each SDG, with a level of confidence attributed to each interaction based on the amount and agreement of the scientific evidence (see Chapter 5).

Sustainable development implications of alternative mitigation choices for 1.5°C pathways

deployment of specific mitigation measures can interact in various ways with SDGs

- + potential synergies with SDG achievement
- risk of trade-offs with SDG achievement
- + both risk of trade-offs and potential for synergies
- neutral or no direct interaction identified in the literature

a level of confidence is assigned based on scientific evidence

bold symbols indicate where all available evidence suggests a similar interaction (see Chapter 5)

- +** low confidence
- medium confidence
- +** high confidence

SDG interaction per mitigation measure and scale of deployment in pathway archetypes

pathways vary in their portfolio of mitigation measures, here illustrated by the four archetype pathways (LED, S1, S2, S5) which vary in their societal developments and mitigation strategies to achieve a 1.5°C-consistent emission pathway (see Section 2.1)

climate change mitigation measure and its interaction with SDGs

Demand

- Accelerating energy efficiency improvements in end-use sectors
- Behavioural response reducing building and transport demand
- Fuel switch and access to modern low-carbon energy
- Behavioural response: sustainable healthy diets and reduced food waste

	social					environment					economic				
	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	8.1	8.2	8.3	8.4	8.5
Accelerating energy efficiency improvements in end-use sectors	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Behavioural response reducing building and transport demand	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Fuel switch and access to modern low-carbon energy	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Behavioural response: sustainable healthy diets and reduced food waste	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

relative deployment of climate mitigation measures, based on proxy indicators

low medium high

indicator 1

indicator 2

indicator 3

indicator 4

Supply

- Non-biomass renewables: solar, wind, hydro
- Increased use of biomass
- Nuclear/Advanced Nuclear
- Bioenergy with carbon capture and storage (BECCS)
- Fossil fuel with carbon capture and storage (fossil-CCS)

	social					environment					economic				
	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	8.1	8.2	8.3	8.4	8.5
Non-biomass renewables: solar, wind, hydro	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Increased use of biomass	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Nuclear/Advanced Nuclear	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Bioenergy with carbon capture and storage (BECCS)	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Fossil fuel with carbon capture and storage (fossil-CCS)	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

indicator 1

indicator 4

indicator 7

indicator 8

indicator 9

Land

- Land based greenhouse gas reduction and soil carbon sequestration
- GHG reduction from improved livestock production and manure management
- Reduced deforestation, REDD+, afforestation and reforestation

	social					environment					economic				
	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	8.1	8.2	8.3	8.4	8.5
Land based greenhouse gas reduction and soil carbon sequestration	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
GHG reduction from improved livestock production and manure management	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Reduced deforestation, REDD+, afforestation and reforestation	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

indicator 10

indicator 11

indicator 12

this leads to different relative scenario SDG risk and synergy profiles for each respective pathway archetype

	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	8.1	8.2	8.3	8.4	8.5
LED	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
S1	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
S2	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
S5	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

combining the relative deployment of climate mitigation measures and their SDG interactions results in SDG synergy and risk profiles, which allow to assess the relative desirability of a mitigation pathway strategy in the context of sustainable development

Figure 2.28 | Interactions of individual mitigation measures and alternative mitigations portfolios for 1.5°C with Sustainable Development Goals (SDGs). The assessment of interactions between mitigation measures and individual SDGs is based on the assessment of Chapter 5, Section 5.4. Proxy indicators and synthesis method are described in Supplementary Material 2.SM.1.5.

Figure 2.28 shows how the scale and combination of individual mitigation measures (i.e., their mitigation portfolios) influence the extent of synergies and trade-offs with other societal objectives. All pathways generate multiple synergies with sustainable development dimensions and can advance several other SDGs simultaneously. Some, however, show higher risks for trade-offs. An example is increased biomass production and its potential to increase pressure on land and water resources, food production, and biodiversity and to reduce air quality when combusted inefficiently. At the same time, mitigation actions in energy-demand sectors and behavioural response options with appropriate management of rebound effects can advance multiple SDGs simultaneously, more so than energy supply-side mitigation actions (see Chapter 5, Section 5.4, Table 5.1 and Figure 5.3 for more examples). Of the four pathway archetypes used in this chapter (LED, S1, S2, and S5, referred to as P1, P2, P3, and P4 in the Summary for Policymakers), the S1 and LED pathways show the largest number of synergies and least number of potential trade-offs, while for the S5 pathway more potential trade-offs are identified. In general, pathways with emphasis on demand reductions and policies that incentivize behavioural change, sustainable consumption patterns, healthy diets and relatively low use of CDR (or only afforestation) show relatively more synergies with individual SDGs than other pathways.

There is *robust evidence* and *high agreement* in the pathway literature that multiple strategies can be considered to limit warming to 1.5°C (see Sections 2.1.3, 2.3 and 2.4). Together with the extensive evidence on the existence of interactions of mitigation measures with other societal objectives (Chapter 5, Section 5.4), this results in *high confidence* that the choice of mitigation portfolio or strategy can markedly affect the achievement of other societal objectives. For instance, action on SLCFs has been suggested to facilitate the achievement of SDGs (Shindell et al., 2017b) and to reduce regional impacts, for example, from black carbon sources on snow and ice loss in the Arctic and alpine regions (Painter et al., 2013), with particular focus on the warming sub-set of SLCFs. Reductions in both surface aerosols and ozone through methane reductions provide health and ecosystem co-benefits (Jacobson, 2002, 2010; Anenberg et al., 2012; Shindell et al., 2012; Stohl et al., 2015; Collins et al., 2018). Public health benefits of stringent mitigation pathways in line with 1.5°C pathways can be sizeable. For instance, a study examining a more rapid reduction of fossil-fuel usage to achieve 1.5°C relative to 2°C, similar to that of other recent studies (Grubler et al., 2018; van Vuuren et al., 2018), found that improved air quality would lead to more than 100 million avoided premature deaths over the 21st century (Shindell et al., 2018). These benefits are assumed to be in addition to those occurring under 2°C pathways (e.g., Silva et al., 2016), and could in monetary terms offset either a large portion or all of the initial mitigation costs (West et al., 2013; Shindell et al., 2018). However, some sources of SLCFs with important impacts for public health (e.g., traditional biomass burning) are only mildly affected by climate policy in the available integrated pathways and are more strongly impacted by baseline assumptions about future societal development and preferences, and technologies instead (Rao et al., 2016, 2017).

At the same time, the literature on climate–SDG interactions is still an emergent field of research and hence there is *low to medium confidence* in the precise magnitude of the majority of these

interactions. Very limited literature suggests that achieving co-benefits is not automatically assured but results from conscious and carefully coordinated policies and implementation strategies (Shukla and Chaturvedi, 2012; Clarke et al., 2014; McCollum et al., 2018). Understanding these mitigation–SDG interactions is key for selecting mitigation options that maximize synergies and minimize trade-offs towards the 1.5°C and sustainable development objectives (van Vuuren et al., 2015; Hildingsson and Johansson, 2016; Jakob and Steckel, 2016; von Stechow et al., 2016; Delponte et al., 2017).

In summary, the combined evidence indicates that the chosen mitigation portfolio can have a distinct impact on the achievement of other societal policy objectives (*high confidence*); however, there is uncertainty regarding the specific extent of climate–SDG interactions.

2.6 Knowledge Gaps

This section summarizes the knowledge gaps articulated in earlier sections of the chapter.

2.6.1 Geophysical Understanding

Knowledge gaps are associated with the carbon cycle response, the role of non-CO₂ emissions and the evaluation of an appropriate historic baseline.

Quantifying how the carbon cycle responds to negative emissions is an important knowledge gap for strong mitigation pathways (Section 2.2). Earth system feedback uncertainties are important to consider for the longer-term response, particularly in how permafrost melting might affect the carbon budget (Section 2.2). Future research and ongoing observations over the next years will provide a better indication as to how the 2006–2015 base period compares with the long-term trends and might at present bias the carbon budget estimates.

The future emissions of short-lived climate forcers and their temperature response are a large source of uncertainty in 1.5°C pathways, having a greater relative uncertainty than in higher CO₂ emission pathways. Their global emissions, their sectoral and regional disaggregation, and their climate response are generally less well quantified than for CO₂ (Sections 2.2 and 2.3). Emissions from the agricultural sector, including land-use based mitigation options, in 1.5°C pathways constitute the main source of uncertainty here and are an important gap in understanding the potential achievement of stringent mitigation scenarios (Sections 2.3 and 2.4). This also includes uncertainties surrounding the mitigation potential of the long-lived GHG nitrous oxide (Sections 2.3 and 2.4).

There is considerable uncertainty in how future emissions of aerosol precursors will affect the effective radiative forcing from aerosol–cloud interaction. The potential future warming from mitigation of these emissions reduces remaining carbon budgets and increases peak temperatures (Section 2.2). The potential co-benefits of mitigating air pollutants and how the reduction in air pollution may affect the carbon sink are also important sources of uncertainty (Sections 2.2 and 2.5).

The pathway classification employed in this chapter employs results from the MAGICC model with its AR5 parameter sets. The alternative representation of the relationship between emissions and effective radiative forcing and response in the FAIR model would lead to a different classification that would make 1.5°C targets more achievable (Section 2.2 and Supplementary Material 2.SM.1.1). Such a revision would significantly alter the temperature outcomes for the pathways and, if the result is found to be robust, future research and assessments would need to adjust their classifications accordingly. Any possible high bias in the MAGICC response may be partly or entirely offset by missing Earth system feedbacks that are not represented in either climate emulator and that would act to increase the temperature response (Section 2.2). For this assessment report, any possible bias in the MAGICC setup applied in this and earlier reports is not established enough in the literature to change the classification approach. However, we only place *medium confidence* in the classification adopted by the chapter.

2.6.2 Integrated Assessment Approaches

IAMs attempt to be as broad as possible in order to explore interactions between various societal subsystems, like the economy, land, and energy system. They hence include stylized and simplified representations of these subsystems. Climate damages, avoided impacts and societal co-benefits of the modelled transformations remain largely unaccounted for and are important knowledge gaps. Furthermore, rapid technological changes and uncertainties about input data present continuous challenges.

The IAMs used in this report do not account for climate impacts (Section 2.1), and similarly, none of the Gross Domestic Product (GDP) projections in the mitigation pathway literature assessed in this chapter included the feedback of climate damages on economic growth (Section 2.3). Although some IAMs do allow for climate impact feedbacks in their modelling frameworks, particularly in their land components, such feedbacks were by design excluded in pathways developed in the context of the SSP framework. The SSP framework aims at providing an integrative framework for the assessment of climate change adaptation and mitigation. IAMs are typically developed to inform the mitigation component of this question, while the assessment of impacts is carried out by specialized impact models. However, the use of a consistent set of socio-economic drivers embodied by the SSPs allows for an integrated assessment of climate change impacts and mitigation challenges at a later stage. Further integration of these two strands of research will allow a better understanding of climate impacts on mitigation studies.

Many of the IAMs that contributed mitigation pathways to this assessment include a process-based description of the land system in addition to the energy system, and several have been extended to cover air pollutants and water use. These features make them increasingly fit to explore questions beyond those that touch upon climate mitigation only. The models do not, however, fully account for all constraints that could affect realization of pathways (Section 2.1).

While the representation of renewable energy resource potentials, technology costs and system integration in IAMs has been updated since AR5, bottom-up studies find higher mitigation potentials in the

industry, buildings, and transport sector in that realized by selected pathways from IAMs, indicating the possibility to strengthen sectoral decarbonization strategies compared to the IAM 1.5°C pathways assessed in this chapter (Section 2.1).

Studies indicate that a major shift in investment patterns is required to limit global warming to 1.5°C. This assessment would benefit from a more explicit representation and understanding of the financial sector within the modelling approaches. Assumptions in modelling studies imply low-to-zero transaction costs for market agents and that regulatory oversight mechanisms and fiduciary duty need to be highly robust to guarantee stable and credible financial markets in the long term. This area can be subject to high uncertainty, however. The heterogeneity of actors (e.g., banks, insurance companies, asset managers, or credit rating agencies) and financial products also needs to be taken into account, as does the mobilization of capital and financial flows between countries and regions (Section 2.5).

The literature on interactions between 1.5°C mitigation pathways and SDGs is an emergent field of research (Section 2.3.5, 2.5 and Chapter 5). Whereas the choice of mitigation strategies can noticeably affect the attainment of various societal objectives, there is uncertainty regarding the extent of the majority of identified interactions. Understanding climate–SDG interactions helps inform the choice of mitigation options that minimize trade-offs and risks and maximize synergies towards sustainable development objectives and the 1.5°C goal (Section 2.5).

2.6.3 Carbon Dioxide Removal (CDR)

Most 1.5°C and 2°C pathways are heavily reliant on CDR at a speculatively large scale before mid-century. There are a number of knowledge gaps associated with such technologies. Chapter 4 performs a detailed assessment of CDR technologies.

There is uncertainty in the future deployment of CCS given the limited pace of current deployment, the evolution of CCS technology that would be associated with deployment, and the current lack of incentives for large-scale implementation of CCS (Chapter 4, Section 4.2.7). Technologies other than BECCS and afforestation have yet to be comprehensively assessed in integrated assessment approaches. No proposed technology is close to deployment at scale, and regulatory frameworks are not established. This limits how they can be realistically implemented within IAMs. (Section 2.3)

Evaluating the potential from BECCS is problematic due to large uncertainties in future land projections due to differences in modelling approaches in current land-use models, and these differences are at least as great as the differences attributed to climate scenario variations. (Section 2.3)

There is substantial uncertainty about the adverse effects of large-scale CDR deployment on the environment and societal sustainable development goals. It is not fully understood how land-use and land-management choices for large-scale BECCS will affect various ecosystem services and sustainable development, and how they further translate into indirect impacts on climate, including GHG emissions other than CO₂. (Section 2.3, Section 2.5.3)

Frequently Asked Questions

FAQ 2.1 | What Kind of Pathways Limit Warming to 1.5°C and are we on Track?

Summary: *There is no definitive way to limit global temperature rise to 1.5°C above pre-industrial levels. This Special Report identifies two main conceptual pathways to illustrate different interpretations. One stabilizes global temperature at, or just below, 1.5°C. Another sees global temperature temporarily exceed 1.5°C before coming back down. Countries' pledges to reduce their emissions are currently not in line with limiting global warming to 1.5°C.*

Scientists use computer models to simulate the emissions of greenhouse gases that would be consistent with different levels of warming. The different possibilities are often referred to as 'greenhouse gas emission pathways'. There is no single, definitive pathway to limiting warming to 1.5°C.

This IPCC special report identifies two main pathways that explore global warming of 1.5°C. The first involves global temperature stabilizing at or below before 1.5°C above pre-industrial levels. The second pathway sees warming exceed 1.5°C around mid-century, remain above 1.5°C for a maximum duration of a few decades, and return to below 1.5°C before 2100. The latter is often referred to as an 'overshoot' pathway. Any alternative situation in which global temperature continues to rise, exceeding 1.5°C permanently until the end of the 21st century, is not considered to be a 1.5°C pathway.

The two types of pathway have different implications for greenhouse gas emissions, as well as for climate change impacts and for achieving sustainable development. For example, the larger and longer an 'overshoot', the greater the reliance on practices or technologies that remove CO₂ from the atmosphere, on top of reducing the sources of emissions (mitigation). Such ideas for CO₂ removal have not been proven to work at scale and, therefore, run the risk of being less practical, effective or economical than assumed. There is also the risk that the use of CO₂ removal techniques ends up competing for land and water, and if these trade-offs are not appropriately managed, they can adversely affect sustainable development. Additionally, a larger and longer overshoot increases the risk for irreversible climate impacts, such as the onset of the collapse of polar ice shelves and accelerated sea level rise.

Countries that formally accept or 'ratify' the Paris Agreement submit pledges for how they intend to address climate change. Unique to each country, these pledges are known as Nationally Determined Contributions (NDCs). Different groups of researchers around the world have analysed the combined effect of adding up all the NDCs. Such analyses show that current pledges are not on track to limit global warming to 1.5°C above pre-industrial levels. If current pledges for 2030 are achieved but no more, researchers find very few (if any) ways to reduce emissions after 2030 sufficiently quickly to limit warming to 1.5°C. This, in turn, suggests that with the national pledges as they stand, warming would exceed 1.5°C, at least for a period of time, and practices and technologies that remove CO₂ from the atmosphere at a global scale would be required to return warming to 1.5°C at a later date.

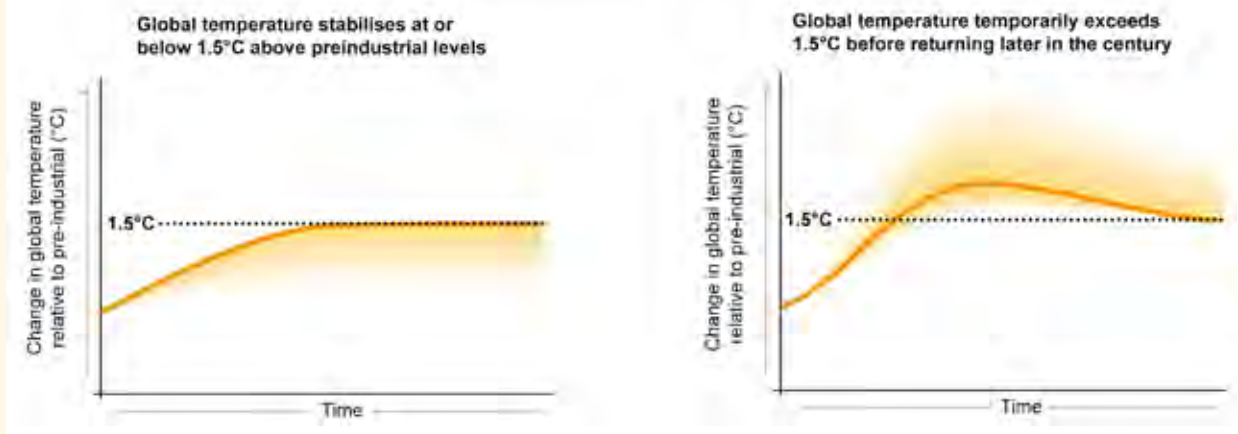
A world that is consistent with holding warming to 1.5°C would see greenhouse gas emissions rapidly decline in the coming decade, with strong international cooperation and a scaling up of countries' combined ambition beyond current NDCs. In contrast, delayed action, limited international cooperation, and weak or fragmented policies that lead to stagnating or increasing greenhouse gas emissions would put the possibility of limiting global temperature rise to 1.5°C above pre-industrial levels out of reach.

(continued on next page)

FAQ 2.1 (continued)

FAQ2.1: Conceptual pathways that limit global warming to 1.5°C

Two main pathways illustrate different interpretations for limiting global warming to 1.5°C. The consequences will be different depending on the pathway



FAQ 2.1, Figure 1 | Two main pathways for limiting global temperature rise to 1.5°C above pre-industrial levels are discussed in this Special Report. These are: stabilizing global temperature at, or just below, 1.5°C (left) and global temperature temporarily exceeding 1.5°C before coming back down later in the century (right). Temperatures shown are relative to pre-industrial but pathways are illustrative only, demonstrating conceptual not quantitative characteristics.

Frequently Asked Questions

FAQ 2.2 | What do Energy Supply and Demand have to do with Limiting Warming to 1.5°C?

Summary: *Limiting global warming to 1.5°C above pre-industrial levels would require major reductions in greenhouse gas emissions in all sectors. But different sectors are not independent of each other, and making changes in one can have implications for another. For example, if we as a society use a lot of energy, then this could mean we have less flexibility in the choice of mitigation options available to limit warming to 1.5°C. If we use less energy, the choice of possible actions is greater – for example, we could be less reliant on technologies that remove carbon dioxide (CO₂) from the atmosphere.*

To stabilize global temperature at any level, 'net' CO₂ emissions would need to be reduced to zero. This means the amount of CO₂ entering the atmosphere must equal the amount that is removed. Achieving a balance between CO₂ 'sources' and 'sinks' is often referred to as 'net zero' emissions or 'carbon neutrality'. The implication of net zero emissions is that the concentration of CO₂ in the atmosphere would slowly decline over time until a new equilibrium is reached, as CO₂ emissions from human activity are redistributed and taken up by the oceans and the land biosphere. This would lead to a near-constant global temperature over many centuries.

Warming will not be limited to 1.5°C or 2°C unless transformations in a number of areas achieve the required greenhouse gas emissions reductions. Emissions would need to decline rapidly across all of society's main sectors, including buildings, industry, transport, energy, and agriculture, forestry and other land use (AFOLU). Actions that can reduce emissions include, for example, phasing out coal in the energy sector, increasing the amount of energy produced from renewable sources, electrifying transport, and reducing the 'carbon footprint' of the food we consume.

The above are examples of 'supply-side' actions. Broadly speaking, these are actions that can reduce greenhouse gas emissions through the use of low-carbon solutions. A different type of action can reduce how much energy human society uses, while still ensuring increasing levels of development and well-being. Known as 'demand-side' actions, this category includes improving energy efficiency in buildings and reducing consumption of energy- and greenhouse-gas intensive products through behavioural and lifestyle changes, for example. Demand- and supply-side measures are not an either-or question, they work in parallel with each other. But emphasis can be given to one or the other.

Making changes in one sector can have consequences for another, as they are not independent of each other. In other words, the choices that we make now as a society in one sector can either restrict or expand our options later on. For example, a high demand for energy could mean we would need to deploy almost all known options to reduce emissions in order to limit global temperature rise to 1.5°C above pre-industrial levels, with the potential for adverse side-effects. In particular, a pathway with high energy demand would increase our reliance on practices and technologies that remove CO₂ from the atmosphere. As of yet, such techniques have not been proven to work on a large scale and, depending on how they are implemented, could compete for land and water. By leading to lower overall energy demand, effective demand-side measures could allow for greater flexibility in how we structure our energy system. However, demand-side measures are not easy to implement and barriers have prevented the most efficient practices being used in the past.

(continued on next page)

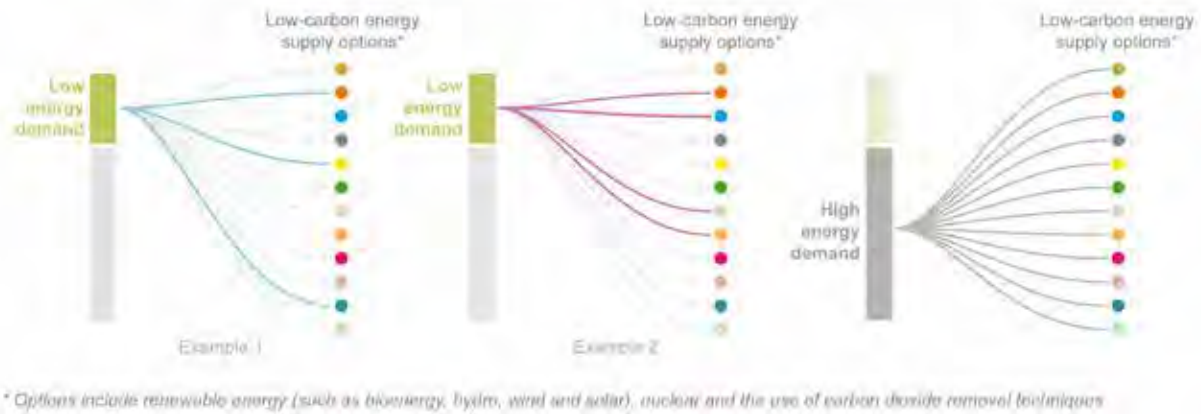
FAQ 2.2 (continued)

FAQ2.2: Energy demand and supply in 1.5°C world

Lower energy demand could allow for greater flexibility in how we structure our energy system.

Low energy demand allows more choice about which low-carbon energy supply options to use to limit warming to 1.5°C.

With high energy demand, there is less flexibility as virtually all available options would need to be considered.



FAQ 2.2, Figure 1 | Having a lower energy demand increases the flexibility in choosing options for supplying energy. A larger energy demand means many more low carbon energy supply options would need to be used.

References

- Ackerman, F. and E.A. Stanton, 2012: Climate Risks and Carbon Prices: Revising the Social Cost of Carbon. *Economics: The Open-Access, Open-Assessment E-Journal*, **6(2012-10)**, 1–25, doi:[10.5018/economics-ejournal.ja.2012-10](https://doi.org/10.5018/economics-ejournal.ja.2012-10).
- Adler, M.D. and N. Treich, 2015: Prioritarianism and Climate Change. *Environmental and Resource Economics*, **62(2)**, 279–308, doi:[10.1007/s10640-015-9960-7](https://doi.org/10.1007/s10640-015-9960-7).
- Adler, M.D. et al., 2017: Priority for the worse-off and the social cost of carbon. *Nature Climate Change*, **7(6)**, 443–449, doi:[10.1038/nclimate3298](https://doi.org/10.1038/nclimate3298).
- Akimoto, K., F. Sano, and T. Tomoda, 2017: GHG emission pathways until 2300 for the 1.5°C temperature rise target and the mitigation costs achieving the pathways. *Mitigation and Adaptation Strategies for Global Change*, 1–14, doi:[10.1007/s11027-017-9762-z](https://doi.org/10.1007/s11027-017-9762-z).
- Alcalde, J. et al., 2018: Estimating geological CO₂ storage security to deliver on climate mitigation. *Nature Communications*, **9(1)**, 2201, doi:[10.1038/s41467-018-04423-1](https://doi.org/10.1038/s41467-018-04423-1).
- Aldy, J.E. and R.N. Stavins, 2012: The Promise and Problems of Pricing Carbon. *The Journal of Environment & Development*, **21(2)**, 152–180, doi:[10.1177/1070496512442508](https://doi.org/10.1177/1070496512442508).
- Aldy, J.E. et al., 2016: Economic tools to promote transparency and comparability in the Paris Agreement. *Nature Climate Change*, **6(11)**, 1000–1004, doi:[10.1038/nclimate3106](https://doi.org/10.1038/nclimate3106).
- Allen, M.R. et al., 2009: Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, **458(7242)**, 1163–1166, doi:[10.1038/nature08019](https://doi.org/10.1038/nature08019).
- Allen, M.R. et al., 2016: New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nature Climate Change*, **6(5)**, 1–5, doi:[10.1038/nclimate2998](https://doi.org/10.1038/nclimate2998).
- Allen, M.R. et al., 2018: A solution to the misrepresentations of CO₂-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *npj Climate and Atmospheric Science*, **1(1)**, 16, doi:[10.1038/s41612-018-0026-8](https://doi.org/10.1038/s41612-018-0026-8).
- Allwood, J.M., M.F. Ashby, T.G. Gutowski, and E. Worrell, 2013: Material efficiency: providing material services with less material production. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **371(1986)**, 20120496, doi:[10.1098/rsta.2012.0496](https://doi.org/10.1098/rsta.2012.0496).
- Anderson, K. and G. Peters, 2016: The trouble with negative emissions. *Science*, **354(6309)**, 182–183, doi:[10.1126/science.aah4567](https://doi.org/10.1126/science.aah4567).
- Anenberg, S.C. et al., 2012: Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls. *Environmental Health Perspectives*, **120(6)**, 831–839, doi:[10.1289/ehp.1104301](https://doi.org/10.1289/ehp.1104301).
- Anthoff, D. and R.S.J. Tol, 2009: The impact of climate change on the balanced growth equivalent: An application of FUND. *Environmental and Resource Economics*, **43(3)**, 351–367, doi:[10.1007/s10640-009-9269-5](https://doi.org/10.1007/s10640-009-9269-5).
- Armour, K.C., 2017: Energy budget constraints on climate sensitivity in light of inconstant climate feedbacks. *Nature Climate Change*, **7(5)**, 331–335, doi:[10.1038/nclimate3278](https://doi.org/10.1038/nclimate3278).
- Arnett, A. et al., 2010: Terrestrial biogeochemical feedbacks in the climate system. *Nature Geoscience*, **3(8)**, 525–532, doi:[10.1038/ngeo905](https://doi.org/10.1038/ngeo905).
- Arroyo-Currás, T. et al., 2015: Carbon leakage in a fragmented climate regime: The dynamic response of global energy markets. *Technological Forecasting and Social Change*, **90**, 192–203, doi:[10.1016/j.techfore.2013.10.002](https://doi.org/10.1016/j.techfore.2013.10.002).
- Bachu, S., 2015: Review of CO₂ storage efficiency in deep saline aquifers. *International Journal of Greenhouse Gas Control*, **40**, 188–202, doi:[10.1016/j.ijggc.2015.01.007](https://doi.org/10.1016/j.ijggc.2015.01.007).
- Bachu, S. et al., 2007a: *Phase II Final Report from the Task Force for Review and Identification of Standards for CO₂ Storage Capacity Estimation*. CSLF-T-2007-04, Task Force on CO₂ Storage Capacity Estimation for the Technical Group (TG) of the Carbon Sequestration Leadership Forum (CSLF), 43 pp.
- Bachu, S. et al., 2007b: CO₂ storage capacity estimation: Methodology and gaps. *International Journal of Greenhouse Gas Control*, **1(4)**, 430–443, doi:[10.1016/s1750-5836\(07\)00086-2](https://doi.org/10.1016/s1750-5836(07)00086-2).
- Bajželj, B. et al., 2014: Importance of food-demand management for climate mitigation. *Nature Climate Change*, **4(10)**, 924–929, doi:[10.1038/nclimate2353](https://doi.org/10.1038/nclimate2353).
- Banerjee, R. et al., 2012: Energy End-Use: Industry. In: *Global Energy Assessment – Toward a Sustainable Future* [Johansson, T.B., N. Nakicenovic, A. Patwardhan, and L. Gomez-Echeverri (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 513–574, doi:[10.1017/cbo9780511793677.014](https://doi.org/10.1017/cbo9780511793677.014).
- Baranzini, A. et al., 2017: Carbon pricing in climate policy: seven reasons, complementary instruments, and political economy considerations. *Wiley Interdisciplinary Reviews: Climate Change*, **8(4)**, e462, doi:[10.1002/wcc.462](https://doi.org/10.1002/wcc.462).
- Bataille, C., H. Waisman, M. Colombier, L. Segafredo, and J. Williams, 2016a: The Deep Decarbonization Pathways Project (DDPP): insights and emerging issues. *Climate Policy*, **16(sup1)**, S1–S6, doi:[10.1080/14693062.2016.1179620](https://doi.org/10.1080/14693062.2016.1179620).
- Bataille, C. et al., 2016b: The need for national deep decarbonization pathways for effective climate policy. *Climate Policy*, **16(sup1)**, S7–S26, doi:[10.1080/14693062.2016.1173005](https://doi.org/10.1080/14693062.2016.1173005).
- Bauer, N. et al., 2017: Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives. *Global Environmental Change*, **42**, 316–330, doi:[10.1016/j.gloenvcha.2016.07.006](https://doi.org/10.1016/j.gloenvcha.2016.07.006).
- Bauer, N. et al., 2018: Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. *Climatic Change*, 1–16, doi:[10.1007/s10584-018-2226-y](https://doi.org/10.1007/s10584-018-2226-y).
- Beck, S. and M. Mahony, 2017: The IPCC and the politics of anticipation. *Nature Climate Change*, **7(5)**, 311–313, doi:[10.1038/nclimate3264](https://doi.org/10.1038/nclimate3264).
- Bentham, M., T. Mallows, J. Lowndes, and A. Green, 2014: CO₂ STORage evaluation database (CO₂ Stored). The UK's online storage atlas. *Energy Procedia*, **63**, 5103–5113, doi:[10.1016/j.egypro.2014.11.540](https://doi.org/10.1016/j.egypro.2014.11.540).
- Benveniste, H. et al., 2018: Impacts of nationally determined contributions on 2030 global greenhouse gas emissions: Uncertainty analysis and distribution of emissions. *Environmental Research Letters*, **13(1)**, 014022, doi:[10.1088/1748-9326/aaa0b9](https://doi.org/10.1088/1748-9326/aaa0b9).
- Berger, A. et al., 2017a: Nuclear energy and bio energy carbon capture and storage, keys for obtaining 1.5°C mean surface temperature limit. *International Journal of Global Energy Issues*, **40(3/4)**, 240–254, doi:[10.1504/ijgei.2017.086622](https://doi.org/10.1504/ijgei.2017.086622).
- Berger, A. et al., 2017b: How much can nuclear energy do about global warming? *International Journal of Global Energy Issues*, **40(1/2)**, 43–78, doi:[10.1504/ijgei.2017.080766](https://doi.org/10.1504/ijgei.2017.080766).
- Bertram, C. et al., 2015a: Carbon lock-in through capital stock inertia associated with weak near-term climate policies. *Technological Forecasting and Social Change*, **90(Part A)**, 62–72, doi:[10.1016/j.techfore.2013.10.001](https://doi.org/10.1016/j.techfore.2013.10.001).
- Bertram, C. et al., 2015b: Complementing carbon prices with technology policies to keep climate targets within reach. *Nature Climate Change*, **5(3)**, 235–239, doi:[10.1038/nclimate2514](https://doi.org/10.1038/nclimate2514).
- Bertram, C. et al., 2018: Targeted policies can compensate most of the increased sustainability risks in 1.5°C mitigation scenarios. *Environmental Research Letters*, **13(6)**, 064038, doi:[10.1088/1748-9326/aac3ec](https://doi.org/10.1088/1748-9326/aac3ec).
- Bindoff, N. et al., 2013: Detection and Attribution of Climate Change: from Global to Regional. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 867–952.
- Blanco, G. et al., 2014: Drivers, Trends and Mitigation. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 351–412.
- Boardman, A.E., D.H. Greenberg, A.R. Vining, and D.L. Weimer, 2006: *Cost-Benefit Analysis: Concepts and Practice (3rd edition)*. Pearson/Prentice Hall, Upper Saddle River, NJ, USA, 560 pp.
- Bodirsky, B.L. et al., 2012: N₂O emissions from the global agricultural nitrogen cycle-current state and future scenarios. *Biogeosciences*, **9(10)**, 4169–4197, doi:[10.5194/bg-9-4169-2012](https://doi.org/10.5194/bg-9-4169-2012).
- Bodirsky, B.L. et al., 2014: Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. *Nature Communications*, **5**, 3858, doi:[10.1038/ncomms4858](https://doi.org/10.1038/ncomms4858).
- Bond, T.C. et al., 2013: Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres*, **118(11)**, 5380–5552, doi:[10.1002/jgrd.50171](https://doi.org/10.1002/jgrd.50171).
- Bonsch, M. et al., 2014: Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy*, **8(1)**, 11–24, doi:[10.1111/gcbb.12226](https://doi.org/10.1111/gcbb.12226).

- Bosetti, V. and D.G. Victor, 2011: Politics and Economics of Second-Best Regulation of Greenhouse Gases: The Importance of Regulatory Credibility. *The Energy Journal*, **32(1)**, 1–24. www.jstor.org/stable/41323391.
- Bosetti, V., C. Carraro, E. Massetti, and M. Tavoni, 2008: International energy R&D spillovers and the economics of greenhouse gas atmospheric stabilization. *Energy Economics*, **30(6)**, 2912–2929, doi:[10.1016/j.eneco.2008.04.008](https://doi.org/10.1016/j.eneco.2008.04.008).
- Bosetti, V., C. Carraro, A. Sgobbi, and M. Tavoni, 2009: Delayed action and uncertain stabilisation targets. How much will the delay cost? *Climatic Change*, **96(3)**, 299–312, doi:[10.1007/s10584-009-9630-2](https://doi.org/10.1007/s10584-009-9630-2).
- Bosetti, V., C. Carraro, M. Galeotti, E. Massetti, and M. Tavoni, 2006: WITCH – A World Induced Technical Change Hybrid Model. *The Energy Journal*, **27**, 13–37, www.jstor.org/stable/23297044.
- Bosetti, V. et al., 2015: Sensitivity to energy technology costs: A multi-model comparison analysis. *Energy Policy*, **80**, 244–263, doi:[10.1016/j.enpol.2014.12.012](https://doi.org/10.1016/j.enpol.2014.12.012).
- Boucher, O. and G.A. Folberth, 2010: New Directions: Atmospheric methane removal as a way to mitigate climate change? *Atmospheric Environment*, **44(27)**, 3343–3345, doi:[10.1016/j.atmosenv.2010.04.032](https://doi.org/10.1016/j.atmosenv.2010.04.032).
- Bowen, A., E. Campiglio, and M. Tavoni, 2014: A macroeconomic perspective on climate change mitigation: Meeting the financing challenge. *Climate Change Economics*, **5(1)**, 1440005, doi:[10.1142/s2010007814400053](https://doi.org/10.1142/s2010007814400053).
- Bowman, N.H.A., D.J. Frame, C. Huntingford, J.A. Lowe, and M.R. Allen, 2011: Cumulative carbon emissions, emissions floors and short-term rates of warming: implications for policy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **369(1934)**, 45–66, doi:[10.1098/rsta.2010.0288](https://doi.org/10.1098/rsta.2010.0288).
- Bowman, N.H.A. et al., 2013: The role of short-lived climate pollutants in meeting temperature goals. *Nature Climate Change*, **3(12)**, 1021–1024, doi:[10.1038/nclimate2034](https://doi.org/10.1038/nclimate2034).
- Boysen, L.R., W. Lucht, and D. Gerten, 2017a: Trade-offs for food production, nature conservation and climate limit the terrestrial carbon dioxide removal potential. *Global Change Biology*, **23(10)**, 4303–4317, doi:[10.1111/gcb.13745](https://doi.org/10.1111/gcb.13745).
- Boysen, L.R., W. Lucht, D. Gerten, and V. Heck, 2016: Impacts devalue the potential of large-scale terrestrial CO₂ removal through biomass plantations. *Environmental Research Letters*, **11(9)**, 1–10, doi:[10.1088/1748-9326/11/9/095010](https://doi.org/10.1088/1748-9326/11/9/095010).
- Boysen, L.R. et al., 2017b: The limits to global-warming mitigation by terrestrial carbon removal. *Earth's Future*, **5(5)**, 463–474, doi:[10.1002/2016ef000469](https://doi.org/10.1002/2016ef000469).
- Breyer, C. et al., 2017: On the role of solar photovoltaics in global energy transition scenarios. *Progress in Photovoltaics: Research and Applications*, **25(8)**, 727–745, doi:[10.1002/ppp.2885](https://doi.org/10.1002/ppp.2885).
- Brown, M.A. and Y. Li, 2018: Carbon pricing and energy efficiency: pathways to deep decarbonization of the US electric sector. *Energy Efficiency*, 1–19, doi:[10.1007/s12053-018-9686-9](https://doi.org/10.1007/s12053-018-9686-9).
- Brown, P.T. and K. Caldeira, 2017: Greater future global warming inferred from Earth's recent energy budget. *Nature*, **552(7683)**, 45–50, doi:[10.1038/nature24672](https://doi.org/10.1038/nature24672).
- Bruckner, T., I.A. Bashmakov, and Y. Mulugetta, 2014: Energy Systems. 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. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 511–598.
- Brunner, S. and K. Enting, 2014: Climate finance: A transaction cost perspective on the structure of state-to-state transfers. *Global Environmental Change*, **27**, 138–143, doi:[10.1016/j.gloenvcha.2014.05.005](https://doi.org/10.1016/j.gloenvcha.2014.05.005).
- Brynnolf, S., M. Taljegard, M. Grahn, and J. Hansson, 2018: Electrofuels for the transport sector: A review of production costs. *Renewable and Sustainable Energy Reviews*, **81**, 1887–1905, doi:[10.1016/j.rser.2017.05.288](https://doi.org/10.1016/j.rser.2017.05.288).
- Buck, H.J., 2016: Rapid scale-up of negative emissions technologies: social barriers and social implications. *Climatic Change*, 1–13, doi:[10.1007/s10584-016-1770-6](https://doi.org/10.1007/s10584-016-1770-6).
- Burke, E.J., I.P. Hartley, and C.D. Jones, 2012: Uncertainties in the global temperature change caused by carbon release from permafrost thawing. *Cryosphere*, **6(5)**, 1063–1076, doi:[10.5194/tc-6-1063-2012](https://doi.org/10.5194/tc-6-1063-2012).
- Burke, E.J. et al., 2017: Quantifying uncertainties of permafrost carbon-climate feedbacks. *Biogeosciences*, **14(12)**, 3051–3066, doi:[10.5194/bg-14-3051-2017](https://doi.org/10.5194/bg-14-3051-2017).
- Burns, W. and S. Nicholson, 2017: Bioenergy and carbon capture with storage (BECCS): the prospects and challenges of an emerging climate policy response. *Journal of Environmental Studies and Sciences*, **7(4)**, 527–534, doi:[10.1007/s13412-017-0445-6](https://doi.org/10.1007/s13412-017-0445-6).
- Cadule, P., L. Bopp, and P. Friedlingstein, 2009: A revised estimate of the processes contributing to global warming due to climate-carbon feedback. *Geophysical Research Letters*, **36(14)**, L14705, doi:[10.1029/2009gl038681](https://doi.org/10.1029/2009gl038681).
- Cai, Y., K.L. Judd, T.M. Lenton, T.S. Lontzek, and D. Narita, 2015: Environmental tipping points significantly affect the cost-benefit assessment of climate policies. *Proceedings of the National Academy of Sciences*, **112(15)**, 4606–4611, doi:[10.1073/pnas.1503890112](https://doi.org/10.1073/pnas.1503890112).
- Calvin, K. et al., 2014: Trade-offs of different land and bioenergy policies on the path to achieving climate targets. *Climatic Change*, **123(3–4)**, 691–704, doi:[10.1007/s10584-013-0897-y](https://doi.org/10.1007/s10584-013-0897-y).
- Calvin, K. et al., 2017: The SSP4: A world of deepening inequality. *Global Environmental Change*, **42**, 284–296, doi:[10.1016/j.gloenvcha.2016.06.010](https://doi.org/10.1016/j.gloenvcha.2016.06.010).
- Canadell, J.G. and M.R. Raupach, 2008: Managing Forests for Climate Change Mitigation. *Science*, **320(5882)**, 1456–1457, doi:[10.1126/science.1155458](https://doi.org/10.1126/science.1155458).
- Carlsaw, K.S. et al., 2013: Large contribution of natural aerosols to uncertainty in indirect forcing. *Nature*, **503(7474)**, 67–71, doi:[10.1038/nature12674](https://doi.org/10.1038/nature12674).
- Ceppi, P. and J.M. Gregory, 2017: Relationship of tropospheric stability to climate sensitivity and Earth's observed radiation budget. *Proceedings of the National Academy of Sciences*, **114(50)**, 13126–13131, doi:[10.1073/pnas.1714308114](https://doi.org/10.1073/pnas.1714308114).
- Chan, S., P. Ellinger, and O. Widerberg, 2018: Exploring national and regional orchestration of non-state action for a <1.5°C world. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 135–152, doi:[10.1007/s10784-018-9384-2](https://doi.org/10.1007/s10784-018-9384-2).
- Chen, C. and M. Tavoni, 2013: Direct air capture of CO₂ and climate stabilization: A model based assessment. *Climatic Change*, **118(1)**, 59–72, doi:[10.1007/s10584-013-0714-7](https://doi.org/10.1007/s10584-013-0714-7).
- Choi, Y.-S., D. Young, S. Nešić, and L.G.S. Gray, 2013: Wellbore integrity and corrosion of carbon steel in CO₂ geologic storage environments: A literature review. *International Journal of Greenhouse Gas Control*, **16**, S70–S77, doi:[10.1016/j.ijggc.2012.12.028](https://doi.org/10.1016/j.ijggc.2012.12.028).
- Clack, C.T.M. et al., 2017: Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar. *Proceedings of the National Academy of Sciences*, **114(26)**, 6722–6727, doi:[10.1073/pnas.1610381114](https://doi.org/10.1073/pnas.1610381114).
- Clarke, L. et al., 2014: Assessing transformation pathways. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 413–510.
- Collins, M. et al., 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1029–1136.
- Collins, W.J. et al., 2018: Increased importance of methane reduction for a 1.5 degree target. *Environmental Research Letters*, **13(5)**, 054003, doi:[10.1088/1748-9326/aab89c](https://doi.org/10.1088/1748-9326/aab89c).
- Comyn-Platt, E. et al., 2018: Carbon budgets for 1.5 and 2°C targets lowered by natural wetland and permafrost feedbacks. *Nature Geoscience*, **11(8)**, 568–573, doi:[10.1038/s41561-018-0174-9](https://doi.org/10.1038/s41561-018-0174-9).
- Cox, P.M., C. Huntingford, and M.S. Williamson, 2018: Emergent constraint on equilibrium climate sensitivity from global temperature variability. *Nature*, **553(7688)**, 319–322, doi:[10.1038/nature25450](https://doi.org/10.1038/nature25450).
- Crespo Cuaresma, J., 2017: Income projections for climate change research: A framework based on human capital dynamics. *Global Environmental Change*, **42**, 226–236, doi:[10.1016/j.gloenvcha.2015.02.012](https://doi.org/10.1016/j.gloenvcha.2015.02.012).
- Creutzig, F., 2016: Evolving Narratives of Low-Carbon Futures in Transportation. *Transport Reviews*, **36(3)**, 341–360, doi:[10.1080/01441647.2015.1079277](https://doi.org/10.1080/01441647.2015.1079277).
- Creutzig, F. et al., 2012: Reconciling top-down and bottom-up modelling on future bioenergy deployment. *Nature Climate Change*, **2(5)**, 320–327, doi:[10.1038/nclimate1416](https://doi.org/10.1038/nclimate1416).
- Creutzig, F. et al., 2015: Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy*, **7(5)**, 916–944, doi:[10.1111/gcbb.12205](https://doi.org/10.1111/gcbb.12205).
- Creutzig, F. et al., 2017: The underestimated potential of solar energy to mitigate climate change. *Nature Energy*, **2(9)**, 17140, doi:[10.1038/nenergy.2017.140](https://doi.org/10.1038/nenergy.2017.140).
- Davis, S.C. et al., 2013: Management swing potential for bioenergy crops. *GCB Bioenergy*, **5(6)**, 623–638, doi:[10.1111/gcbb.12042](https://doi.org/10.1111/gcbb.12042).
- Davis, S.J. and K. Caldeira, 2010: Consumption-based accounting of CO₂ emissions. *Proceedings of the National Academy of Sciences*, **107(12)**, 5687–92, doi:[10.1073/pnas.0906974107](https://doi.org/10.1073/pnas.0906974107).

- de Richter, R., T. Ming, P. Davies, W. Liu, and S. Caillol, 2017: Removal of non-CO₂ greenhouse gases by large-scale atmospheric solar photocatalysis. *Progress in Energy and Combustion Science*, **60**, 68–96, doi:10.1016/j.pecs.2017.01.001.
- de Vries, W., M. Posch, D. Simpson, and G.J. Reinds, 2017: Modelling long-term impacts of changes in climate, nitrogen deposition and ozone exposure on carbon sequestration of European forest ecosystems. *Science of The Total Environment*, **605–606**, 1097–1116, doi:10.1016/j.scitotenv.2017.06.132.
- Dell, M., B.F. Jones, and B.A. Olken, 2014: What Do We Learn from the Weather? The New Climate–Economy Literature. *Journal of Economic Literature*, **52(3)**, 740–798, www.jstor.org/stable/24434109.
- Dellink, R., J. Chateau, E. Lanzi, and B. Magné, 2017: Long-term economic growth projections in the Shared Socioeconomic Pathways. *Global Environmental Change*, **42**, 1–15, doi:10.1016/j.gloenvcha.2015.06.004.
- Delponte, I., I. Pittaluga, and C. Schenone, 2017: Monitoring and evaluation of Sustainable Energy Action Plan: Practice and perspective. *Energy Policy*, **100**, 9–17, doi:10.1016/j.enpol.2016.10.003.
- den Elzen, M.G.J., D.P. van Vuuren, and J. van Vliet, 2010: Postponing emission reductions from 2020 to 2030 increases climate risks and long-term costs. *Climatic Change*, **99(1)**, 313–320, doi:10.1007/s10584-010-9798-5.
- den Elzen, M.G.J. et al., 2016: Contribution of the G20 economies to the global impact of the Paris agreement climate proposals. *Climatic Change*, **137(3–4)**, 655–665, doi:10.1007/s10584-016-1700-7.
- Dennig, F., M.B. Budolfson, M. Fleurbaey, A. Siebert, and R.H. Soclow, 2015: Inequality climate impacts on the future poor, and carbon prices. *Proceedings of the National Academy of Sciences*, **112(52)**, 15827–15832, doi:10.1073/pnas.1513967112.
- Di, H.J. and K. Cameron, 2016: Inhibition of nitrification to mitigate nitrate leaching and nitrous oxide emissions in grazed grassland: A review. *Journal of Soils and Sediments*, **16**, 1401–1420, doi:10.1007/s11368-016-1403-8.
- Doelman, J.C. et al., 2018: Exploring SSP land-use dynamics using the IMAGE model: Regional and gridded scenarios of land-use change and land-based climate change mitigation. *Global Environmental Change*, **48**, 119–135, doi:10.1016/j.gloenvcha.2017.11.014.
- Dooley, J.J., 2013: Estimating the supply and demand for deep geologic CO₂ storage capacity over the course of the 21st century: A meta-analysis of the literature. *Energy Procedia*, **37**, 5141–5150, doi:10.1016/j.egypro.2013.06.429.
- Dooley, K. and S. Kartha, 2018: Land-based negative emissions: risks for climate mitigation and impacts on sustainable development. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 79–98, doi:10.1007/s10784-017-9382-9.
- Duce, R.A. et al., 2008: Impacts of Atmospheric Anthropogenic Nitrogen on the Open Ocean. *Science*, **320(5878)**, 893–897, doi:10.1126/science.1150369.
- EC, 2017: *High-Level Expert Group on Sustainable Finance interim report – Financing a sustainable European economy*. European Commission, Brussels, Belgium, 72 pp.
- Edenhofer, O., J.C. Steckel, M. Jakob, and C. Bertram, 2018: Reports of coal's terminal decline may be exaggerated. *Environmental Research Letters*, **13(2)**, 024019, doi:10.1088/1748-9326/aa3a3a2.
- Erb, K.-H., H. Haberl, and C. Plutzer, 2012: Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability. *Energy Policy*, **47**, 260–269, doi:10.1016/j.enpol.2012.04.066.
- Erb, K.-H. et al., 2016a: Biomass turnover time in terrestrial ecosystems halved by land use. *Nature Geoscience*, **9(9)**, 674–678, doi:10.1038/ngeo2782.
- Erb, K.-H. et al., 2016b: Exploring the biophysical option space for feeding the world without deforestation. *Nature Communications*, **7**, 11382, doi:10.1038/ncomms11382.
- Erb, K.-H. et al., 2018: Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature*, **553**, 73–76, doi:10.1038/nature25138.
- Erickson, P., S. Kartha, M. Lazarus, and K. Tempest, 2015: Assessing carbon lock-in. *Environmental Research Letters*, **10(8)**, 084023, doi:10.1088/1748-9326/10/8/084023.
- Etminan, M., G. Myhre, E.J. Highwood, and K.P. Shine, 2016: Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters*, **43(24)**, 12,614–12,623, doi:10.1002/2016gl071930.
- Faehn, T. and E. Isaksen, 2016: Diffusion of Climate Technologies in the Presence of Commitment Problems. *The Energy Journal*, **37(2)**, 155–180, doi:10.5547/01956574.37.2.tf.ae.
- Fankhauser, S., A. Sahni, A. Savvas, and J. Ward, 2016: Where are the gaps in climate finance? *Climate and Development*, **8(3)**, 203–206, doi:10.1080/17565529.2015.1064811.
- FAOSTAT, 2018: Database Collection of the Food and Agriculture Organization of the United Nations. FAO. Retrieved from: www.fao.org/faostat.
- Fawcett, A.A. et al., 2015: Can Paris pledges avert severe climate change? *Science*, **350(6265)**, 1168–1169, doi:10.1126/science.aad5761.
- Forster, P.M., 2016: Inference of Climate Sensitivity from Analysis of Earth's Energy Budget. *Annual Review of Earth and Planetary Sciences*, **44(1)**, 85–106, doi:10.1146/annurev-earth-060614-105156.
- Frank, S. et al., 2017: Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters*, **12(10)**, 105004, doi:10.1088/1748-9326/aa8c83.
- Frank, S. et al., 2018: Structural change as a key component for agricultural non-CO₂ mitigation efforts. *Nature Communications*, **9(1)**, 1060, doi:10.1038/s41467-018-03489-1.
- Frankfurt School-UNEP Centre/BNEF, 2017: *Global Trends in Renewable Energy Investment 2017*. Frankfurt School of Finance & Management gGmbH, Frankfurt, Germany, 90 pp.
- Fricko, O. et al., 2016: Energy sector water use implications of a 2°C climate policy. *Environmental Research Letters*, **11(3)**, 034011, doi:10.1088/1748-9326/11/3/034011.
- Fricko, O. et al., 2017: The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change*, **42**, 251–267, doi:10.1016/j.gloenvcha.2016.06.004.
- Friedlingstein, P. et al., 2014a: Persistent growth of CO₂ emissions and implications for reaching climate targets. *Nature Geoscience*, **7(10)**, 709–715, doi:10.1038/ngeo2248.
- Friedlingstein, P. et al., 2014b: Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks. *Journal of Climate*, **27(2)**, 511–526, doi:10.1175/jcli-d-12-00579.1.
- Frölicher, T.L. and F. Joos, 2010: Reversible and irreversible impacts of greenhouse gas emissions in multi-century projections with the NCAR global coupled carbon cycle–climate model. *Climate Dynamics*, **35(7)**, 1439–1459, doi:10.1007/s00382-009-0727-0.
- Fuglestedt, J.S. et al., 2010: Transport impacts on atmosphere and climate: Metrics. *Atmospheric Environment*, **44(37)**, 4648–4677, doi:10.1016/j.atmosenv.2009.04.044.
- Fujimori, S., 2017: SSP3: AIM Implementation of Shared Socioeconomic Pathways. *Global Environmental Change*, **42**, 268–283, doi:10.1016/j.gloenvcha.2016.06.009.
- Fujimori, S. et al., 2016: Implication of Paris Agreement in the context of long-term climate mitigation goals. *SpringerPlus*, **5(1)**, 1620, doi:10.1186/s40064-016-3235-9.
- Fuss, S. et al., 2014: Betting on negative emissions. *Nature Climate Change*, **4(10)**, 850–853, doi:10.1038/nclimate2392.
- Fuss, S. et al., 2016: Research priorities for negative emissions. *Environmental Research Letters*, **11(11)**, 115007, doi:10.1088/1748-9326/11/11/115007.
- Fuss, S. et al., 2018: Negative emissions – Part 2: Costs, potentials and side effects. *Environmental Research Letters*, **13(6)**, 063002, doi:10.1088/1748-9326/aaab9f.
- Geden, O., 2015: Policy: Climate advisers must maintain integrity. *Nature*, **521(7550)**, 27–28, doi:10.1038/521027a.
- Geels, F.W., B.K. Sovacool, T. Schwanen, and S. Sorrell, 2017: Sociotechnical transitions for deep decarbonization. *Science*, **357(6357)**, 1242–1244, doi:10.1126/science.aao3760.
- Gerber, P.J. et al., 2013: *Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 115 pp.
- Gernaat, D.E.H.J. et al., 2015: Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. *Global Environmental Change*, **33**, 142–153, doi:10.1016/j.gloenvcha.2015.04.010.
- Ghan, S.J. et al., 2013: A simple model of global aerosol indirect effects. *Journal of Geophysical Research: Atmospheres*, **118(12)**, 6688–6707, doi:10.1002/jgrd.50567.
- Giannakidis, G., K. Karlsson, M. Labriet, and B. Ó Gallachóir (eds.), 2018: *Limiting Global Warming to Well Below 2°C: Energy System Modelling and Policy Development*. Springer International Publishing, Cham, Switzerland, 423 pp., doi:10.1007/978-3-319-74424-7.
- Gillett, N.P., V.K. Arora, D. Matthews, and M.R. Allen, 2013: Constraining the Ratio of Global Warming to Cumulative CO₂ Emissions Using CMIP5 Simulations. *Journal of Climate*, **26(18)**, 6844–6858, doi:10.1175/jcli-d-12-00476.1.
- Gillett, N.P., V.K. Arora, K. Zickfeld, S.J. Marshall, and W.J. Merryfield, 2011: Ongoing climate change following a complete cessation of carbon dioxide emissions. *Nature Geoscience*, **4(2)**, 83–87, doi:10.1038/ngeo1047.

- Global CCS Institute, 2016: *The Global Status of CCS: 2016 Summary Report*. Global CCS Institute, Melbourne, Australia, 28 pp.
- González-Eguino, M., A. Olabe, and T. Ribera, 2017: New Coal-Fired Plants Jeopardise Paris Agreement. *Sustainability*, **9(2)**, 168, doi:[10.3390/su9020168](https://doi.org/10.3390/su9020168).
- Goodwin, P., S. Brown, I.D. Haigh, R.J. Nicholls, and J.M. Matter, 2018a: Adjusting Mitigation Pathways to Stabilize Climate at 1.5°C and 2.0°C Rise in Global Temperatures to Year 2300. *Earth's Future*, 0–3, doi:[10.1002/2017ef000732](https://doi.org/10.1002/2017ef000732).
- Goodwin, P. et al., 2018b: Pathways to 1.5 and 2°C warming based on observational and geological constraints. *Nature Geoscience*, **11(1)**, 1–22, doi:[10.1038/s41561-017-0054-8](https://doi.org/10.1038/s41561-017-0054-8).
- Gota, S., C. Huizenga, K. Peet, N. Medimorec, and S. Bakker, 2018: Decarbonising transport to achieve Paris Agreement targets. *Energy Efficiency*, 1–24, doi:[10.1007/s12053-018-9671-3](https://doi.org/10.1007/s12053-018-9671-3).
- Gough, C. and P. Upham, 2011: Biomass energy with carbon capture and storage (BECCS or Bio-CCS). *Greenhouse Gases: Science and Technology*, **1(4)**, 324–334, doi:[10.1002/ghg.34](https://doi.org/10.1002/ghg.34).
- Goulder, L. and A. Schein, 2013: Carbon Taxes vs. Cap and Trade: A Critical Review. *Climate Change Economics*, **04(03)**, 1350010, doi:[10.1142/s2010007813500103](https://doi.org/10.1142/s2010007813500103).
- Grassi, G. et al., 2017: The key role of forests in meeting climate targets requires science for credible mitigation. *Nature Climate Change*, **7(3)**, 220–226, doi:[10.1038/nclimate3227](https://doi.org/10.1038/nclimate3227).
- Greene, C.H. et al., 2017: Geoengineering, marine microalgae, and climate stabilization in the 21st century. *Earth's Future*, **5(3)**, 278–284, doi:[10.1002/2016ef000486](https://doi.org/10.1002/2016ef000486).
- Gregory, J.M. and T. Andrews, 2016: Variation in climate sensitivity and feedback parameters during the historical period. *Geophysical Research Letters*, **43(8)**, 3911–3920, doi:[10.1002/2016gl068406](https://doi.org/10.1002/2016gl068406).
- Gren, I.-M. and A.Z. Akliu, 2016: Policy design for forest carbon sequestration: A review of the literature. *Forest Policy and Economics*, **70**, 128–136, doi:[10.1016/j.forpol.2016.06.008](https://doi.org/10.1016/j.forpol.2016.06.008).
- Griscom, B.W. et al., 2017: Natural climate solutions. *Proceedings of the National Academy of Sciences*, **114(44)**, 11645–11650, doi:[10.1073/pnas.1710465114](https://doi.org/10.1073/pnas.1710465114).
- Grubb, M., J.C. Hourcade, and K. Neuhoﬀ, 2014: *Planetary economics: Energy, climate change and the three domains of sustainable development*. Routledge Earthscan, Abingdon, UK and New York, NY, USA, 520 pp.
- Grubler, A. and C. Wilson (eds.), 2014: *Energy Technology Innovation: Learning from Historical Successes and Failures*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 400 pp., doi:[10.1017/cbo9781139150880](https://doi.org/10.1017/cbo9781139150880).
- 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. *Nature Energy*, **3(6)**, 515–527, doi:[10.1038/s41560-018-0172-6](https://doi.org/10.1038/s41560-018-0172-6).
- Guivarch, C. and J. Rogelj, 2017: *Carbon price variations in 2°C scenarios explored*. Carbon Pricing Leadership Coalition (CPLC), 15 pp.
- Güneralp, B. et al., 2017: Global scenarios of urban density and its impacts on building energy use through 2050. *Proceedings of the National Academy of Sciences*, **114(34)**, 8945–8950, doi:[10.1073/pnas.1606035114](https://doi.org/10.1073/pnas.1606035114).
- Gupta, S. and J. Harnisch, 2014: Cross-cutting Investment and Finance Issues. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the 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. Zwinkel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1207–1246.
- Haberl, H., 2015: Competition for land: A sociometabolic perspective. *Ecological Economics*, **119**, 424–431, doi:[10.1016/j.ecolecon.2014.10.002](https://doi.org/10.1016/j.ecolecon.2014.10.002).
- Haberl, H. et al., 2011: Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. *Biomass and Bioenergy*, **35(12)**, 4753–4769, doi:[10.1016/j.biombioe.2011.04.035](https://doi.org/10.1016/j.biombioe.2011.04.035).
- Haberl, H. et al., 2013: Bioenergy: how much can we expect for 2050? *Environmental Research Letters*, **8(3)**, 031004, doi:[10.1088/1748-9326/8/3/031004](https://doi.org/10.1088/1748-9326/8/3/031004).
- Harmes, A., 2011: The Limits of Carbon Disclosure: Theorizing the Business Case for Investor Environmentalism. *Global Environmental Politics*, **11(2)**, 98–119, doi:[10.1162/glep_a.00057](https://doi.org/10.1162/glep_a.00057).
- Hartmann, J. et al., 2013: Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Reviews of Geophysics*, **51(2)**, 113–149, doi:[10.1002/rog.20004](https://doi.org/10.1002/rog.20004).
- Hauglustaine, D.A., Y. Balkanski, and M. Schulz, 2014: A global model simulation of present and future nitrate aerosols and their direct radiative forcing of climate. *Atmospheric Chemistry and Physics*, **14**, 11031–11063, doi:[10.5194/acp-14-11031-2014](https://doi.org/10.5194/acp-14-11031-2014).
- Havlik, P. et al., 2013: Crop Productivity and the Global Livestock Sector: Implications for Land Use Change and Greenhouse Gas Emissions. *American Journal of Agricultural Economics*, **95(2)**, 442–448, doi:[10.1093/ajae/aas085](https://doi.org/10.1093/ajae/aas085).
- Havlik, P. et al., 2014: Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences*, **111(10)**, 3709–3714, doi:[10.1073/pnas.1308044111](https://doi.org/10.1073/pnas.1308044111).
- Heck, V., D. Gerten, W. Lucht, and L.R. Boysen, 2016: Is extensive terrestrial carbon dioxide removal a 'green' form of geoengineering? A global modelling study. *Global and Planetary Change*, **137**, 123–130, doi:[10.1016/j.gloplacha.2015.12.008](https://doi.org/10.1016/j.gloplacha.2015.12.008).
- Heck, V., D. Gerten, W. Lucht, and A. Popp, 2018: Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change*, **8(2)**, 151–155, doi:[10.1038/s41558-017-0064-y](https://doi.org/10.1038/s41558-017-0064-y).
- Hejazi, M. et al., 2014: Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. *Technological Forecasting and Social Change*, **81**, 205–226, doi:[10.1016/j.techfore.2013.05.006](https://doi.org/10.1016/j.techfore.2013.05.006).
- Herrero, M. et al., 2016: Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change*, **6(5)**, 452–461, doi:[10.1038/nclimate2925](https://doi.org/10.1038/nclimate2925).
- Herrington, T. and K. Zickfeld, 2014: Path independence of climate and carbon cycle response over a broad range of cumulative carbon emissions. *Earth System Dynamics*, **5**, 409–422, doi:[10.5194/esd-5-409-2014](https://doi.org/10.5194/esd-5-409-2014).
- Herzog, H., K. Caldeira, and J. Reilly, 2003: An Issue of Permanence: Assessing the Effectiveness of Temporary Carbon Storage. *Climatic Change*, **59(3)**, 293–310, doi:[10.1023/a:1024801618900](https://doi.org/10.1023/a:1024801618900).
- Hildingsson, R. and B. Johansson, 2016: Governing low-carbon energy transitions in sustainable ways: Potential synergies and conflicts between climate and environmental policy objectives. *Energy Policy*, **88**, 245–252, doi:[10.1016/j.enpol.2015.10.029](https://doi.org/10.1016/j.enpol.2015.10.029).
- Hoesly, R.M. et al., 2018: Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). *Geoscientific Model Development*, **11(1)**, 369–408, doi:[10.5194/gmd-11-369-2018](https://doi.org/10.5194/gmd-11-369-2018).
- Hof, A.F. et al., 2017: Global and regional abatement costs of Nationally Determined Contributions (NDCs) and of enhanced action to levels well below 2°C and 1.5°C. *Environmental Science & Policy*, **71**, 30–40, doi:[10.1016/j.envsci.2017.02.008](https://doi.org/10.1016/j.envsci.2017.02.008).
- Höglund-Isaksson, L. et al., 2017: Cost estimates of the Kigali Amendment to phase-down hydrofluorocarbons. *Environmental Science & Policy*, **75**, 138–147, doi:[10.1016/j.envsci.2017.05.006](https://doi.org/10.1016/j.envsci.2017.05.006).
- Holz, C., S. Kartha, and T. Athanasiou, 2018a: Fairly sharing 1.5: national fair shares of a 1.5°C-compliant global mitigation effort. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 117–134, doi:[10.1007/s10784-017-9371-z](https://doi.org/10.1007/s10784-017-9371-z).
- Holz, C., L.S. Siegel, E. Johnston, A.P. Jones, and J. Sterman, 2018b: Ratcheting ambition to limit warming to 1.5°C – trade-offs between emission reductions and carbon dioxide removal. *Environmental Research Letters*, **13(6)**, 064028, doi:[10.1088/1748-9326/aa0c01](https://doi.org/10.1088/1748-9326/aa0c01).
- Honegger, M. and D. Reiner, 2018: The political economy of negative emissions technologies: consequences for international policy design. *Climate Policy*, **18(3)**, 306–321, doi:[10.1080/14693062.2017.1413322](https://doi.org/10.1080/14693062.2017.1413322).
- Hong, S., C.J.A. Bradshaw, and B.W. Brook, 2015: Global zero-carbon energy pathways using viable mixes of nuclear and renewables. *Applied Energy*, **143**, 451–459, doi:[10.1016/j.apenergy.2015.01.006](https://doi.org/10.1016/j.apenergy.2015.01.006).
- Hope, C., 2006: The Marginal Impact of CO₂ from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern. *The Integrated Assessment Journal*, **6(1)**, 19–56, http://journals.sfu.ca/int_assess/index.php/iaj/article/viewarticle/227.
- Hristov, A.N. et al., 2015: An inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production. *Proceedings of the National Academy of Sciences*, **112(34)**, 10663–8, doi:[10.1073/pnas.1504124112](https://doi.org/10.1073/pnas.1504124112).
- Hsiang, S. et al., 2017: Estimating economic damage from climate change in the United States. *Science*, **356(6345)**, 1362–1369, doi:[10.1126/science.aal4369](https://doi.org/10.1126/science.aal4369).
- Humpenöder, F. et al., 2014: Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environmental Research Letters*, **9(6)**, 064029, doi:[10.1088/1748-9326/9/6/064029](https://doi.org/10.1088/1748-9326/9/6/064029).

- Humpenöder, F. et al., 2018: Large-scale bioenergy production: how to resolve sustainability trade-offs? *Environmental Research Letters*, **13**(2), 024011, doi:[10.1088/1748-9326/aa9e3b](https://doi.org/10.1088/1748-9326/aa9e3b).
- Huntingford, C. and J. Lowe, 2007: "Overshoot" Scenarios and Climate Change. *Science*, **316**(5826), 829, doi:[10.1126/science.316.5826.829b](https://doi.org/10.1126/science.316.5826.829b).
- IEA, 2014: *Energy Technology Perspectives 2014: Harnessing Electricity's Potential*. International Energy Agency (IEA), Paris, France, 382 pp.
- IEA, 2015a: *Energy and Climate Change. World Energy Outlook Special Report*. International Energy Agency (IEA), Paris, France, 200 pp.
- IEA, 2015b: *Energy Technology Perspectives 2015: Mobilising Innovation to Accelerate Climate Action*. International Energy Agency (IEA), Paris, France, 418 pp.
- IEA, 2016a: *Energy Technology Perspectives 2016: Towards Sustainable Urban Energy Systems*. International Energy Agency (IEA), Paris, France, 418 pp.
- IEA, 2016b: *World Energy Investment 2016*. International Energy Agency (IEA), Paris, France, 177 pp.
- IEA, 2017a: *Energy Technology Perspectives 2017: Catalyzing Energy Technology Transformations*. International Energy Agency (IEA), Paris, France, 443 pp.
- IEA, 2017b: *Renewables Information – Overview (2017 edition)*. International Energy Agency (IEA), Paris, 11 pp.
- IEA, 2017c: *World Energy Investment 2017*. International Energy Agency (IEA), Paris, France, 191 pp.
- IEA, 2017d: *World Energy Outlook 2017*. International Energy Agency (IEA), Paris, France, 782 pp.
- IEA, 2017e: *World Energy Statistics 2017*. International Energy Agency (IEA). OECD Publishing, Paris, France, 847 pp., doi:[10.1787/world_energy_stats-2017-en](https://doi.org/10.1787/world_energy_stats-2017-en).
- IEAGHG, 2006: *Near zero emission technology for CO₂ capture from power plant*. IEAGHG 2006/13, IEA Greenhouse Gas R&D Programme, Cheltenham, UK, 114 pp.
- Ilyina, T., D. Wolf-Gladrow, G. Munhoven, and C. Heinze, 2013: Assessing the potential of calcium-based artificial ocean alkalization to mitigate rising atmospheric CO₂ and ocean acidification. *Geophysical Research Letters*, **40**(22), 5909–5914, doi:[10.1002/2013gl057981](https://doi.org/10.1002/2013gl057981).
- IPCC, 2005: IPCC Special Report on Carbon Dioxide Capture and Storage. [Metz, B., O. Davidson, H.C. de Coninck, M. Loos, and L.A. Meyer (eds.)]. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.
- IPCC, 2013a: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.
- IPCC, 2013b: *Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.
- IPCC, 2014a: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. [Core Writing Team, R.K. Pachauri, and L.A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 151 pp.
- IPCC, 2014b: Summary for Policymakers. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadne, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–30.
- IPCC/TEAP, 2005: Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons. [Metz, B., L. Kuijpers, S. Solomon, S.O. Andersen, O. Davidson, J. Pons, D. Jager, T. Kestin, M. Manning, and L. Meyer (eds.)]. A Special Report of the Intergovernmental Panel on Climate Change (IPCC) and Technology and Economic Assessment Panel (TEAP). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 485 pp.
- Irlam, L., 2017: *Global Costs of Carbon Capture and Storage*. Global CCS Institute, Melbourne, Australia, 14 pp.
- IWG, 2016: *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866*. Interagency Working Group on Social Cost of Greenhouse Gases, United States, 35 pp.
- Iyer, G.C. et al., 2015: Improved representation of investment decisions in assessments of CO₂ mitigation. *Nature Climate Change*, **5**(5), 436–440, doi:[10.1038/nclimate2553](https://doi.org/10.1038/nclimate2553).
- Jackson, R.B. et al., 2017: Warning signs for stabilizing global CO₂ emissions. *Environmental Research Letters*, **12**(11), 110202, doi:[10.1088/1748-9326/aa9662](https://doi.org/10.1088/1748-9326/aa9662).
- Jacobson, M.Z., 2002: Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming. *Journal of Geophysical Research: Atmospheres*, **107**(D19), 4410, doi:[10.1029/2001jd001376](https://doi.org/10.1029/2001jd001376).
- Jacobson, M.Z., 2010: Short-term effects of controlling fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health. *Journal of Geophysical Research: Atmospheres*, **115**(D14), D14209, doi:[10.1029/2009jd013795](https://doi.org/10.1029/2009jd013795).
- Jacobson, M.Z., 2017: Roadmaps to Transition Countries to 100% Clean, Renewable Energy for All Purposes to Curtail Global Warming, Air Pollution, and Energy Risk. *Earth's Future*, **5**(10), 948–952, doi:[10.1002/2017ef000672](https://doi.org/10.1002/2017ef000672).
- Jacobson, M.Z. et al., 2017: 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. *Joule*, **1**(1), 108–121, doi:[10.1016/j.joule.2017.07.005](https://doi.org/10.1016/j.joule.2017.07.005).
- Jakob, M. and J.C. Steckel, 2016: Implications of climate change mitigation for sustainable development. *Environmental Research Letters*, **11**(10), 104010, doi:[10.1088/1748-9326/11/10/104010](https://doi.org/10.1088/1748-9326/11/10/104010).
- Jakob, M. et al., 2014: Feasible mitigation actions in developing countries. *Nature Climate Change*, **4**(11), 961–968, doi:[10.1038/nclimate2370](https://doi.org/10.1038/nclimate2370).
- Johnson, N. et al., 2015: Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. *Technological Forecasting and Social Change*, **90**, 89–102, doi:[10.1016/j.techfore.2014.02.028](https://doi.org/10.1016/j.techfore.2014.02.028).
- Jones, A., J.M. Haywood, and C.D. Jones, 2018: Can reducing black carbon and methane below RCP2.6 levels keep global warming below 1.5°C? *Atmospheric Science Letters*, **19**(6), e821, doi:[10.1002/asl.821](https://doi.org/10.1002/asl.821).
- Jones, C.D. et al., 2016: Simulating the Earth system response to negative emissions. *Environmental Research Letters*, **11**(9), 095012, doi:[10.1088/1748-9326/11/9/095012](https://doi.org/10.1088/1748-9326/11/9/095012).
- Jones, D.G. et al., 2015: Developments since 2005 in understanding potential environmental impacts of CO₂ leakage from geological storage. *International Journal of Greenhouse Gas Control*, **40**, 350–377, doi:[10.1016/j.ijggc.2015.05.032](https://doi.org/10.1016/j.ijggc.2015.05.032).
- Joshi, V. and S. Kumar, 2015: Meat Analogues: Plant based alternatives to meat products – A review. *International Journal of Food Fermentation and Technology*, **5**(2), 107–119, doi:[10.5958/2277-9396.2016.00001.5](https://doi.org/10.5958/2277-9396.2016.00001.5).
- Kandlikar, M., 1995: The relative role of trace gas emissions in greenhouse abatement policies. *Energy Policy*, **23**(10), 879–883, doi:[10.1016/0301-4215\(95\)00108-u](https://doi.org/10.1016/0301-4215(95)00108-u).
- KC, S. and W. Lutz, 2017: The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change*, **42**, 181–192, doi:[10.1016/j.gloenvcha.2014.06.004](https://doi.org/10.1016/j.gloenvcha.2014.06.004).
- Kearns, J. et al., 2017: Developing a consistent database for regional geologic CO₂ storage capacity worldwide. *Energy Procedia*, **114**, 4697–4709, doi:[10.1016/j.egypro.2017.03.1603](https://doi.org/10.1016/j.egypro.2017.03.1603).
- Keith, D.W. and J.S. Rhodes, 2002: Bury, Burn or Both: A Two-for-One Deal on Biomass Carbon and Energy. *Climatic Change*, **54**(3), 375–377, doi:[10.1023/a:1016187420442](https://doi.org/10.1023/a:1016187420442).
- Keith, D.W., M. Ha-Duong, and J.K. Stolaroff, 2006: Climate Strategy with CO₂ Capture from the Air. *Climatic Change*, **74**(1–3), 17–45, doi:[10.1007/s10584-005-9026-x](https://doi.org/10.1007/s10584-005-9026-x).
- Khesghi, H.S., 1995: Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. *Energy*, **20**(9), 915–922, doi:[10.1016/0360-5442\(95\)00035-f](https://doi.org/10.1016/0360-5442(95)00035-f).
- Kim, S.H., K. Wada, A. Kurosawa, and M. Roberts, 2014: Nuclear energy response in the EMF27 study. *Climatic Change*, **123**(3–4), 443–460, doi:[10.1007/s10584-014-1098-z](https://doi.org/10.1007/s10584-014-1098-z).
- Klein, D. et al., 2014: The value of bioenergy in low stabilization scenarios: An assessment using REMIND-MAGPIE. *Climatic Change*, **123**(3–4), 705–718, doi:[10.1007/s10584-013-0940-z](https://doi.org/10.1007/s10584-013-0940-z).
- Klimont, Z. et al., 2017: Global anthropogenic emissions of particulate matter including black carbon. *Atmospheric Chemistry and Physics*, **17**(14), 8681–8723, doi:[10.5194/acp-17-8681-2017](https://doi.org/10.5194/acp-17-8681-2017).
- Klinsky, S. and H. Winkler, 2018: Building equity in: strategies for integrating equity into modelling for a 1.5°C world. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**(2119), 20160461, doi:[10.1098/rsta.2016.0461](https://doi.org/10.1098/rsta.2016.0461).

- Knutti, R. and J. Rogelj, 2015: The legacy of our CO₂ emissions: a clash of scientific facts, politics and ethics. *Climatic Change*, **133**(3), 361–373, doi:[10.1007/s10584-015-1340-3](https://doi.org/10.1007/s10584-015-1340-3).
- Knutti, R., M.A.A. Rugenstein, and G.C. Hegerl, 2017: Beyond equilibrium climate sensitivity. *Nature Geoscience*, **10**(10), 727–736, doi:[10.1038/ngeo3017](https://doi.org/10.1038/ngeo3017).
- Kolstad, C. et al., 2014: Social, Economic and Ethical Concepts and Methods. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadne, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 207–282.
- Krasting, J.P., J.P. Dunne, E. Shevliakova, and R.J. Stouffer, 2014: Trajectory sensitivity of the transient climate response to cumulative carbon emissions. *Geophysical Research Letters*, **41**(7), 2520–2527, doi:[10.1002/\(issn\)1944-8007](https://doi.org/10.1002/(issn)1944-8007).
- Krause, A. et al., 2017: Global consequences of afforestation and bioenergy cultivation on ecosystem service indicators. *Biogeosciences*, **14**(21), 4829–4850, doi:[10.5194/bg-14-4829-2017](https://doi.org/10.5194/bg-14-4829-2017).
- Kraxner, F. et al., 2013: Global bioenergy scenarios – Future forest development, land-use implications, and trade-offs. *Biomass and Bioenergy*, **57**, 86–96, doi:[10.1016/j.biombioe.2013.02.003](https://doi.org/10.1016/j.biombioe.2013.02.003).
- Kreidenweis, U. et al., 2016: Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects. *Environmental Research Letters*, **11**(8), 085001, doi:[10.1088/1748-9326/11/8/085001](https://doi.org/10.1088/1748-9326/11/8/085001).
- Kretzschmar, J. et al., 2017: Comment on “Rethinking the Lower Bound on Aerosol Radiative Forcing”. *Journal of Climate*, **30**(16), 6579–6584, doi:[10.1175/jcli-d-16-0668.1](https://doi.org/10.1175/jcli-d-16-0668.1).
- Krey, V., G. Luderer, L. Clarke, and E. Kriegler, 2014a: Getting from here to there – energy technology transformation pathways in the EMF27 scenarios. *Climatic Change*, **123**, 369–382, doi:[10.1007/s10584-013-0947-5](https://doi.org/10.1007/s10584-013-0947-5).
- Krey, V. et al., 2014b: Annex II: Metrics & Methodology. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1281–1328.
- Kriegler, E., O. Edenhofer, L. Reuster, G. Luderer, and D. Klein, 2013a: Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Climatic Change*, **118**(1), 45–57, doi:[10.1007/s10584-012-0681-4](https://doi.org/10.1007/s10584-012-0681-4).
- Kriegler, E. et al., 2012: The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. *Global Environmental Change*, **22**(4), 807–822, doi:[10.1016/j.gloenvcha.2012.05.005](https://doi.org/10.1016/j.gloenvcha.2012.05.005).
- Kriegler, E. et al., 2013b: What Does the 2°C Target Imply for a Global Climate Agreement in 2020? The Limits Study on Durban Platform Scenarios. *Climate Change Economics*, **4**(4), 1340008, doi:[10.1142/s2010007813400083](https://doi.org/10.1142/s2010007813400083).
- Kriegler, E. et al., 2014a: A new scenario framework for climate change research: the concept of shared climate policy assumptions. *Climatic Change*, **122**(3), 401–414, doi:[10.1007/s10584-013-0971-5](https://doi.org/10.1007/s10584-013-0971-5).
- Kriegler, E. et al., 2014b: The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change*, **123**(3–4), 353–367, doi:[10.1007/s10584-013-0953-7](https://doi.org/10.1007/s10584-013-0953-7).
- Kriegler, E. et al., 2015a: Diagnostic indicators for integrated assessment models of climate policy. *Technological Forecasting and Social Change*, **90**(Part A), 45–61, doi:[10.1016/j.techfore.2013.09.020](https://doi.org/10.1016/j.techfore.2013.09.020).
- Kriegler, E. et al., 2015b: Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technological Forecasting and Social Change*, **90**(Part A), 24–44, doi:[10.1016/j.techfore.2013.09.021](https://doi.org/10.1016/j.techfore.2013.09.021).
- Kriegler, E. et al., 2016: Will economic growth and fossil fuel scarcity help or hinder climate stabilization?: Overview of the RoSE multi-model study. *Climatic Change*, **136**(1), 7–22, doi:[10.1007/s10584-016-1668-3](https://doi.org/10.1007/s10584-016-1668-3).
- Kriegler, E. et al., 2017: Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Global Environmental Change*, **42**, 297–315, doi:[10.1016/j.gloenvcha.2016.05.015](https://doi.org/10.1016/j.gloenvcha.2016.05.015).
- Kriegler, E. et al., 2018a: Short term policies to keep the door open for Paris climate goals. *Environmental Research Letters*, **13**(7), 074022, doi:[10.1088/1748-9326/aac4f1](https://doi.org/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? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**(2119), 20160457, doi:[10.1098/rsta.2016.0457](https://doi.org/10.1098/rsta.2016.0457).
- Kuramochi, T. et al., 2017: Ten key short-term sectoral benchmarks to limit warming to 1.5°C. *Climate Policy*, **18**(3), 1–19, doi:[10.1080/14693062.2017.1397495](https://doi.org/10.1080/14693062.2017.1397495).
- Lamarque, J.-F. et al., 2011: Global and regional evolution of short-lived radiatively-active gases and aerosols in the Representative Concentration Pathways. *Climatic Change*, **109**(1–2), 191–212, doi:[10.1007/s10584-011-0155-0](https://doi.org/10.1007/s10584-011-0155-0).
- Lambin, E.F. and P. Meyfroidt, 2011: Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences*, **108**(9), 3465–72, doi:[10.1073/pnas.1100480108](https://doi.org/10.1073/pnas.1100480108).
- Le Quéré, C. et al., 2018: Global Carbon Budget 2017. *Earth System Science Data*, **10**(1), 405–448, doi:[10.5194/essd-10-405-2018](https://doi.org/10.5194/essd-10-405-2018).
- Lehtilä, A. and T. Koljonen, 2018: Pathways to Post-fossil Economy in a Well Below 2°C World. In: *Limiting Global Warming to Well Below 2°C: Energy System Modelling and Policy Development* [Giannakidis, G., K. Karlsson, M. Labriet, and B. Gallachóir (eds.)]. Springer International Publishing, Cham, Switzerland, pp. 33–49, doi:[10.1007/978-3-319-74424-7_3](https://doi.org/10.1007/978-3-319-74424-7_3).
- Leimbach, M., E. Kriegler, N. Roming, and J. Schwanitz, 2017: Future growth patterns of world regions – A GDP scenario approach. *Global Environmental Change*, **42**, 215–225, doi:[10.1016/j.gloenvcha.2015.02.005](https://doi.org/10.1016/j.gloenvcha.2015.02.005).
- Lemoine, D. and C. Traeger, 2014: Watch Your Step: Optimal Policy in a Tipping Climate. *American Economic Journal: Economic Policy*, **6**(1), 137–166, doi:[10.1257/pol.6.1.137](https://doi.org/10.1257/pol.6.1.137).
- Lenton, A., R.J. Matear, D.P. Keller, V. Scott, and N.E. Vaughan, 2018: Assessing carbon dioxide removal through global and regional ocean alkalization under high and low emission pathways. *Earth System Dynamics*, **9**(2), 339–357, doi:[10.5194/esd-9-339-2018](https://doi.org/10.5194/esd-9-339-2018).
- Lewis, N. and J.A. Curry, 2015: The implications for climate sensitivity of AR5 forcing and heat uptake estimates. *Climate Dynamics*, **45**(3–4), 1009–1023, doi:[10.1007/s00382-014-2342-y](https://doi.org/10.1007/s00382-014-2342-y).
- Lewis, N. and J. Curry, 2018: The impact of recent forcing and ocean heat uptake data on estimates of climate sensitivity. *Journal of Climate*, JCLI–D–17–0667.1, doi:[10.1175/jcli-d-17-0667.1](https://doi.org/10.1175/jcli-d-17-0667.1).
- Liu, J., T.W. Hertel, F. Taheripour, T. Zhu, and C. Ringler, 2014: International trade buffers the impact of future irrigation shortfalls. *Global Environmental Change*, **29**, 22–31, doi:[10.1016/j.gloenvcha.2014.07.010](https://doi.org/10.1016/j.gloenvcha.2014.07.010).
- 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 Management*, 1–11, doi:[10.1080/17583004.2018.1477374](https://doi.org/10.1080/17583004.2018.1477374).
- Löffler, K. et al., 2017: Designing a Model for the Global Energy System—GENESYS—MOD: An Application of the Open-Source Energy Modeling System (OSEMOSYS). *Energies*, **10**(10), 1468, doi:[10.3390/en10101468](https://doi.org/10.3390/en10101468).
- Lontzek, T.S., Y. Cai, K.L. Judd, and T.M. Lenton, 2015: Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy. *Nature Climate Change*, **5**(5), 441–444, doi:[10.1038/nclimate2570](https://doi.org/10.1038/nclimate2570).
- Lowe, J.A. and D. Bernie, 2018: The impact of Earth system feedbacks on carbon budgets and climate response. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376**(2119), 20170263, doi:[10.1098/rsta.2017.0263](https://doi.org/10.1098/rsta.2017.0263).
- Lowe, J.A. et al., 2009: How difficult is it to recover from dangerous levels of global warming? *Environmental Research Letters*, **4**(1), 014012, doi:[10.1088/1748-9326/4/1/014012](https://doi.org/10.1088/1748-9326/4/1/014012).
- Lucon, O. et al., 2014: Buildings. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 671–738.
- Luderer, G., C. Bertram, K. Calvin, E. De Cian, and E. Kriegler, 2016a: Implications of weak near-term climate policies on long-term mitigation pathways. *Climatic Change*, **136**(1), 127–140, doi:[10.1007/s10584-013-0899-9](https://doi.org/10.1007/s10584-013-0899-9).
- Luderer, G. et al., 2013: Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environmental Research Letters*, **8**(3), 034033, doi:[10.1088/1748-9326/8/3/034033](https://doi.org/10.1088/1748-9326/8/3/034033).
- Luderer, G. et al., 2014: The role of renewable energy in climate stabilization: results from the {EMF}27 scenarios. *Climatic Change*, **123**(3–4), 427–441, doi:[10.1007/s10584-013-0924-z](https://doi.org/10.1007/s10584-013-0924-z).

- Luderer, G. et al., 2016b: *Deep Decarbonisation towards 1.5°C – 2°C stabilization: Policy findings from the ADVANCE project*. The ADVANCE Consortium, 42 pp.
- Luderer, G. et al., 2017: Assessment of wind and solar power in global low-carbon energy scenarios: An introduction. *Energy Economics*, **64**, 542–551, doi:10.1016/j.eneco.2017.03.027.
- Luderer, G. et al., 2018: Residual fossil CO₂ emissions in 1.5–2°C pathways. *Nature Climate Change*, **8(7)**, 626–633, doi:10.1038/s41558-018-0198-6.
- Lutz, W. and S. KC, 2011: Global Human Capital: Integrating Education and Population. *Science*, **333(6042)**, 587–592, doi:10.1126/science.1206964.
- MacDougall, A.H., N.C. Swart, and R. Knutti, 2017: The Uncertainty in the Transient Climate Response to Cumulative CO₂ Emissions Arising from the Uncertainty in Physical Climate Parameters. *Journal of Climate*, **30(2)**, 813–827, doi:10.1175/jcli-d-16-0205.1.
- MacDougall, A.H., K. Zickfeld, R. Knutti, and H.D. Matthews, 2015: Sensitivity of carbon budgets to permafrost carbon feedbacks and non-CO₂ forcings. *Environmental Research Letters*, **10(12)**, 125003, doi:10.1088/1748-9326/10/12/125003.
- Madeira, M.S. et al., 2017: Microalgae as feed ingredients for livestock production and meat quality: A review. *Livestock Science*, **205**, 111–121, doi:10.1016/j.livsci.2017.09.020.
- Mahowald, N.M. et al., 2017: Aerosol Deposition Impacts on Land and Ocean Carbon Cycles. *Current Climate Change Reports*, **3(1)**, 16–31, doi:10.1007/s40641-017-0056-z.
- Malavelle, F.F. et al., 2017: Strong constraints on aerosol–cloud interactions from volcanic eruptions. *Nature*, **546(7659)**, 485–491, doi:10.1038/nature22974.
- Marangoni, G. and M. Tavoni, 2014: The Clean Energy R&D Strategy for 2°C. *Climate Change Economics*, **5(1)**, 1440003, doi:10.1142/s201000781440003x.
- Marangoni, G. et al., 2017: Sensitivity of projected long-term CO₂ emissions across the Shared Socioeconomic Pathways. *Nature Climate Change*, **7(1)**, 113–119, doi:10.1038/nclimate3199.
- Marcucci, A., S. Kypreos, and E. Panos, 2017: The road to achieving the long-term Paris targets: Energy transition and the role of direct air capture. *Climatic Change*, **144(2)**, 181–193, doi:10.1007/s10584-017-2051-8.
- Marten, A.L., E.A. Kopits, C.W. Griffiths, S.C. Newbold, and A. Wolverton, 2015: Incremental CH₄ and N₂O mitigation benefits consistent with the US Government's SC-CO₂ estimates. *Climate Policy*, **15(2)**, 272–298, doi:10.1080/14693062.2014.912981.
- Marvel, K., G.A. Schmidt, R.L. Miller, and L.S. Nazarenko, 2016: Implications for climate sensitivity from the response to individual forcings. *Nature Climate Change*, **6(4)**, 386–389, doi:10.1038/nclimate2888.
- Masui, T. et al., 2011: An emission pathway for stabilization at 6 W m⁻² radiative forcing. *Climatic Change*, **109(1)**, 59–76, doi:10.1007/s10584-011-0150-5.
- Matter, J.M. et al., 2016: Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science*, **352(6291)**, 1312–1314, doi:10.1126/science.aad8132.
- Matthews, H.D. and K. Caldeira, 2008: Stabilizing climate requires near-zero emissions. *Geophysical Research Letters*, **35(4)**, 1–5, doi:10.1029/2007gl032388.
- Matthews, H.D. and K. Zickfeld, 2012: Climate response to zeroed emissions of greenhouse gases and aerosols. *Nature Climate Change*, **2(5)**, 338–341, doi:10.1038/nclimate1424.
- Matthews, H.D., N.P. Gillett, P.A. Stott, and K. Zickfeld, 2009: The proportionality of global warming to cumulative carbon emissions. *Nature*, **459(7248)**, 829–832, doi:10.1038/nature08047.
- Matthews, H.D. et al., 2017: Estimating Carbon Budgets for Ambitious Climate Targets. *Current Climate Change Reports*, **3**, 69–77, doi:10.1007/s40641-017-0055-0.
- Mazzotti, M. et al., 2005: Mineral carbonation and industrial uses of carbon dioxide. In: *IPCC Special Report on Carbon Dioxide Capture and Storage* [Metz, B., O. Davidson, H.C. de Coninck, M. Loos, and L.A. Meyer (eds.)]. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 319–338.
- McCollum, D.L., V. Krey, and K. Riahi, 2011: An integrated approach to energy sustainability. *Nature Climate Change*, **1(9)**, 428–429, doi:10.1038/nclimate1297.
- McCollum, D.L. et al., 2013: Energy Investments under Climate Policy: A Comparison of Global Models. *Climate Change Economics*, **4(4)**, 1340010, doi:10.1142/s2010007813400101.
- McCollum, D.L. et al., 2017: Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. *Transportation Research Part D: Transport and Environment*, **55**, 322–342, doi:10.1016/j.trd.2016.04.003.
- McCollum, D.L. et al., 2018: Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy*, **3(7)**, 589–599, doi:10.1038/s41560-018-0179-z.
- McFarland, J.R., A.A. Fawcett, A.C. Morris, J.M. Reilly, and P.J. Wilcoxon, 2018: Overview of the EMF 32 Study on U.S. Carbon Tax Scenarios. *Climate Change Economics*, **9(1)**, 1840002, doi:10.1142/s201000781840002x.
- McLeod, E. et al., 2011: A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO₂. *Frontiers in Ecology and the Environment*, **9(10)**, 552–560, doi:10.1890/110004.
- Mehling, M. and E. Tvinnereim, 2018: Carbon Pricing and the 1.5°C Target: Near-Term Decarbonisation and the Importance of an Instrument Mix. *Carbon & Climate Law Review*, **12(1)**, 50–61, doi:10.21552/cclr/2018/1/9.
- Meinshausen, M., S.C.B. Raper, and T.M.L. Wigley, 2011a: Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmospheric Chemistry and Physics*, **11(4)**, 1417–1456, doi:10.5194/acp-11-1417-2011.
- Meinshausen, M. et al., 2009: Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature*, **458(7242)**, 1158–1162, doi:10.1038/nature08017.
- Meinshausen, M. et al., 2011b: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change*, **109(1–2)**, 213–241, doi:10.1007/s10584-011-0156-z.
- Méjean, A., C. Guivarch, J. Lefèvre, and M. Hamdi-Cherif, 2018: The transition in energy demand sectors to limit global warming to 1.5°C. *Energy Efficiency*, 1–22, doi:10.1007/s12053-018-9682-0.
- Mengis, N., A.-Partanen, J. Jalbert, and H.D. Matthews, 2018: 1.5°C carbon budget dependent on carbon cycle uncertainty and future non-CO₂ forcing. *Scientific Reports*, **8(1)**, 5831, doi:10.1038/s41598-018-24241-1.
- Michaelowa, A., M. Allen, and F. Sha, 2018: Policy instruments for limiting global temperature rise to 1.5°C – can humanity rise to the challenge? *Climate Policy*, **18(3)**, 275–286, doi:10.1080/14693062.2018.1426977.
- Millar, R.J. and P. Friedlingstein, 2018: The utility of the historical record for assessing the transient climate response to cumulative emissions. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, 20160449, doi:10.1098/rsta.2016.0449.
- Millar, R.J. et al., 2017: Emission budgets and pathways consistent with limiting warming to 1.5°C. *Nature Geoscience*, **10(10)**, 741–747, doi:10.1038/ngeo3031.
- Minx, J.C., W.F. Lamb, M.W. Callaghan, L. Bornmann, and S. Fuss, 2017: Fast growing research on negative emissions. *Environmental Research Letters*, **12(3)**, 035007, doi:10.1088/1748-9326/aa5ee5.
- Minx, J.C. et al., 2018: Negative emissions-Part 1: Research landscape and synthesis. *Environmental Research Letters*, **13(6)**, 063001, doi:10.1088/1748-9326/aabf9b.
- Moore, F.C. and D.B. Diaz, 2015: Temperature impacts on economic growth warrant stringent mitigation policy. *Nature Climate Change*, **5(1)**, 127–132, doi:10.1038/nclimate2481.
- Mouratiadou, I. et al., 2016: The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways. *Environmental Science & Policy*, **64**, 48–58, doi:10.1016/j.envsci.2016.06.007.
- Muller, A. et al., 2017: Strategies for feeding the world more sustainably with organic agriculture. *Nature Communications*, **8(1)**, 1290, doi:10.1038/s41467-017-01410-w.
- Mundaca, L. and A. Markandya, 2016: Assessing regional progress towards a Green Energy Economy. *Applied Energy*, **179**, 1372–1394, doi:10.1016/j.apenergy.2015.10.098.
- Mundaca, L., M. Mansoz, L. Neij, and G. Timilsina, 2013: Transaction costs analysis of low-carbon technologies. *Climate Policy*, **13(4)**, 490–513, doi:10.1080/14693062.2013.781452.
- Mundaca, L., L. Neij, A. Markandya, P. Henricke, and J. Yan, 2016: Towards a Green Energy Economy? Assessing policy choices, strategies and transitional pathways. *Applied Energy*, **179**, 1283–1292, doi:10.1016/j.apenergy.2016.08.086.
- Myhre, G. et al., 2013: Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659–740.
- Myhre, G. et al., 2017: Multi-model simulations of aerosol and ozone radiative forcing due to anthropogenic emission changes during the period 1990–2015. *Atmospheric Chemistry and Physics*, **17(4)**, 2709–2720, doi:10.5194/acp-17-2709-2017.

- Narayan, C., P.M. Fernandes, J. van Brusselen, and A. Schuck, 2007: Potential for CO₂ emissions mitigation in Europe through prescribed burning in the context of the Kyoto Protocol. *Forest Ecology and Management*, **251(3)**, 164–173, doi:[10.1016/j.foreco.2007.06.042](https://doi.org/10.1016/j.foreco.2007.06.042).
- NASEM, 2016: *Assessment of Approaches to Updating the Social Cost of Carbon: Phase 1 Report on a Near-Term Update*. National Academies of Sciences, Engineering, and Medicine (NASEM). The National Academies Press, Washington DC, USA, 72 pp., doi:[10.17226/21898](https://doi.org/10.17226/21898).
- NASEM, 2017: *Valuing Climate Damages: Updating estimation of the social costs of carbon dioxide*. National Academies of Sciences, Engineering, and Medicine (NASEM), The National Academies Press, Washington DC, USA, 262 pp., doi:[10.17226/24651](https://doi.org/10.17226/24651).
- Naudts, K. et al., 2016: Europe's forest management did not mitigate climate warming. *Science*, **351(6273)**, 597–600, doi:[10.1126/science.aad7270](https://doi.org/10.1126/science.aad7270).
- Nelson, G.C. et al., 2014: Climate change effects on agriculture: economic responses to biophysical shocks. *Proceedings of the National Academy of Sciences*, **111(9)**, 3274–9, doi:[10.1073/pnas.1222465110](https://doi.org/10.1073/pnas.1222465110).
- Nemet, G.F. et al., 2018: Negative emissions – Part 3: Innovation and upscaling. *Environmental Research Letters*, **13(6)**, 063003, doi:[10.1088/1748-9326/aabff4](https://doi.org/10.1088/1748-9326/aabff4).
- NETL, 2013: *Cost and performance of PC and IGCC plants for a range of carbon dioxide capture: Revision 1*. DOE/NETL-2011/1498, U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL), 500 pp.
- NETL, 2015: *Carbon Storage Atlas – Fifth Edition (Atlas V)*. U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL), 114 pp.
- Nicol, A. et al., 2013: Induced seismicity; observations, risks and mitigation measures at CO₂ storage sites. *Energy Procedia*, **37**, 4749–4756, doi:[10.1016/j.egypro.2013.06.384](https://doi.org/10.1016/j.egypro.2013.06.384).
- Nohara, D. et al., 2015: Examination of a climate stabilization pathway via zero-emissions using Earth system models. *Environmental Research Letters*, **10(9)**, 095005, doi:[10.1088/1748-9326/10/9/095005](https://doi.org/10.1088/1748-9326/10/9/095005).
- Nordhaus, W.D., 2007a: A Review of The Stern Review on the Economics of Climate Change. *Journal of Economic Literature*, **45(3)**, 686–702, www.jstor.org/stable/27646843.
- Nordhaus, W.D., 2007b: To Tax or Not to Tax: Alternative Approaches to Slowing Global Warming. *Review of Environmental Economics and Policy*, **1(1)**, 26–44, doi:[10.1093/reep/rem008](https://doi.org/10.1093/reep/rem008).
- Nordhaus, W.D., 2013: *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World*. Yale University Press, New Haven, CT, USA, 392 pp.
- Nordhaus, W.D., 2014: Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches. *Journal of the Association of Environmental and Resource Economists*, **1(1–2)**, 273–312, doi:[10.1086/676035](https://doi.org/10.1086/676035).
- Nordhaus, W.D., 2017: Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, **114(7)**, 1518–1523, doi:[10.1073/pnas.1609244114](https://doi.org/10.1073/pnas.1609244114).
- Nordhaus, W.D. and J. Boyer, 2000: *Warming the World: Economic Models of Global Warming*. MIT Press, Cambridge, MA, USA and London, UK, 244 pp.
- NRC, 2015: *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. National Research Council (NRC). The National Academies Press, Washington DC, USA, 140 pp., doi:[10.17226/18805](https://doi.org/10.17226/18805).
- O'Neill, B.C. et al., 2014: A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change*, **122(3)**, 387–400, doi:[10.1007/s10584-013-0905-2](https://doi.org/10.1007/s10584-013-0905-2).
- O'Neill, B.C. et al., 2017: The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, **42**, 169–180, doi:[10.1016/j.gloenvcha.2015.01.004](https://doi.org/10.1016/j.gloenvcha.2015.01.004).
- Obersteiner, M. et al., 2001: Managing Climate Risk. *Science*, **294(5543)**, 786–787, doi:[10.1126/science.294.5543.786b](https://doi.org/10.1126/science.294.5543.786b).
- Obersteiner, M. et al., 2016: Assessing the land resource–food price nexus of the Sustainable Development Goals. *Science Advances*, **2(9)**, e1501499, doi:[10.1126/sciadv.1501499](https://doi.org/10.1126/sciadv.1501499).
- Obersteiner, M. et al., 2018: How to spend a dwindling greenhouse gas budget. *Nature Climate Change*, **8(1)**, 7–10, doi:[10.1038/s41558-017-0045-1](https://doi.org/10.1038/s41558-017-0045-1).
- OECD, 2017: *Investing in Climate, Investing in Growth*. OECD Publishing, Paris, France, 314 pp., doi:[10.1787/9789264273528-en](https://doi.org/10.1787/9789264273528-en).
- OECD/IEA and IRENA, 2017: *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*. OECD/IEA and IRENA, 204 pp.
- Ogawa, T., S. Nakanishi, T. Shidahara, T. Okumura, and E. Hayashi, 2011: Saline-aquifer CO₂ sequestration in Japan-methodology of storage capacity assessment. *International Journal of Greenhouse Gas Control*, **5(2)**, 318–326, doi:[10.1016/j.ijggc.2010.09.009](https://doi.org/10.1016/j.ijggc.2010.09.009).
- Painter, T.H. et al., 2013: End of the Little Ice Age in the Alps forced by industrial black carbon. *Proceedings of the National Academy of Sciences*, **110(38)**, 15216–21, doi:[10.1073/pnas.1302570110](https://doi.org/10.1073/pnas.1302570110).
- Patt, A., 2017: Beyond the tragedy of the commons: Reframing effective climate change governance. *Energy Research & Social Science*, **34**, 1–3, doi:[10.1016/j.erss.2017.05.023](https://doi.org/10.1016/j.erss.2017.05.023).
- Patterson, J.J. et al., 2018: Political feasibility of 1.5°C societal transformations: the role of social justice. *Current Opinion in Environmental Sustainability*, **31**, 1–9, doi:[10.1016/j.cosust.2017.11.002](https://doi.org/10.1016/j.cosust.2017.11.002).
- Paustian, K. et al., 2016: Climate-smart soils. *Nature*, **532(7597)**, 49–57, doi:[10.1038/nature17174](https://doi.org/10.1038/nature17174).
- Pawar, R.J. et al., 2015: Recent advances in risk assessment and risk management of geologic CO₂ storage. *International Journal of Greenhouse Gas Control*, **40**, 292–311, doi:[10.1016/j.ijggc.2015.06.014](https://doi.org/10.1016/j.ijggc.2015.06.014).
- Pehl, M. et al., 2017: Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. *Nature Energy*, **2(12)**, 939–945, doi:[10.1038/s41560-017-0032-9](https://doi.org/10.1038/s41560-017-0032-9).
- Peters, G.P., 2016: The 'best available science' to inform 1.5°C policy choices. *Nature Climate Change*, **6(7)**, 646–649, doi:[10.1038/nclimate3000](https://doi.org/10.1038/nclimate3000).
- Pietzcker, R.C. et al., 2017: System integration of wind and solar power in integrated assessment models: A cross-model evaluation of new approaches. *Energy Economics*, **64**, 583–599, doi:[10.1016/j.eneco.2016.11.018](https://doi.org/10.1016/j.eneco.2016.11.018).
- Pikaar, I. et al., 2018: Decoupling Livestock from Land Use through Industrial Feed Production Pathways. *Environmental Science & Technology*, **52(13)**, 7351–7359, doi:[10.1021/acs.est.8b00216](https://doi.org/10.1021/acs.est.8b00216).
- Pindyck, R.S., 2013: Climate Change Policy: What Do the Models Tell Us? *Journal of Economic Literature*, **51(3)**, 1–23, doi:[10.1257/jel.51.3.860](https://doi.org/10.1257/jel.51.3.860).
- Pizer, W. et al., 2014: Using and improving the social cost of carbon. *Science*, **346(6214)**, 1189–1190, doi:[10.1126/science.1259774](https://doi.org/10.1126/science.1259774).
- Popp, A., H. Lotze-Campen, and B. Bodirsky, 2010: Food consumption, diet shifts and associated non-CO₂ greenhouse gases from agricultural production. *Global Environmental Change*, **20(3)**, 451–462, doi:[10.1016/j.gloenvcha.2010.02.001](https://doi.org/10.1016/j.gloenvcha.2010.02.001).
- Popp, A. et al., 2014a: Land-use protection for climate change mitigation. *Nature Climate Change*, **4(12)**, 1095–1098, doi:[10.1038/nclimate2444](https://doi.org/10.1038/nclimate2444).
- Popp, A. et al., 2014b: Land-use transition for bioenergy and climate stabilization: Model comparison of drivers, impacts and interactions with other land use based mitigation options. *Climatic Change*, **123(3–4)**, 495–509, doi:[10.1007/s10584-013-0926-x](https://doi.org/10.1007/s10584-013-0926-x).
- Popp, A. et al., 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, **42**, 331–345, doi:[10.1016/j.gloenvcha.2016.10.002](https://doi.org/10.1016/j.gloenvcha.2016.10.002).
- Post, M.J., 2012: Cultured meat from stem cells: Challenges and prospects. *Meat Science*, **92(3)**, 297–301, doi:[10.1016/j.meatsci.2012.04.008](https://doi.org/10.1016/j.meatsci.2012.04.008).
- Prestele, R. et al., 2016: Hotspots of uncertainty in land-use and land-cover change projections: a global-scale model comparison. *Global Change Biology*, **22(12)**, 3967–3983, doi:[10.1111/gcb.13337](https://doi.org/10.1111/gcb.13337).
- Proistosescu, C. and P.J. Huybers, 2017: Slow climate mode reconciles historical and model-based estimates of climate sensitivity. *Science Advances*, **3(7)**, e1602821, doi:[10.1126/sciadv.1602821](https://doi.org/10.1126/sciadv.1602821).
- Psarras, P. et al., 2017: Slicing the pie: how big could carbon dioxide removal be? *Wiley Interdisciplinary Reviews: Energy and Environment*, **6(5)**, e253, doi:[10.1002/wene.253](https://doi.org/10.1002/wene.253).
- Purohit, P. and L. Höglund-Isaksson, 2017: Global emissions of fluorinated greenhouse gases 2005–2050 with abatement potentials and costs. *Atmospheric Chemistry and Physics*, **17(4)**, 2795–2816, doi:[10.5194/acp-17-2795-2017](https://doi.org/10.5194/acp-17-2795-2017).
- Rao, S. et al., 2016: A multi-model assessment of the co-benefits of climate mitigation for global air quality. *Environmental Research Letters*, **11(12)**, 124013, doi:[10.1088/1748-9326/11/12/124013](https://doi.org/10.1088/1748-9326/11/12/124013).
- Rao, S. et al., 2017: Future air pollution in the Shared Socio-economic Pathways. *Global Environmental Change*, **42**, 346–358, doi:[10.1016/j.gloenvcha.2016.05.012](https://doi.org/10.1016/j.gloenvcha.2016.05.012).
- Rau, G.H., 2011: CO₂ Mitigation via Capture and Chemical Conversion in Seawater. *Environmental Science & Technology*, **45(3)**, 1088–1092, doi:[10.1021/es102671x](https://doi.org/10.1021/es102671x).
- Revesz, R. et al., 2014: Global warming: Improve economic models of climate change. *Nature*, **508(7495)**, 173–175, doi:[10.1038/508173a](https://doi.org/10.1038/508173a).
- Riahi, K. et al., 2011: RCP 8.5 – A scenario of comparatively high greenhouse gas emissions. *Climatic Change*, **109(1)**, 33, doi:[10.1007/s10584-011-0149-y](https://doi.org/10.1007/s10584-011-0149-y).
- Riahi, K. et al., 2012: Energy Pathways for Sustainable Development. In: *Global Energy Assessment – Toward a Sustainable Future*. Cambridge, United Kingdom and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 1203–1306, doi:[10.1017/cbo9780511793677.023](https://doi.org/10.1017/cbo9780511793677.023).

- Riahi, K. et al., 2015: Locked into Copenhagen pledges – Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change*, **90(Part A)**, 8–23, doi:[10.1016/j.techfore.2013.09.016](https://doi.org/10.1016/j.techfore.2013.09.016).
- Riahi, K. et al., 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, **42**, 153–168, doi:[10.1016/j.gloenvcha.2016.05.009](https://doi.org/10.1016/j.gloenvcha.2016.05.009).
- Ricke, K.L., R.J. Millar, and D.G. MacMartin, 2017: Constraints on global temperature target overshoot. *Scientific Reports*, **7(1)**, 1–7, doi:[10.1038/s41598-017-14503-9](https://doi.org/10.1038/s41598-017-14503-9).
- Riis, F. and E. Halland, 2014: CO₂ storage atlas of the Norwegian Continental shelf: Methods used to evaluate capacity and maturity of the CO₂ storage potential. *Energy Procedia*, **63**, 5258–5265, doi:[10.1016/j.egypro.2014.11.557](https://doi.org/10.1016/j.egypro.2014.11.557).
- Rockström, J. et al., 2017: A roadmap for rapid decarbonization. *Science*, **355(6331)**, 1269–1271, doi:[10.1126/science.aah3443](https://doi.org/10.1126/science.aah3443).
- Roelfsema, M., M. Harmsen, J.J.G. Olivier, A.F. Hof, and D.P. van Vuuren, 2018: Integrated assessment of international climate mitigation commitments outside the UNFCCC. *Global Environmental Change*, **48**, 67–75, doi:[10.1016/j.gloenvcha.2017.11.001](https://doi.org/10.1016/j.gloenvcha.2017.11.001).
- Rogelj, J., D.L. McCollum, B.C. O'Neill, and K. Riahi, 2013a: 2020 emissions levels required to limit warming to below 2°C. *Nature Climate Change*, **3(4)**, 405–412, doi:[10.1038/nclimate1758](https://doi.org/10.1038/nclimate1758).
- Rogelj, J., M. Meinshausen, J. Sedláček, and R. Knutti, 2014a: Implications of potentially lower climate sensitivity on climate projections and policy. *Environmental Research Letters*, **9(3)**, 031003, doi:[10.1088/1748-9326/9/3/031003](https://doi.org/10.1088/1748-9326/9/3/031003).
- Rogelj, J., D.L. McCollum, A. Reisinger, M. Meinshausen, and K. Riahi, 2013b: Probabilistic cost estimates for climate change mitigation. *Nature*, **493(7430)**, 79–83, doi:[10.1038/nature11787](https://doi.org/10.1038/nature11787).
- Rogelj, J., M. Meinshausen, M. Schaeffer, R. Knutti, and K. Riahi, 2015a: Impact of short-lived non-CO₂ mitigation on carbon budgets for stabilizing global warming. *Environmental Research Letters*, **10(7)**, 075001, doi:[10.1088/1748-9326/10/7/075001](https://doi.org/10.1088/1748-9326/10/7/075001).
- Rogelj, J. et al., 2011: Emission pathways consistent with a 2°C global temperature limit. *Nature Climate Change*, **1(8)**, 413–418, doi:[10.1038/nclimate1258](https://doi.org/10.1038/nclimate1258).
- Rogelj, J. et al., 2014b: Disentangling the effects of CO₂ and short-lived climate forcer mitigation. *Proceedings of the National Academy of Sciences*, **111(46)**, 16325–16330, doi:[10.1073/pnas.1415631111](https://doi.org/10.1073/pnas.1415631111).
- Rogelj, J. et al., 2015b: Energy system transformations for limiting end-of-century warming to below 1.5°C. *Nature Climate Change*, **5(6)**, 519–527, doi:[10.1038/nclimate2572](https://doi.org/10.1038/nclimate2572).
- Rogelj, J. et al., 2015c: Mitigation choices impact carbon budget size compatible with low temperature goals. *Environmental Research Letters*, **10(7)**, 075003, doi:[10.1088/1748-9326/10/7/075003](https://doi.org/10.1088/1748-9326/10/7/075003).
- Rogelj, J. et al., 2015d: Zero emission targets as long-term global goals for climate protection. *Environmental Research Letters*, **10(10)**, 105007, doi:[10.1088/1748-9326/10/10/105007](https://doi.org/10.1088/1748-9326/10/10/105007).
- Rogelj, J. et al., 2016a: Paris Agreement climate proposals need a boost to keep warming well below 2°C. *Nature*, **534(7609)**, 631–639, doi:[10.1038/nature18307](https://doi.org/10.1038/nature18307).
- Rogelj, J. et al., 2016b: Differences between carbon budget estimates unravelled. *Nature Climate Change*, **6(3)**, 245–252, doi:[10.1038/nclimate2868](https://doi.org/10.1038/nclimate2868).
- Rogelj, J. et al., 2017: Understanding the origin of Paris Agreement emission uncertainties. *Nature Communications*, **8**, 15748, doi:[10.1038/ncomms15748](https://doi.org/10.1038/ncomms15748).
- Rogelj, J. et al., 2018: Scenarios towards limiting global mean temperature increase below 1.5°C. *Nature Climate Change*, **8(4)**, 325–332, doi:[10.1038/s41558-018-0091-3](https://doi.org/10.1038/s41558-018-0091-3).
- Rose, S.K., 2012: The role of the social cost of carbon in policy. *Wiley Interdisciplinary Reviews: Climate Change*, **3(2)**, 195–212, doi:[10.1002/wcc.163](https://doi.org/10.1002/wcc.163).
- Rose, S.K., D.B. Diza, and G.J. Blanford, 2017a: Understanding the Social Cost of Carbon: A Model diagnostic and Inter-comparison Study. *Climate Change Economics*, **8(2)**, 1750009, doi:[10.1142/s2010007817500099](https://doi.org/10.1142/s2010007817500099).
- Rose, S.K., R. Richels, G. Blanford, and T. Rutherford, 2017b: The Paris Agreement and next steps in limiting global warming. *Climatic Change*, **142(1–2)**, 1–16, doi:[10.1007/s10584-017-1935-y](https://doi.org/10.1007/s10584-017-1935-y).
- Rose, S.K. et al., 2014a: Bioenergy in energy transformation and climate management. *Climatic Change*, **123(3–4)**, 477–493, doi:[10.1007/s10584-013-0965-3](https://doi.org/10.1007/s10584-013-0965-3).
- Rose, S.K. et al., 2014b: Non-Kyoto radiative forcing in long-run greenhouse gas emissions and climate change scenarios. *Climatic Change*, **123(3–4)**, 511–525, doi:[10.1007/s10584-013-0955-5](https://doi.org/10.1007/s10584-013-0955-5).
- Rugenstein, M.A.A. et al., 2016: Multiannual Ocean-Atmosphere Adjustments to Radiative Forcing. *Journal of Climate*, **29(15)**, 5643–5659, doi:[10.1175/jcli-d-16-0312.1](https://doi.org/10.1175/jcli-d-16-0312.1).
- Samset, B.H. et al., 2016: Fast and slow precipitation responses to individual climate forcers: A PDRMIP multimodel study. *Geophysical Research Letters*, **43(6)**, 2782–2791, doi:[10.1002/2016gl068064](https://doi.org/10.1002/2016gl068064).
- Samset, B.H. et al., 2018: Climate impacts from a removal of anthropogenic aerosol emissions. *Geophysical Research Letters*, **45(2)**, 1020–1029, doi:[10.1002/2017gl076079](https://doi.org/10.1002/2017gl076079).
- Sand, M. et al., 2015: Response of Arctic temperature to changes in emissions of short-lived climate forcers. *Nature Climate Change*, **6(3)**, 286–289, doi:[10.1038/nclimate2880](https://doi.org/10.1038/nclimate2880).
- Sanderson, B.M., B.C. O'Neill, and C. Tebaldi, 2016: What would it take to achieve the Paris temperature targets? *Geophysical Research Letters*, **43(13)**, 7133–7142, doi:[10.1002/2016gl069563](https://doi.org/10.1002/2016gl069563).
- Sands, R.D., 2018: U.S. Carbon Tax Scenarios and Bioenergy. *Climate Change Economics*, **9(1)**, 1840010, doi:[10.1142/2010007818400109](https://doi.org/10.1142/2010007818400109).
- Sarofim, M.C., S.T. Waldhoff, and S.C. Anenberg, 2017: Valuing the Ozone-Related Health Benefits of Methane Emission Controls. *Environmental and Resource Economics*, **66(1)**, 45–63, doi:[10.1007/s10640-015-9937-6](https://doi.org/10.1007/s10640-015-9937-6).
- Saunders, H.D., 2015: Recent Evidence for Large Rebound: Elucidating the Drivers and their Implications for Climate Change Models. *The Energy Journal*, **36(1)**, 23–48, doi:[10.5547/01956574.36.1.2](https://doi.org/10.5547/01956574.36.1.2).
- Schädel, C. et al., 2014: Circumpolar assessment of permafrost C quality and its vulnerability over time using long-term incubation data. *Global Change Biology*, **20(2)**, 641–652, doi:[10.1111/gcb.12417](https://doi.org/10.1111/gcb.12417).
- Schädel, C. et al., 2016: Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. *Nature Climate Change*, **6(10)**, 950–953, doi:[10.1038/nclimate3054](https://doi.org/10.1038/nclimate3054).
- Schleussner, C.-F. et al., 2016: Science and policy characteristics of the Paris Agreement temperature goal. *Nature Climate Change*, **6(7)**, 827–835, doi:[10.1038/nclimate3096](https://doi.org/10.1038/nclimate3096).
- Schmidt, M.G.W., H. Held, E. Kriegler, and A. Lorenz, 2013: Climate Policy Under Uncertain and Heterogeneous Climate Damages. *Environmental and Resource Economics*, **54(1)**, 79–99, doi:[10.1007/s10640-012-9582-2](https://doi.org/10.1007/s10640-012-9582-2).
- Schmitz, C. et al., 2012: Trading more food: Implications for land use, greenhouse gas emissions, and the food system. *Global Environmental Change*, **22(1)**, 189–209, doi:[10.1016/j.gloenvcha.2011.09.013](https://doi.org/10.1016/j.gloenvcha.2011.09.013).
- Schneider, T. et al., 2017: Climate goals and computing the future of clouds. *Nature Climate Change*, **7(1)**, 3–5, doi:[10.1038/nclimate3190](https://doi.org/10.1038/nclimate3190).
- Schneider von Deimling, T. et al., 2012: Estimating the near-surface permafrost-carbon feedback on global warming. *Biogeosciences*, **9(2)**, 649–665, doi:[10.5194/bg-9-649-2012](https://doi.org/10.5194/bg-9-649-2012).
- Schneider von Deimling, T. et al., 2015: Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity. *Biogeosciences*, **12(11)**, 3469–3488, doi:[10.5194/bg-12-3469-2015](https://doi.org/10.5194/bg-12-3469-2015).
- Schilling, R.D. and P. Krijgsmann, 2006: Enhanced Weathering: An Effective and Cheap Tool to Sequester CO₂. *Climatic Change*, **74(1–3)**, 349–354, doi:[10.1007/s10584-005-3485-y](https://doi.org/10.1007/s10584-005-3485-y).
- Schurer, A.P. et al., 2018: Interpretations of the Paris climate target. *Nature Geoscience*, **11(4)**, 220–221, doi:[10.1038/s41561-018-0086-8](https://doi.org/10.1038/s41561-018-0086-8).
- Schuur, E.A.G. et al., 2015: Climate change and the permafrost carbon feedback. *Nature*, **520(7546)**, 171–179, doi:[10.1038/nature14338](https://doi.org/10.1038/nature14338).
- Scott, C.E. et al., 2018: Substantial large-scale feedbacks between natural aerosols and climate. *Nature Geoscience*, **11(1)**, 44–48, doi:[10.1038/s41561-017-0020-5](https://doi.org/10.1038/s41561-017-0020-5).
- Scott, V., R.S. Haszeldine, S.F.B. Tett, and A. Oschlies, 2015: Fossil fuels in a trillion tonne world. *Nature Climate Change*, **5(5)**, 419–423, doi:[10.1038/nclimate2578](https://doi.org/10.1038/nclimate2578).
- Searle, S.Y. and C.J. Malins, 2014: Will energy crop yields meet expectations? *Biomass and Bioenergy*, **65**, 3–12, doi:[10.1016/j.biombioe.2014.01.001](https://doi.org/10.1016/j.biombioe.2014.01.001).
- Séférian, R., M. Rocher, C. Guivarch, and J. Colin, 2018: Constraints on biomass energy deployment in mitigation pathways: the case of water limitation. *Environmental Research Letters*, 1–32, doi:[10.1088/1748-9326/aabdc7](https://doi.org/10.1088/1748-9326/aabdc7).
- Seto, K.C. et al., 2016: Carbon Lock-In: Types, Causes, and Policy Implications. *Annual Review of Environment and Resources*, **41(1)**, 425–452, doi:[10.1146/annurev-environ-110615-085934](https://doi.org/10.1146/annurev-environ-110615-085934).
- Shah, N., M. Wei, V. Letschert, and A. Phadke, 2015: *Benefits of Leapfrogging to Superefficiency and Low Global Warming Potential Refrigerants in Room Air Conditioning*. LBNL-1003671, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA, USA, 58 pp.
- Shearer, C., N. Mathew-Shah, L. Myllyvirta, A. Yu, and T. Nace, 2018: *Boom and Bust 2018: Tracking the Global Coal Plant Pipeline*. CoalSwarm, Greenpeace USA, and Sierra Club, 16 pp.

- Shell International B.V., 2018: *Shell Scenarios: Sky – Meeting the Goals of the Paris Agreement*. Shell International B.V. 36 pp.
- Sherwood, S.C., S. Bony, and J.-L. Dufresne, 2014: Spread in model climate sensitivity traced to atmospheric convective mixing. *Nature*, **505(7481)**, 37–42, doi:10.1038/nature12829.
- Shindell, D.T., 2015: The social cost of atmospheric release. *Climatic Change*, **130(2)**, 313–326, doi:10.1007/s10584-015-1343-0.
- Shindell, D.T. and G. Faluvegi, 2010: The net climate impact of coal-fired power plant emissions. *Atmospheric Chemistry and Physics*, **10(7)**, 3247–3260, doi:10.5194/acp-10-3247-2010.
- Shindell, D.T., Y. Lee, and G. Faluvegi, 2016: Climate and health impacts of US emissions reductions consistent with 2°C. *Nature Climate Change*, **6(5)**, 503–507, doi:10.1038/nclimate2935.
- Shindell, D.T., J.S. Fuglested, and W.J. Collins, 2017a: The social cost of methane: theory and applications. *Faraday Discussions*, **200**, 429–451, doi:10.1039/c7fd00009j.
- Shindell, D.T., G. Faluvegi, L. Rotstayn, and G. Milly, 2015: Spatial patterns of radiative forcing and surface temperature response. *Journal of Geophysical Research: Atmospheres*, **120(11)**, 5385–5403, doi:10.1002/2014jd022752.
- Shindell, D.T., G. Faluvegi, K. Seltzer, and C. Shindell, 2018: Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. *Nature Climate Change*, **8(4)**, 291–295, doi:10.1038/s41558-018-0108-y.
- Shindell, D.T. et al., 2012: Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. *Science*, **335(6065)**, 183–189, doi:10.1126/science.1210026.
- Shindell, D.T. et al., 2017b: A climate policy pathway for near- and long-term benefits. *Science*, **356(6337)**, 493–494, doi:10.1126/science.aak9521.
- Shukla, P.R. and V. Chaturvedi, 2012: Low carbon and clean energy scenarios for India: Analysis of targets approach. *Energy Economics*, **34(sup3)**, S487–S495, doi:10.1016/j.eneco.2012.05.002.
- Siegmeier, J. et al., 2018: The fiscal benefits of stringent climate change mitigation: an overview. *Climate Policy*, **18(3)**, 352–367, doi:10.1080/14693062.2017.1400943.
- Silva, R.A. et al., 2016: The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble. *Atmospheric Chemistry and Physics*, **16(15)**, 9847–9862, doi:10.5194/acp-16-9847-2016.
- Sims, R. et al., 2014: Transport. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 599–670.
- Smith, C.J. et al., 2018: FAIR v1.3: a simple emissions-based impulse response and carbon cycle model. *Geoscientific Model Development*, **11(6)**, 2273–2297, doi:10.5194/gmd-11-2273-2018.
- Smith, L.J. and M.S. Torn, 2013: Ecological limits to terrestrial biological carbon dioxide removal. *Climatic Change*, **118(1)**, 89–103, doi:10.1007/s10584-012-0682-3.
- Smith, P., 2016: Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*, **22(3)**, 1315–1324, doi:10.1111/gcb.13178.
- Smith, P. and M. Bustamante, 2014: Agriculture, Forestry and Other Land Use (AFOLU). In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 811–922.
- Smith, P. et al., 2013: How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Global Change Biology*, **19(8)**, 2285–2302, doi:10.1111/gcb.12160.
- Smith, P. et al., 2015: Biophysical and economic limits to negative CO₂ emissions. *Nature Climate Change*, **6(1)**, 42–50, doi:10.1038/nclimate2870.
- Snopkowski, K., M.C. Townner, M.K. Shenk, and H. Collieran, 2016: Pathways from education to fertility decline: a multi-site comparative study. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371(1692)**, 20150156, doi:10.1098/rstb.2015.0156.
- Socolow, R. et al., 2011: *Direct Air Capture of CO₂ with Chemicals: A Technology Assessment for the APS Panel on Public Affairs*. American Physical Society (APS), College Park, MD, USA, 100 pp.
- Somanthan, E. et al., 2014: National and Sub-national Policies and Institutions. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1141–1206.
- Sonnenschein, J., R. Van Buskirk, J.L. Richter, and C. Dalhammar, 2018: Minimum energy performance standards for the 1.5°C target: an effective complement to carbon pricing. *Energy Efficiency*, 1–16, doi:10.1007/s12053-018-9669-x.
- Spencer, T., R. Pierfederici, H. Waisman, and M. Colombier, 2015: *Beyond the Numbers. Understanding the Transformation Induced by INDCs*. Study N°05/15, MILES Project Consortium, Paris, France, 80 pp.
- Springmann, M., H.C.J. Godfray, M. Rayner, and P. Scarborough, 2016: Analysis and valuation of the health and climate change cobenefits of dietary change. *Proceedings of the National Academy of Sciences*, **113(15)**, 4146–4151, doi:10.1073/pnas.1523119113.
- Steckel, J.C., O. Edenhofer, and M. Jakob, 2015: Drivers for the renaissance of coal. *Proceedings of the National Academy of Sciences*, **112(29)**, E3775–E3781, doi:10.1073/pnas.1422722112.
- Stehfest, E. et al., 2009: Climate benefits of changing diet. *Climatic Change*, **95(1–2)**, 83–102, doi:10.1007/s10584-008-9534-6.
- Stern, N., 2007: *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 692 pp., doi:10.1017/cbo9780511817434.
- Stern, N., 2013: The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models. *Journal of Economic Literature*, **51(3)**, 838–859, doi:10.1257/jel.51.3.838.
- Stern, N., 2016: Current climate models are grossly misleading. *Nature*, **530**, 407–409, doi:10.1038/530407a.
- Stevanović, M. et al., 2017: Mitigation Strategies for Greenhouse Gas Emissions from Agriculture and Land-Use Change: Consequences for Food Prices. *Environmental Science & Technology*, **51(1)**, 365–374, doi:10.1021/acs.est.6b04291.
- Stiglitz, J.E. et al., 2017: *Report of the High-Level Commission on Carbon Prices*. Carbon Pricing Leadership Coalition (CPLC), 68 pp.
- Stocker, T.F. et al., 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33–115.
- Stohl, A. et al., 2015: Evaluating the climate and air quality impacts of short-lived pollutants. *Atmospheric Chemistry and Physics*, **15(18)**, 10529–10566, doi:10.5194/acp-15-10529-2015.
- Strapasson, A. et al., 2017: On the global limits of bioenergy and land use for climate change mitigation. *GCB Bioenergy*, **9(12)**, 1721–1735, doi:10.1111/gcbb.12456.
- Strefler, J., T. Amann, N. Baur, E. Kriegler, and J. Hartmann, 2018a: Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters*, **13(3)**, 034010, doi:10.1088/1748-9326/aaa9c4.
- Strefler, J. et al., 2018b: Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. *Environmental Research Letters*, **13(4)**, 044015, doi:10.1088/1748-9326/aab2ba.
- Su, X. et al., 2017: Emission pathways to achieve 2.0°C and 1.5°C climate targets. *Earth's Future*, **5(6)**, 592–604, doi:10.1002/2016ef000492.
- Subbarao, G. et al., 2013: Potential for biological nitrification inhibition to reduce nitrification and N₂O emissions in pasture crop-livestock systems. *Animal*, **7(s2)**, 322–332, doi:10.1017/s1751731113000761.
- Subharat, S. et al., 2016: Vaccination of Sheep with a Methanogen Protein Provides Insight into Levels of Antibody in Saliva Needed to Target Ruminant Methanogens. *PLOS ONE*, **11(7)**, e0159861, doi:10.1371/journal.pone.0159861.
- Szulczewski, M.L., C.W. MacMinn, and R. Juanes, 2014: Theoretical analysis of how pressure buildup and CO₂ migration can both constrain storage capacity in deep saline aquifers. *International Journal of Greenhouse Gas Control*, **23**, 113–118, doi:10.1016/j.ijggc.2014.02.006.
- Tachiiri, K., T. Hajima, and M. Kawamiya, 2015: Increase of uncertainty in transient climate response to cumulative carbon emissions after stabilization of atmospheric CO₂ concentration. *Environmental Research Letters*, **10(12)**, 125018, doi:10.1088/1748-9326/10/12/125018.

- Tan, I., T. Storelvmo, and M.D. Zelinka, 2016: Observational constraints on mixed-phase clouds imply higher climate sensitivity. *Science*, **352(6282)**, 224–227, doi:[10.1126/science.aad5300](https://doi.org/10.1126/science.aad5300).
- Tavoni, M. and R.S.J. Tol, 2010: Counting only the hits? The risk of underestimating the costs of stringent climate policy. *Climatic Change*, **100(3–4)**, 769–778, doi:[10.1007/s10584-010-9867-9](https://doi.org/10.1007/s10584-010-9867-9).
- The Royal Society, 2009: *Geoengineering the climate: science, governance and uncertainty*. RS Policy document 10/09, The Royal Society, London, UK, 82 pp.
- Thomson, A.M. et al., 2011: RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Climatic Change*, **109(1–2)**, 77–94, doi:[10.1007/s10584-011-0151-4](https://doi.org/10.1007/s10584-011-0151-4).
- Tilman, D. and M. Clark, 2014: Global diets link environmental sustainability and human health. *Nature*, **515(7528)**, 518–522, doi:[10.1038/nature13959](https://doi.org/10.1038/nature13959).
- Tokarska, K.B. and N.P. Gillett, 2018: Cumulative carbon emissions budgets consistent with 1.5°C global warming. *Nature Climate Change*, **8(4)**, 296–299, doi:[10.1038/s41558-018-0118-9](https://doi.org/10.1038/s41558-018-0118-9).
- Tokarska, K.B., N.P. Gillett, V.K. Arora, W.G. Lee, and K. Zickfeld, 2018: The influence of non-CO₂ forcings on cumulative carbon emissions budgets. *Environmental Research Letters*, **13(3)**, 034039, doi:[10.1088/1748-9326/aaafdd](https://doi.org/10.1088/1748-9326/aaafdd).
- Tol, R.S.J., 1999: Spatial and Temporal Efficiency in Climate Policy: Applications of FUND. *Environmental and Resource Economics*, **14(1)**, 33–49, doi:[10.1023/a:1008314205375](https://doi.org/10.1023/a:1008314205375).
- Tol, R.S.J., 2017: The structure of the climate debate. *Energy Policy*, **104**, 431–438, doi:[10.1016/j.enpol.2017.01.005](https://doi.org/10.1016/j.enpol.2017.01.005).
- Tuomisto, H.L. and M.J. Teixeira de Mattos, 2011: Environmental Impacts of Cultured Meat Production. *Environmental Science & Technology*, **45(14)**, 6117–6123, doi:[10.1021/es200130u](https://doi.org/10.1021/es200130u).
- UNEP, 2015: *Aligning the Financial System with Sustainable Development: Pathways to Scale*. Inquiry: Design of a Sustainable Financial System and United Nations Environment Programme (UNEP), Geneva, Switzerland, 25 pp.
- UNEP, 2016: *The Emissions Gap Report 2016: A UNEP Synthesis Report*. United Nations Environment Programme (UNEP), Nairobi, Kenya, 85 pp.
- UNEP, 2017: *The Emissions Gap Report 2017: A UN Environment Synthesis Report*. United Nations Environment Programme (UNEP), Nairobi, Kenya, 116 pp.
- UNFCCC, 2016: *Aggregate effect of the intended nationally determined contributions: an update*. FCCC/CP/2016/2, The Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany, 75 pp.
- Unruh, G.C. and J. Carrillo-Hermosilla, 2006: Globalizing carbon lock-in. *Energy Policy*, **34(10)**, 1185–1197, doi:[10.1016/j.enpol.2004.10.013](https://doi.org/10.1016/j.enpol.2004.10.013).
- Unruh, J.D., 2011: Tree-Based Carbon Storage in Developing Countries: Neglect of the Social Sciences. *Society & Natural Resources*, **24(2)**, 185–192, doi:[10.1080/08941920903410136](https://doi.org/10.1080/08941920903410136).
- US EPA, 2013: *Global Mitigation of Non-CO₂ Greenhouse Gases: 2010–2030*. Report No. EPA-430-R-13-011. United States Environmental Protection Agency (US EPA), Washington DC, USA, 410 pp.
- Valin, H. et al., 2013: Agricultural productivity and greenhouse gas emissions: trade-offs or synergies between mitigation and food security? *Environmental Research Letters*, **8(3)**, 035019, doi:[10.1088/1748-9326/8/3/035019](https://doi.org/10.1088/1748-9326/8/3/035019).
- van den Bergh, J.C.J.M., 2017: Rebound policy in the Paris Agreement: instrument comparison and climate-club revenue offsets. *Climate Policy*, **17(6)**, 801–813, doi:[10.1080/14693062.2016.1169499](https://doi.org/10.1080/14693062.2016.1169499).
- van Sluiseveld, M.A.E., S.H. Martínez, V. Daioglou, and D.P. van Vuuren, 2016: Exploring the implications of lifestyle change in 2°C mitigation scenarios using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **102**, 309–319, doi:[10.1016/j.techfore.2015.08.013](https://doi.org/10.1016/j.techfore.2015.08.013).
- van Soest, H.L. et al., 2017: Low-emission pathways in 11 major economies: comparison of cost-optimal pathways and Paris climate proposals. *Climatic Change*, **142(3–4)**, 491–504, doi:[10.1007/s10584-017-1964-6](https://doi.org/10.1007/s10584-017-1964-6).
- van Vuuren, D.P. and K. Riahi, 2011: The relationship between short-term emissions and long-term concentration targets. *Climatic Change*, **104(3)**, 793–801, doi:[10.1007/s10584-010-0004-6](https://doi.org/10.1007/s10584-010-0004-6).
- van Vuuren, D.P., A.F. Hof, M.A.E. van Sluiseveld, and K. Riahi, 2017a: Open discussion of negative emissions is urgently needed. *Nature Energy*, **2(12)**, 902–904, doi:[10.1038/s41560-017-0055-2](https://doi.org/10.1038/s41560-017-0055-2).
- van Vuuren, D.P. et al., 2007: Stabilizing greenhouse gas concentrations at low levels: An assessment of reduction strategies and costs. *Climatic Change*, **81(2)**, 119–159, doi:[10.1007/s10584-006-9172-9](https://doi.org/10.1007/s10584-006-9172-9).
- van Vuuren, D.P. et al., 2011a: The representative concentration pathways: An overview. *Climatic Change*, **109(1)**, 5–31, doi:[10.1007/s10584-011-0148-z](https://doi.org/10.1007/s10584-011-0148-z).
- van Vuuren, D.P. et al., 2011b: RCP2.6: Exploring the possibility to keep global mean temperature increase below 2°C. *Climatic Change*, **109(1)**, 95–116, doi:[10.1007/s10584-011-0152-3](https://doi.org/10.1007/s10584-011-0152-3).
- van Vuuren, D.P. et al., 2015: Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **98**, 303–323, doi:[10.1016/j.techfore.2015.03.005](https://doi.org/10.1016/j.techfore.2015.03.005).
- van Vuuren, D.P. et al., 2016: Carbon budgets and energy transition pathways. *Environmental Research Letters*, **11(7)**, 075002, doi:[10.1088/1748-9326/11/7/075002](https://doi.org/10.1088/1748-9326/11/7/075002).
- van Vuuren, D.P. et al., 2017b: Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change*, **42**, 237–250, doi:[10.1016/j.gloenvcha.2016.05.008](https://doi.org/10.1016/j.gloenvcha.2016.05.008).
- van Vuuren, D.P. et al., 2018: Alternative pathways to the 1.5°C target reduce the need for negative emission technologies. *Nature Climate Change*, **8(5)**, 391–397, doi:[10.1038/s41558-018-0119-8](https://doi.org/10.1038/s41558-018-0119-8).
- Vangkilde-Pedersen, T. et al., 2009: Assessing European capacity for geological storage of carbon dioxide—the EU GeoCapacity project. *Energy Procedia*, **1(1)**, 2663–2670, doi:[10.1016/j.egypro.2009.02.034](https://doi.org/10.1016/j.egypro.2009.02.034).
- Veland, S. et al., 2018: Narrative matters for sustainability: the transformative role of storytelling in realizing 1.5°C futures. *Current Opinion in Environmental Sustainability*, **31**, 41–47, doi:[10.1016/j.cosust.2017.12.005](https://doi.org/10.1016/j.cosust.2017.12.005).
- Velders, G.J.M., D.W. Fahey, J.S. Daniel, S.O. Andersen, and M. McFarland, 2015: Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. *Atmospheric Environment*, **123**, 200–209, doi:[10.1016/j.atmosenv.2015.10.071](https://doi.org/10.1016/j.atmosenv.2015.10.071).
- Vogt-Schilb, A. and S. Hallegatte, 2017: Climate policies and nationally determined contributions: reconciling the needed ambition with the political economy. *Wiley Interdisciplinary Reviews: Energy and Environment*, **6(6)**, 1–23, doi:[10.1002/wene.256](https://doi.org/10.1002/wene.256).
- Voigt, C. et al., 2017a: Warming of subarctic tundra increases emissions of all three important greenhouse gases – carbon dioxide, methane, and nitrous oxide. *Global Change Biology*, **23(8)**, 3121–3138, doi:[10.1111/gcb.13563](https://doi.org/10.1111/gcb.13563).
- Voigt, C. et al., 2017b: Increased nitrous oxide emissions from Arctic peatlands after permafrost thaw. *Proceedings of the National Academy of Sciences*, **114(24)**, 6238–6243, doi:[10.1073/pnas.1702902114](https://doi.org/10.1073/pnas.1702902114).
- von Stechow, C. et al., 2015: Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. *Annual Review of Environment and Resources*, **40(1)**, 363–394, doi:[10.1146/annurev-environ-021113-095626](https://doi.org/10.1146/annurev-environ-021113-095626).
- von Stechow, C. et al., 2016: 2°C and SDGs: united they stand, divided they fall? *Environmental Research Letters*, **11(3)**, 034022, doi:[10.1088/1748-9326/11/3/034022](https://doi.org/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. *Environmental Research Letters*, **13(4)**, 044039, doi:[10.1088/1748-9326/aab53e](https://doi.org/10.1088/1748-9326/aab53e).
- Wachsmuth, J. and V. Duscha, 2018: Achievability of the Paris targets in the EU—the role of demand-side-driven mitigation in different types of scenarios. *Energy Efficiency*, 1–19, doi:[10.1007/s12053-018-9670-4](https://doi.org/10.1007/s12053-018-9670-4).
- Walsh, M.J. et al., 2016: Algal food and fuel coproduction can mitigate greenhouse gas emissions while improving land and water-use efficiency. *Environmental Research Letters*, **11(11)**, 114006, doi:[10.1088/1748-9326/11/11/114006](https://doi.org/10.1088/1748-9326/11/11/114006).
- Wang, X. et al., 2016: Taking account of governance: Implications for land-use dynamics, food prices, and trade patterns. *Ecological Economics*, **122**, 12–24, doi:[10.1016/j.ecolecon.2015.11.018](https://doi.org/10.1016/j.ecolecon.2015.11.018).
- Warwick, P.D., M.K. Verma, P.A. Freeman, M.D. Corum, and S.H. Hickman, 2014: U.S. geological survey carbon sequestration – geologic research and assessments. *Energy Procedia*, **63**, 5305–5309, doi:[10.1016/j.egypro.2014.11.561](https://doi.org/10.1016/j.egypro.2014.11.561).
- Wedlock, D.N., P.H. Janssen, S.C. Leahy, D. Shu, and B.M. Buddle, 2013: Progress in the development of vaccines against rumen methanogens. *Animal*, **7(52)**, 244–252, doi:[10.1017/s1751731113000682](https://doi.org/10.1017/s1751731113000682).
- Wei, N. et al., 2013: A preliminary sub-basin scale evaluation framework of site suitability for onshore aquifer-based CO₂ storage in China. *International Journal of Greenhouse Gas Control*, **12**, 231–246, doi:[10.1016/j.ijggc.2012.10.012](https://doi.org/10.1016/j.ijggc.2012.10.012).
- Weindl, I. et al., 2015: Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. *Environmental Research Letters*, **10(9)**, 094021, doi:[10.1088/1748-9326/10/9/094021](https://doi.org/10.1088/1748-9326/10/9/094021).
- Weindl, I. et al., 2017: Livestock and human use of land: Productivity trends and dietary choices as drivers of future land and carbon dynamics. *Global and Planetary Change*, **159**, 1–10, doi:[10.1016/j.gloplacha.2017.10.002](https://doi.org/10.1016/j.gloplacha.2017.10.002).
- Weitzman, M.L., 2014: Can Negotiating a Uniform Carbon Price Help to Internalize the Global Warming Externality? *Journal of the Association of Environmental and Resource Economists*, **1(1/2)**, 29–49, doi:[10.1086/676039](https://doi.org/10.1086/676039).
- Werner, C., H.-P. Schmidt, D. Gerten, W. Lucht, and C. Kammann, 2018: Biogeochemical potential of biomass pyrolysis systems for limiting global warming to 1.5°C. *Environmental Research Letters*, **13(4)**, 044036, doi:[10.1088/1748-9326/aabb0e](https://doi.org/10.1088/1748-9326/aabb0e).

- West, J.J. et al., 2013: Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nature Climate Change*, **3**(10), 885–889, doi:[10.1038/nclimate2009](https://doi.org/10.1038/nclimate2009).
- Weyant, J., 2017: Some Contributions of Integrated Assessment Models of Global Climate Change. *Review of Environmental Economics and Policy*, **11**(1), 115–137, doi:[10.1093/reep/rew018](https://doi.org/10.1093/reep/rew018).
- Weyant, J.P., F.C. Chesnaye, and G.J. Blanford, 2006: Overview of EMF-21: Multigas Mitigation and Climate Policy. *The Energy Journal*, **27**, 1–32, doi:[10.5547/issn0195-6574-ej-volsi2006-nosi3-1](https://doi.org/10.5547/issn0195-6574-ej-volsi2006-nosi3-1).
- Wiebe, K. et al., 2015: Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. *Environmental Research Letters*, **10**(8), 085010, doi:[10.1088/1748-9326/10/8/085010](https://doi.org/10.1088/1748-9326/10/8/085010).
- Wigley, T.M.L., R. Richels, and J. Edmonds, 2007: Overshoot Pathways to CO₂ stabilization in a multi-gas context. In: *Human Induced Climate Change: An Interdisciplinary Perspective* [Schlesinger, M.E., H.S. Khesghi, J. Smith, F.C. de la Chesnaye, J.M. Reilly, T. Wilson, and C. Kolstad (eds.)]. Cambridge University Press, Cambridge, pp. 84–92, doi:[10.1017/cbo9780511619472.009](https://doi.org/10.1017/cbo9780511619472.009).
- Williams, P.J. and L.M.L. Laurens, 2010: Microalgae as biodiesel & biomass feedstocks: Review & analysis of the biochemistry, energetics & economics. *Energy & Environmental Science*, **3**(5), 554–590, doi:[10.1039/b924978h](https://doi.org/10.1039/b924978h).
- Williamson, P., 2016: Emissions reduction: Scrutinize CO₂ removal methods. *Nature*, **530**(153), 153–155, doi:[10.1038/530153a](https://doi.org/10.1038/530153a).
- Williamson, P. and R. Bodle, 2016: *Update on Climate Geoengineering in Relation to the Convention on Biological Diversity: Potential Impacts and Regulatory Framework*. CBD Technical Series No. 84, Secretariat of the Convention on Biological Diversity, Montreal, QC, Canada, 158 pp.
- Wise, M., K. Calvin, P. Kyle, P. Luckow, and J. Edmonds, 2014: Economic and physical modeling of land use in GCAM 3.0 and an application to agricultural productivity, land, and terrestrial carbon. *Climate Change Economics*, **5**(2), 1450003, doi:[10.1142/s2010007814500031](https://doi.org/10.1142/s2010007814500031).
- Woolf, D., J.E. Amonette, F.A. Street-Perrott, J. Lehmann, and S. Joseph, 2010: Sustainable biochar to mitigate global climate change. *Nature Communications*, **1**(5), 1–9, doi:[10.1038/ncomms1053](https://doi.org/10.1038/ncomms1053).
- Xiao, X.-J. and K. Jiang, 2018: China's nuclear power under the global 1.5°C target: Preliminary feasibility study and prospects. *Advances in Climate Change Research*, **9**(2), 138–143, doi:[10.1016/j.accre.2018.05.002](https://doi.org/10.1016/j.accre.2018.05.002).
- Xu, Y. and V. Ramanathan, 2017: Well below 2°C: Mitigation strategies for avoiding dangerous to catastrophic climate changes. *Proceedings of the National Academy of Sciences*, **114**(39), 10315–10323, doi:[10.1073/pnas.1618481114](https://doi.org/10.1073/pnas.1618481114).
- Yeh, S. et al., 2016: Detailed assessment of global transport-energy models' structures and projections. *Transportation Research Part D: Transport and Environment*, **55**, 294–309, doi:[10.1016/j.trd.2016.11.001](https://doi.org/10.1016/j.trd.2016.11.001).
- Zeman, F.S. and K. Lackner, 2004: Capturing Carbon Dioxide directly from the Atmosphere. *World Resource Review*, **16**(2), 157–172.
- Zeman, F.S. and D.W. Keith, 2008: Carbon Neutral Hydrocarbons. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **366**(1882), 3901–3918, doi:[10.1098/rsta.2008.0143](https://doi.org/10.1098/rsta.2008.0143).
- Zhai, C., J.H. Jiang, and H. Su, 2015: Long-term cloud change imprinted in seasonal cloud variation: More evidence of high climate sensitivity. *Geophysical Research Letters*, **42**(20), 8729–8737, doi:[10.1002/2015gl065911](https://doi.org/10.1002/2015gl065911).
- Zhang, R., S. Fujimori, and T. Hanaoka, 2018: The contribution of transport policies to the mitigation potential and cost of 2°C and 1.5°C goals. *Environmental Research Letters*, **13**(5), 054008, doi:[10.1088/1748-9326/aabb0d](https://doi.org/10.1088/1748-9326/aabb0d).
- Zickfeld, K. and T. Herrington, 2015: The time lag between a carbon dioxide emission and maximum warming increases with the size of the emission. *Environmental Research Letters*, **10**(3), 031001, doi:[10.1088/1748-9326/10/3/031001](https://doi.org/10.1088/1748-9326/10/3/031001).
- Zickfeld, K., A.H. MacDougall, and H.D. Matthews, 2016: On the proportionality between global temperature change and cumulative CO₂ emissions during periods of net negative CO₂ emissions. *Environmental Research Letters*, **11**(5), 055006, doi:[10.1088/1748-9326/11/5/055006](https://doi.org/10.1088/1748-9326/11/5/055006).
- Zickfeld, K., M. Eby, H.D. Matthews, and A.J. Weaver, 2009: Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proceedings of the National Academy of Sciences*, **106**(38), 16129–16134, doi:[10.1073/pnas.0805800106](https://doi.org/10.1073/pnas.0805800106).
- Zomer, R.J., D.A. Bossio, R. Sommer, and L.V. Verchot, 2017: Global Sequestration Potential of Increased Organic Carbon in Cropland Soils. *Scientific Reports*, **7**(1), 15554, doi:[10.1038/s41598-017-15794-8](https://doi.org/10.1038/s41598-017-15794-8).
- Zomer, R.J. et al., 2016: Global Tree Cover and Biomass Carbon on Agricultural Land: The contribution of agroforestry to global and national carbon budgets. *Scientific Reports*, **6**, 29987, doi:[10.1038/srep29987](https://doi.org/10.1038/srep29987).