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

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Executive Summary

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

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

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

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

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

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

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

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

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

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

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

Future emissions in 1.5°C-consistent pathways

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

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

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

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

The role of Carbon-Dioxide Removal (CDR)

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

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

Properties of energy transitions in 1.5°C-consistent pathways

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

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

Demand-side mitigation and behavioural changes

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

Links between 1.5°C-consistent pathways and sustainable development

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

2.1 Introduction to Mitigation Pathways and the Sustainable Development Context

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

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

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

2.1.1 Mitigation pathways consistent with 1.5°C

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

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

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

2.1.2 The Use of Scenarios

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

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

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

2.1.3 New scenario information since AR5

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

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

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

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

specific characteristics of scenarios more stringent than the lowest scenario category assessed in AR5 that was assessed to limit warming below 2°C with greater that 66% likelihood (Rogelj et al., 2015b, 2018; Akimoto et al., 2017; Su et al., 2017; Liu et al., 2017; Marcucci et al., 2017; Bauer et al., 2018; Strefler et al., 2018a; van Vuuren et al., 2018; Vrontisi et al., 2018; Zhang et al., 2018; Bertram et al., 2018; Grubler et al., 2018; Kriegler et al., 2018b; Luderer et al., 2018). Those scenarios explore 1.5°C-consistent pathways from multiple perspectives (see 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 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 limit (as defined by Chapter 1), whether they temporarily overshoot that limit, the extent of this potential overshoot, and the likelihood of falling within these bounds. Specifically, they were put into classes that either kept surface temperatures below a given threshold throughout the 21st century or returned to a value below 1.5°C at some point before 2100 after temporarily exceeding that level earlier, referred to as an overshoot (OS). Both groups were further separated based on the probability of being below the threshold and the degree of overshoot, respectively (Table 2.1). Pathways are uniquely classified, with 1.5°C-related classes given higher priority than 2°C classes in cases where a pathway would be applicable to either class.

The probability assessment used in the scenario classification are based on simulations using two reduced complexity carbon-cycle, atmospheric composition and climate models: the ‘Model for the Assessment of Greenhouse Gas Induced Climate Change’ (MAGICC) (Meinshausen et al., 2011a), and the ‘Finite Amplitude Impulse Response’ (FAIRv1.3) model (Smith et al., 2018). For the purpose of this report, and to facilitate comparison with AR5, the range of the key carbon-cycle and climate parameters for MAGICC and its setup are identical to those used in AR5 WGIII (Clarke et al., 2014). For each mitigation pathway, MAGICC and FAIR simulations provide probabilistic estimates of atmospheric concentrations, radiative forcing and global temperature outcomes until 2100. However, the classification uses MAGICC probabilities directly for traceability with AR5 and since this model is more established in the literature. Nevertheless, the overall uncertainty assessment is based on results from both models, which are considered in the context of the latest radiative forcing estimates and observed temperatures (Etminan et al., 2016; Smith et al., 2018) (Section 2.2 and 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.

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

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

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

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

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

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

Detailed process-based IAMs are a diverse set of models ranging from partial equilibrium energy-land models to computable general equilibrium models of the global economy, from myopic to perfect foresight models, and from models with to models without endogenous technological change (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 Socioeconomic Pathways (SSPs), especially those pertaining to energy and food demand (Riahi et al., 2017). See Section 2.3.1 for discussion of these assumptions. Since the AR5, the scenario literature has greatly expanded the exploration of these dimensions. This includes low demand scenarios (Grubler et al., 2018; van Vuuren et al., 2018), scenarios taking into account a larger set of sustainable development goals (Bertram et al., 2018), scenarios with restricted availability of CDR technologies (Bauer et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018b; Strefler et al., 2018b; van Vuuren et al., 2018), scenarios with near-term action dominated by regulatory policies (Kriegler et al., 2018b) and scenario variations across the Shared Socioeconomic Pathways (Riahi et al., 2017; Rogelj et al., 2018). IAM results depend upon multiple underlying assumptions, for example the extent to which global markets and economies are assumed to operate frictionless and policies are cost-optimised, assumptions about technological progress and availability and costs of mitigation and CDR measures, assumptions about underlying socio-economic developments and future energy, food and materials demand, and assumptions about the geographic and temporal pattern of future regulatory and carbon pricing policies (see Supplementary Material 2.SM.1.2 for additional discussion on IAMs and their limitations).

2.2 Geophysical relationships and constraints

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

2.2.1 Geophysical characteristics of mitigation pathways

This section employs the pathway classification introduced in Section 2.1, with geophysical characteristics derived from simulations with the MAGICC reduced-complexity carbon-cycle and climate model and supported by simulations with the FAIR reduced-complexity model (Section 2.1). Within a specific category and between models, there remains a large degree of variance. Most pathways exhibit a temperature overshoot which has been highlighted in several studies focusing on stringent mitigation pathways (Huntingford and Lowe, 2007; Wigley et al., 2007; Nohara et al., 2015; Rogelj et al., 2015d; Zickfeld and Herrington, 2015; Schleussner et al., 2016; Xu and Ramanathan, 2017). Only very few of the scenarios collected in the database for this report hold the average future warming projected by MAGICC below 1.5°C during the entire 21st century (Table 2.1, Figure 2.1). Most 1.5°C-consistent pathways available in the database overshoot 1.5°C around mid-century before peaking and then reducing temperatures so as to return below that level in 2100. However, because of numerous geophysical uncertainties and model dependencies (Section 2.2.1.1, 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 CO_2 emissions due to strongly reduced annual CO_2 emissions and deep reductions in CH_4 emissions (Section 2.3.3). The two reduced-complexity climate models used in this assessment suggest that virtually all available 1.5°C-consistent pathways peak and decline global-mean temperature rise, but with varying rates of temperature decline after the peak (Figure 2.1). The estimated decadal rates of temperature change by the end of the century are smaller than the amplitude of the climate variability as assessed in AR5 (1σ of about ±0.1°C), which hence complicates the detection of a global peak and decline of warming in observations on timescales of on to two decades (Bindoff et al., 2013). In comparison, many pathways limiting warming to 2°C or higher by 2100 still have noticeable increasing trends at the end of the century, and thus imply continued warming.

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

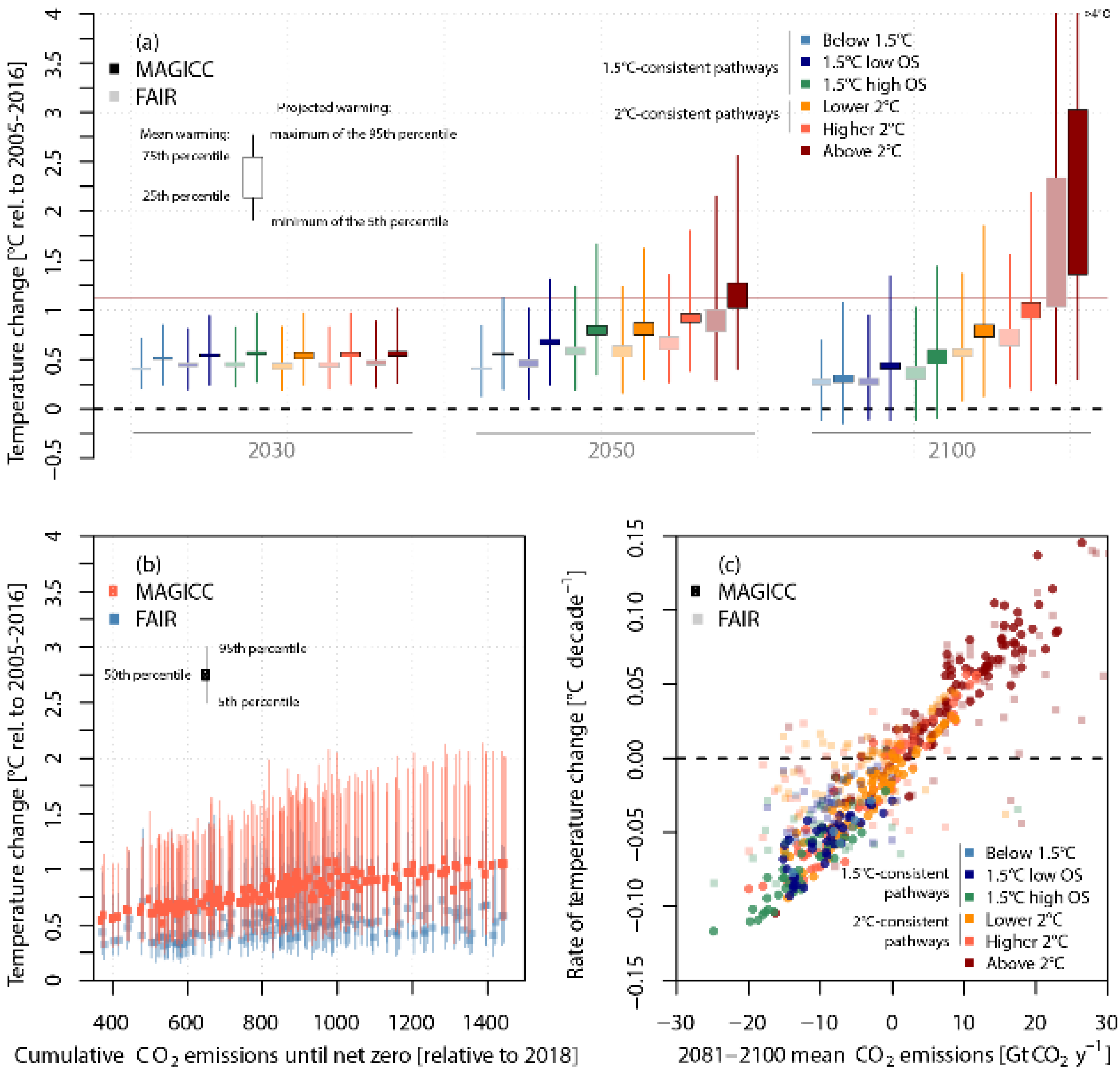

Figure 2.1: **Pathways classification overview.** (a) Average global-mean temperature increase relative to 2010 as projected by FAIR and MAGICC in 2030, 2050 and 2100; (b) response of peak warming to cumulative CO_2 emissions until net zero by MAGICC (red) and FAIR (blue); (c) decadal rate of average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

2.2.1.1 Geophysical uncertainties: non-CO2 forcing agents

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

A first uncertainty arises from the magnitude of the radiative forcing attributed to non-CO_2 climate forcers. Figure 2.2 illustrates how, for one representative 1.5°C-consistent pathway (SSP2-1.9) (Fricko et al., 2017; Rogelj et al., 2018), the effective radiative forcings as estimated by MAGICC and FAIR can differ (see Supplementary Material 2.SM1..1 for further details). This large spread in non-CO_2 effective radiative forcings leads to considerable uncertainty in the predicted temperature response. This uncertainty ultimately affects the assessed temperature outcomes for pathway classes used in this chapter (Section 2.1) and also affects the carbon budget (Section 2.2.2). Figure 2.2 highlights the important role of methane emissions reduction in this scenario in agreement with the recent literature focussing on stringent mitigation pathways (Shindell et al., 2012; Rogelj et al., 2014b, 2015a; Stohl et al., 2015; Collins et al., 2018).

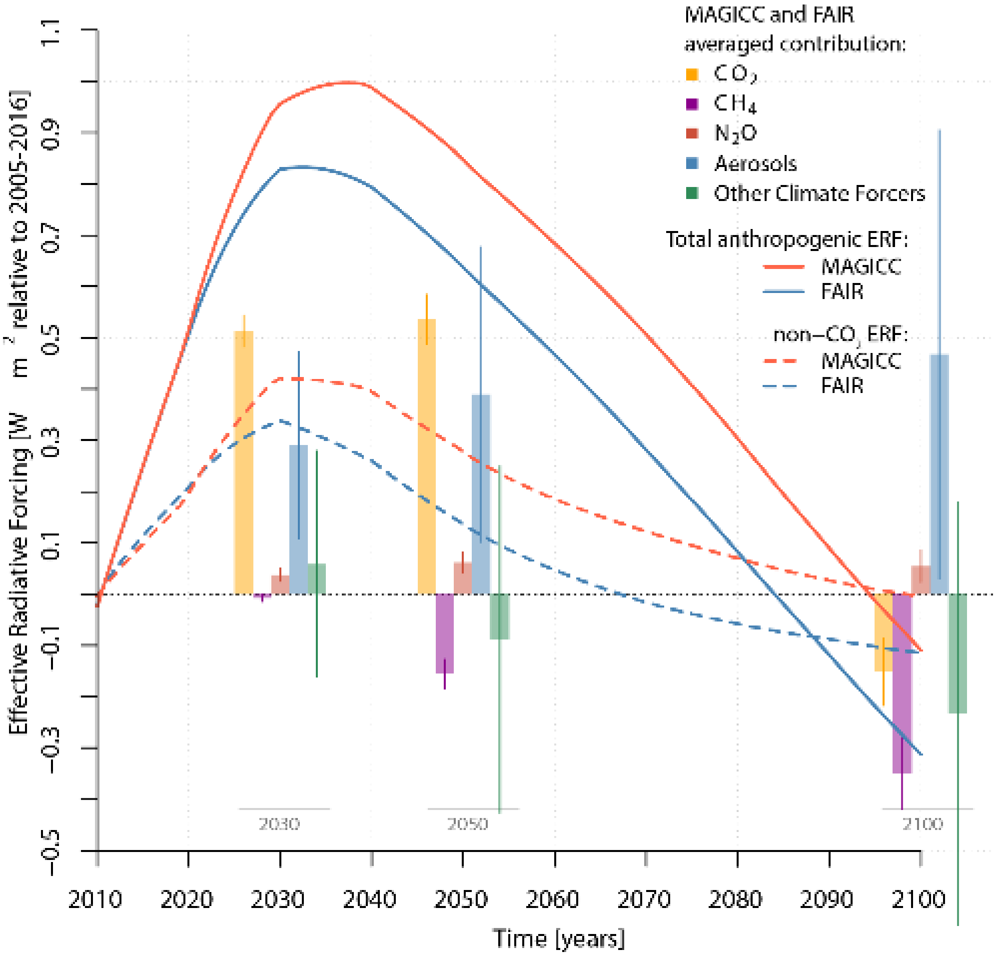

Figure 2.2: Changes and uncertainties in effective radiative forcings (ERF) for one 1.5°C-consistent pathway (SSP2-19) as estimated by MAGICC and FAIR. Solid and dashed lines are indicative of the effective radiative forcing for CO_2 and non-CO_2 agents as represented by MAGICC (red) and FAIR (blue)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

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

Figure 2.2 shows that there are substantial differences in the evolution of estimated effective radiative forcing of non-CO_2 forcers between MAGICC and FAIR. These forcing differences result in MAGICC simulating a larger warming trend in the near term compared to both the FAIR model and the recent observed trends of 0.2°C per decade reported in Chapter 1 (Figure 2.1, Supplementary Material 2.SM.1.1, 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 lead to important uncertainties in the temperature response (Myhre et al., 2013). This uncertainty increases the relative uncertainty of the temperature pathways associated with low emission scenarios compared to high emission scenarios (Clarke et al., 2014). It is also important to note that geographical patterns of temperature change and other climate responses, especially those related to precipitation, depend significantly on the forcing mechanism (Myhre et al., 2013; Shindell et al., 2015; Marvel et al., 2016; Samset et al., 2016) (see also Section 3.6.2.2).

2.2.1.2 Geophysical uncertainties: climate and Earth-system feedbacks

Climate sensitivity uncertainty impacts future projections as well as carbon-budget estimates (Schneider et al., 2017). AR5 assessed the equilibrium climate sensitivity (ECS) to be *likely* in the 1.5–4.5°C range, *extremely unlikely* less than 1°C and *very unlikely* greater than 6°C. The lower bound of this estimate is lower than the range of CMIP5 models (Collins et al., 2013). The evidence for the 1.5°C lower bound on ECS in AR5 was based on analysis of energy-budget changes over the historical period. Work since AR5 has suggested that the climate sensitivity inferred from such changes has been lower than the $2xCO_2$ climate sensitivity for known reasons (Forster, 2016; Gregory and Andrews, 2016; Rugenstein et al., 2016; Armour, 2017; Ceppi and Gregory, 2017; Knutti et al., 2017; Proistosescu and Huybers, 2017). Both a revised interpretation of historical estimates and other lines of evidence based on analysis of climate models with the best representation of today's climate (Sherwood et al., 2014; Zhai et al., 2015; Tan et al., 2016; Brown and Caldeira, 2017; Knutti et al., 2017) suggest that the lower bound of ECS could be revised upwards which would decrease the chances of limiting warming below 1.5°C in assessed pathways. However, such a reassessment has been challenged (Lewis and Curry, 2018), albeit from a single line of evidence. Nevertheless, it is premature to make a major revision to the lower bound. The evidence for a possible revision of the upper bound on ECS is less clear with cases argued from different lines of evidence for both decreasing (Lewis and Curry, 2015, 2018; Cox et al., 2018) and increasing (Brown and Caldeira, 2017) the bound presented in the literature. The tools used in this chapter employ ECS ranges consistent with the AR5 assessment. The MAGICC ECS distribution has not been selected to explicitly reflect this but is nevertheless consistent (Rogelj et al., 2014a). The FAIR model used here to estimate carbon budgets explicitly constructs log-normal distributions of ECS and transient climate response based on a multi parameter fit to the AR5 assessed ranges of climate sensitivity and individual historic effective radiative forcings (Smith et al., 2018) (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., 2017). Among these Earth-system feedbacks, the importance of the permafrost feedback's influence has been highlighted in recent studies. Combined evidence from both models (MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018) and field studies (like Schädel et al., 2014; Schuur et al., 2015) shows *high agreement* that permafrost thawing will release both CO_2 and CH_4 as the Earth warms, amplifying global warming. This thawing could also release N_2O (Voigt et al., 2017a, 2017b). Field, laboratory and modelling studies estimate that the vulnerable fraction in permafrost is about 5–15% of the permafrost soil carbon (~5300–5600 $GtCO_2$ in Schuur et al., 2015) and that carbon emissions are expected to occur beyond 2100 because of system inertia and the large proportion of slowly decomposing carbon in permafrost (Schädel et al., 2014). Published model studies suggest that a large part of the carbon release to the atmosphere is in the form of CO_2 (Schädel et al., 2016), while the amount of CH_4 released by permafrost thawing is estimated to be much smaller than that CO_2. Cumulative CH_4 release by 2100 under RCP2.6 ranges from 0.13 to 0.45 Gt of methane (Burke et al., 2012; Schneider von Deimling et al., 2012, 2015) with fluxes being the highest in the middle of the century because of maximum thermokarst lake extent by mid-century (Schneider von Deimling et al., 2015).

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

2.2.2 The remaining 1.5°C carbon budget

2.2.2.1 Carbon budget estimates

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

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

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

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

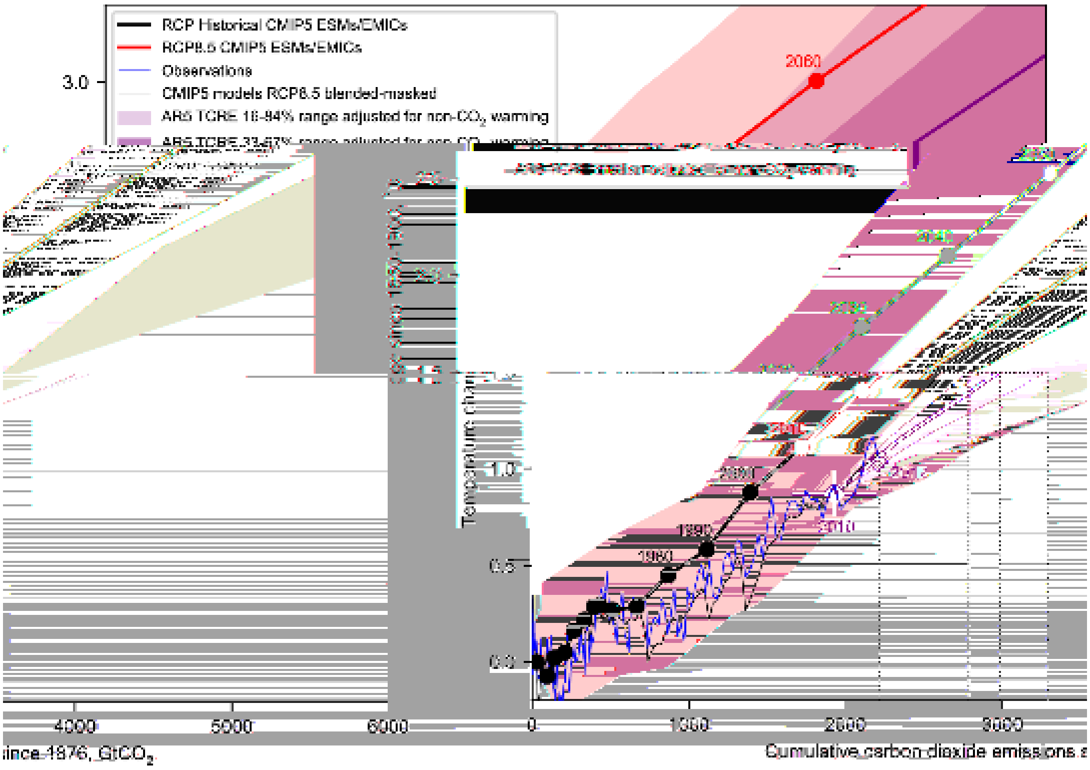

Figure 2.3: Temperature changes from 1850-1900 versus cumulative CO_2 emissions since 1st January 1876.

Solid lines with dots reproduce the temperature response to cumulative CO_2 emissions plus non-CO_2 forcers as assessed in Figure SPM10 of WGI AR5, except that points marked with years relate to a particular year, unlike in WGI AR5 Fig. SPM10 where each point relates to the mean over the previous decade. The AR5 data was derived from available Earth-system models and Earth-system models of Intermediate Complexity for the historic observations (black) and RCP 8.5 scenario (red) and the red shaded plume shows the uncertainty range across the models as presented in the AR5. The purple shaded plume and the line are indicative of the temperature response to cumulative CO_2 emissions and non-CO_2 warming adopted in this report. The non-CO_2 warming contribution is averaged from the MAGICC and FAIR models and the purple shaded range assumes the AR5 WGI TCRE distribution (Supplementary Material 2.SM.1.1.2). The 2010 observations of temperature anomaly (0.87°C based on 2006-2015 mean compared to 1850-1900, Section 1.2.1) and cumulative carbon dioxide emissions from 1876 to the end of 2010 of 1,930 $GtCO_2$ (Le Quéré et al., 2018) is shown as a filled purple diamond. 2017 values based on the latest cumulative carbon emissions up to the end of 2017 of 2,220 $GtCO_2$ (Version 1.3 accessed 22 May 2018) and a temperature anomaly of 1.04°C based on an assumed temperature increase of 0.2°C per decade is shown as a hollow purple diamond. The thin blue line shows annual observations, with CO_2 emissions from (Le Quéré et al., 2018) and temperatures from the average of datasets in Chapter 1, Figure 1.2. The thin black line shows the CMIP5 models blended-masked estimates with CO_2 emissions also from (Le Quéré et al., 2018). Dotted black lines illustrate the remaining carbon budget estimates for 1.5°C given in Table 2.2. Note these remaining budgets exclude possible Earth-system feedbacks that could reduce the budget, such as CO_2 and CH_4 release from permafrost thawing and tropical wetlands (see Section 2.2.2.2).

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

A remaining carbon budget can be estimated from calculating the amount of CO_2 emissions consistent, given a certain value of TCRE, with an allowable additional amount of warming. Here, the allowable warming is the 1.5°C warming threshold minus the current warming taken as the 2006-2015 average, with a further amount removed to account for the estimated non-CO_2 temperature contribution to the remaining warming (Peters, 2016; Rogelj et al., 2016b). This assessment uses the TCRE range from AR5 WGI (Collins et al., 2013) supported by estimates of non-CO_2 contributions that are based on published methods and integrated pathways (Friedlingstein et al., 2014a; Allen et al., 2016, 2018; Peters, 2016; Smith et al., 2018). Table 2.2 and Figure 2.3 show the assessed remaining carbon budgets and key uncertainties for a set of additional warming levels relative to the 2006–2015 period (see 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 (Section 1.2.1), 0.63°C of additional warming would be approximately consistent with a global-mean temperature increase of 1.5°C relative to preindustrial levels. For this level of additional warming, remaining carbon budgets have been estimated (Table 2.2, 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 $GtCO_2$. Accounting for such feedbacks would make the carbon budget more applicable for 2100 temperature targets, but would also increase uncertainty (Table 2.2 and see below). Excluding such feedbacks, the assessed range for the remaining carbon budget is estimated to be 1100, 750, and 550 $GtCO_2$ (rounded to the nearest 50 $GtCO_2$) for the 33rd, 50th and, 67th percentile of TCRE, respectively, with a median non-CO_2 warming contribution and starting from 1 January 2018 onward. Note that future research and ongoing observations over the next years will provide a better indication as to how the 2006–2015 base period compares with the long-term trends and might bias the budget estimates. Similarly, improved understanding in Earth-system feedbacks would result in a better quantification of their impacts on remaining carbon budgets for 1.5°C and 2°C.

After TCRE uncertainty, a major additional source of uncertainty is the magnitude of non-CO_2 forcing and its contribution to the temperature change between the present day and the time of peak warming. Integrated emissions pathways can be used to ensure consistency between CO_2 and non-CO_2 emissions (Bowerman et al., 2013; Collins et al., 2013; Clarke et al., 2014; Rogelj et al., 2014b, 2015a; Tokarska et al., 2018). Friedlingstein et al. (2014a) used pathways with limited to no climate mitigation to find a variation due to non-CO_2 contributions of about ±33% for a 2°C carbon budget. Rogelj et al. (2016b) showed no particular bias in non-CO_2 radiative forcing or warming at the time of exceedance of 2°C or at peak warming between scenarios with increasing emissions and strongly mitigated scenarios (consistent with Stocker et al., 2013).

However, clear differences of the non-CO_2 warming contribution at the time of deriving a 2°C-consistent carbon budget were reported for the four RCPs. Although the spread in non-CO_2 forcing across scenarios can be smaller in absolute terms at lower levels of cumulative emissions, it can be larger in relative terms compared to the remaining carbon budget (Stocker et al., 2013; Friedlingstein et al., 2014a; Rogelj et al., 2016b). Tokarska and Gillett (2018) find no statistically significant differences in 1.5°C-consistent cumulative emissions budgets when calculated for different RCPs from consistent sets of CMIP5 simulations.

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

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

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

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

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

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

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

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

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

Additional warming since 2006-2015 [°C]*(1)	**Approximate warming since 1850-1900 [°C]*(1)**	**Remaining carbon budget (excluding additional Earth-system feedbacks*(5)) [GtCO$_2$ from 1.1.2018]*(2)**			**Key uncertainties and variations*(4)**					
		Percentiles of TCRE*(3)			**Additional Earth-system feedbacks*(5)**	**Non-CO$_2$ scenario variation*(6)**	**Non-CO$_2$ forcing and response uncertainty**	**TCRE distribution uncertainty*(7)**	**Historical temperature uncertainty*(1)**	**Recent emissions uncertainty*(8)**
		33rd	*50th*	*67th*	*[GtCO$_2$]*	*[GtCO$_2$]*	*[GtCO$_2$]*	*[GtCO$_2$]*	*[GtCO$_2$]*	*[GtCO$_2$]*
0.3		290	160	80	Budgets on the left are reduced by about 100 GtCO$_2$ If evaluated to 2100 and potentially more on centennial time scales	+-250	-400 to +200	+100 to +200	+-250	+-20
0.4		530	350	230						
0.5		770	530	380						
0.6		1010	710	530						
0.63	**~1.5°C**	**1080**	**770**	**570**						
0.7		1240	900	680						
0.8		1480	1080	830						
0.9		1720	1260	980						
1		1960	1450	1130						
1.1		2200	1630	1280						
1.13	**~2.°C**	**2270**	**1690**	**1320**						
1.2		2440	1820	1430						

*(1) Chapter 1 has assessed historical warming between the 1850-1900 and 2006-2015 periods to be 0.87°C with a +/- 0.12°C *likely* (1-σ) range

*(2) Historical CO$_2$ emissions since the middle of the 1850-1900 historical base period (1 January 1876) are estimated at 1930 GtCO$_2$ (1630-2230 GtCO$_2$, 1-σ range) until end 2010. Since 1 January 2011, an additional 290 GtCO$_2$ (270-310 GtCO$_2$, 1-σ range) has been emitted until the end of 2017 (Le Quéré et al., 2018, Version 1.3 - accessed 22 May 2018).

*(3) TCRE: transient climate response to cumulative emissions of carbon, assessed by AR5 to fall *likely* between 0.8-2.5°C / 1000 PgC (Collins et al., 2013), considering a normal distribution consistent with AR5 (Stocker et al., 2013). Values are rounded to the nearest 10 GtCO$_2$ in the table and to the nearest 50 GtCO$_2$ in the text.

*(4) Focussing on the impact of various key uncertainties on median budgets for 0.63°C of additional warming.

*(5) Earth system feedbacks include CO$_2$ released by permafrost thawing or methane released by wetlands, see main text.

*(6) Variations due to different scenario assumptions related to the future evolution of non-CO$_2$ emissions.

*(7) The distribution of TCRE is not precisely defined. Here the influence of assuming a log-normal instead of a normal distribution shown.

*(8) Historical emissions uncertainty reflects the uncertainty in historical emissions since 1 January 2011.

2.3 Overview of 1.5°C mitigation pathways

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

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

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

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

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

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

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

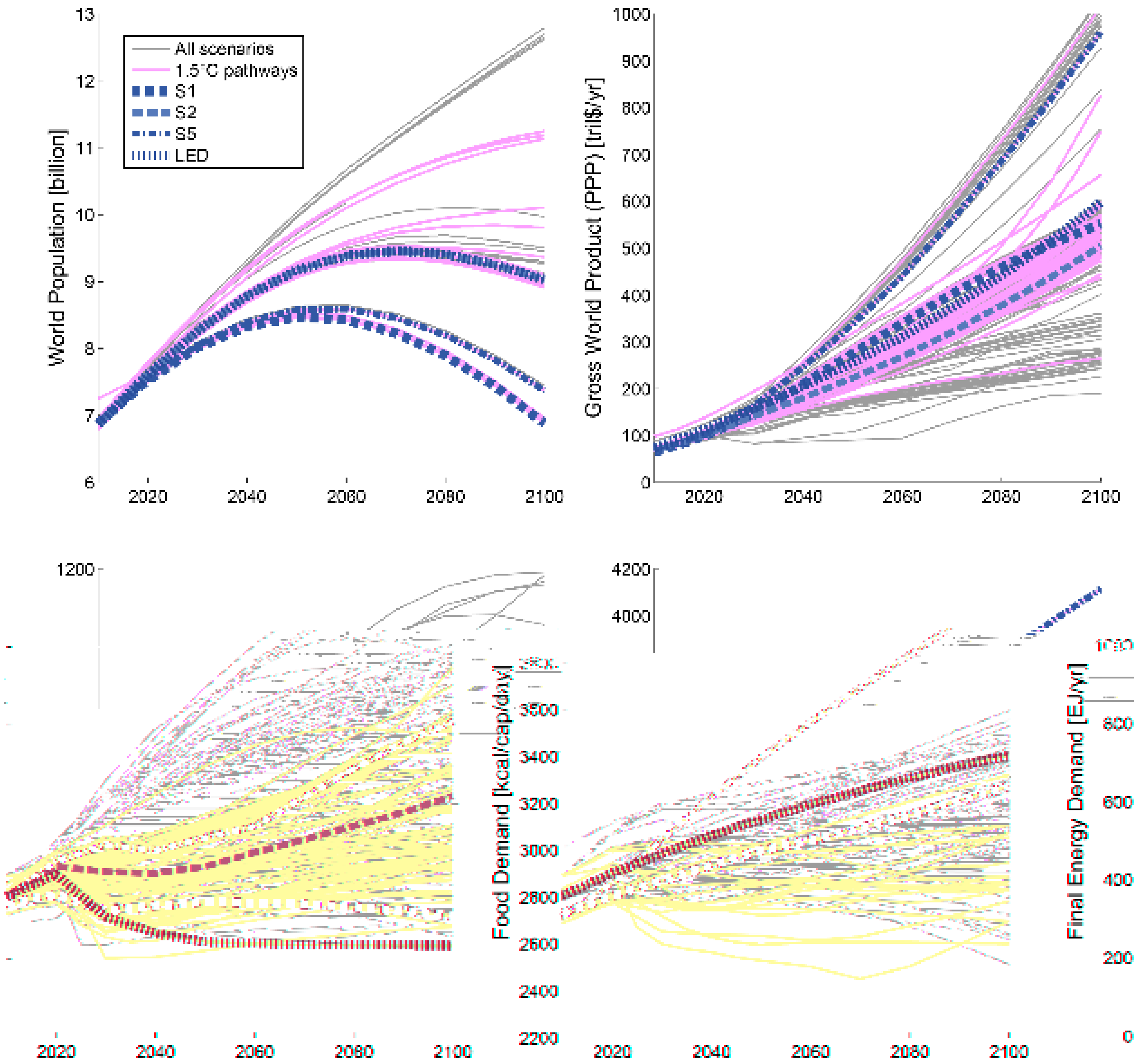

Figure 2.4: **Range of assumptions about socio-economic drivers and projections for energy and food demand in the pathways available to this assessment.** 1.5°C-consistent pathways are pink, other pathways grey. Trajectories for the illustrative 1.5°C-consistent archetypes used in this Chapter (*S1*,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

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

2.3.1.2 Mitigation options in 1.5°C-consistent pathways

In the context of 1.5°C-consistent pathways, the portfolio of mitigation options available to the model becomes an increasingly important factor. IAMs include a wide variety of mitigation options, as well as measures that achieve CDR from the atmosphere (Krey et al., 2014a, 2014b) (see Section 4.3 for a broad assessment of available mitigation measures). For the purpose of this assessment, we elicited technology availability in models that submitted scenarios to the database as summarized in 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 its techno-economic characteristics and future prospects, and computational challenge to represent the measure, e.g., in terms of required spatio-temporal and process detail.

This elicitation (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 Sluisveld et al., 2016; McCollum et al., 2017; Weindl et al., 2017), including in the context of 1.5°C-consistent pathways (Grubler et al., 2018; van Vuuren et al., 2018). The literature on the many diverse CDR options only recently started to develop strongly (Minx et al., 2017) (see Section 4.3.7 for a detailed assessment), and hence these options are only partially included in IAM analyses. IAMs mostly incorporate afforestation and bioenergy with carbon capture and storage (BECCS) and only in few cases also include direct air capture with CCS (DACCS) (Chen and Tavoni, 2013; Marcucci et al., 2017; Strefler et al., 2018b).

Several studies have either directly or indirectly explored the dependence of 1.5°C-consistent pathways on specific (sets of) mitigation and CDR technologies (Liu et al., 2017; Bauer et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018b; Rogelj et al., 2018; Strefler et al., 2018b; van Vuuren et al., 2018). However, there are a few potentially disruptive technologies that are typically not yet well covered in IAMs and that have the potential to alter the shape of mitigation pathways beyond the ranges in the IAM-based literature. Those are also included in 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 (Brynolf et al., 2018). An important element of carbon-neutral Power-2-X applications is the combination of hydrogen generated from renewable electricity and CO_2 captured from the atmosphere (Zeman and Keith, 2008). Alternatively, algae are considered as a bioenergy source with more limited implications for land use and agricultural systems than energy crops (Williams and Laurens, 2010; Walsh et al., 2016; Greene et al., 2017).

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

2.3.1.3 Policy assumptions in 1.5°C-consistent pathways

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

2.3.2 Key characteristics of 1.5°C-consistent pathways

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

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

Be it for the energy, transport, buildings, industry, or AFOLU sector, the literature shows that multiple options and choices are available in each of these sectors to pursue stringent emissions reductions (Section 2.3.1.2, Supplementary Material 2.SM.1.2, Section 4.3). Because the overall emissions total under a pathway is limited by a geophysical carbon budget (Section 2.2.2), choices in one sector affect the efforts that are required from others (Clarke et al., 2014). A robust feature of 1.5°C-consistent pathways, as highlighted by the set of pathway archetypes in Figure 2.5, is a virtually full decarbonisation of the power sector around mid-century, a feature shared with 2°C-consistent pathways. The additional emissions reductions in 1.5°C-consistent compared to 2°C-consistent pathways come predominantly from the transport and industry sectors (Luderer et al., 2018). Emissions can be apportioned differently across sectors, for example, by focussing on reducing the overall amount of CO_2 produced in the energy end use sectors, and using limited contributions of CDR by the AFOLU sector (afforestation and reforestation, *S1* and *LED* pathways in Figure 2.5) (Grubler et al., 2018; Holz et al., 2018b; van Vuuren et al., 2018), or by being more lenient about the amount of CO_2 that continues to be produced in the above-mentioned end-use sectors (both by 2030 and mid-century) and strongly relying on technological CDR options like BECCS (*S2* and *S5* pathways in Figure 2.5) (Luderer et al., 2018; Rogelj et al., 2018). Major drivers of these differences are assumptions about energy and food demand and the stringency of near term climate policy (see the difference between early action in the scenarios *S1*, *LED* and more moderate action until 2030 in the scenarios *S2*, *S5*). Furthermore, the carbon budget in each of these pathways depends also on the non-CO_2 mitigation measures implemented in each of them, particularly for agricultural emissions (Sections 2.2.2, 2.3.3) (Gernaat et al., 2015). Those pathways differ not only in terms of their deployment of mitigation and CDR measures (Sections 2.3.4 and 2.4), but also in terms of the temperature overshoot they imply (Figure 2.1). Furthermore, they have very different implications for the achievement of sustainable development objectives, as further discussed in Section 2.5.3.

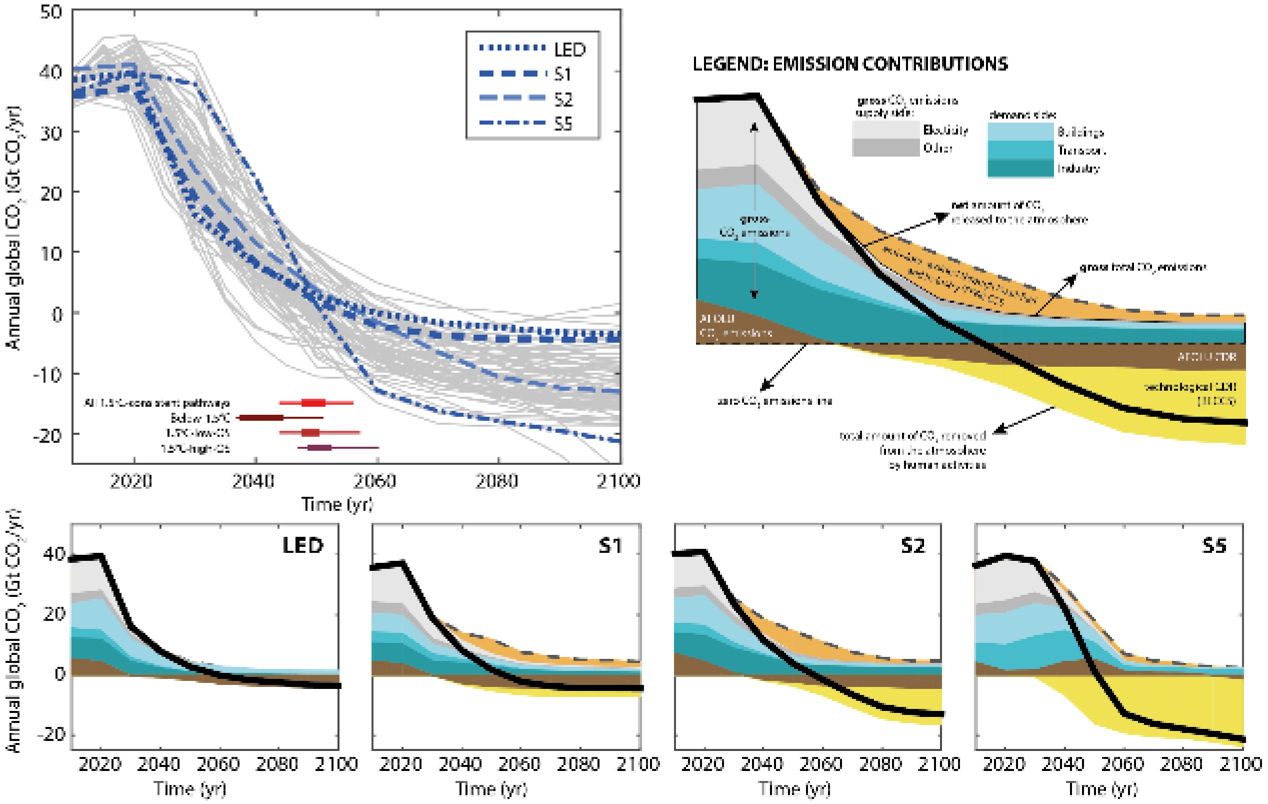

Figure 2.5: **Evolution and break down of global anthropogenic CO_2 emissions until 2100.** The top-left panel shows global net CO_2 emissions in Below-1.5°C, 1.5°C-low-OS, and 1.5°C-high-OS pathways, with the four illustrative 1.5°C-consistent pathway archetypes of this chapter highlighted. Ranges at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

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

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

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

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

To compare these numbers with the remaining carbon budget, Land-Use Change (LUC) CO_2 emissions need to be taken into account. In many of the 1.5°C-consistent pathways LUC CO_2 emissions reach zero at or before mid-century and then turn to negative values (Table 2.4). This means human changes to the land lead to atmospheric carbon being stored in plants and soils. This needs to be distinguished from the natural CO_2 uptake by land which is not accounted for in the anthropogenic LUC CO_2 emissions reported in the pathways. Given the difference in estimating the 'anthropogenic' sink between countries and the global integrated assessment and carbon modelling community (Grassi et al., 2017), the LUC CO_2 estimates included here are not necessarily directly comparable with countries' estimates at global level. The cumulated amount of LUC CO_2 emissions until the time they reach zero combine with the fossil-fuel and industry CO_2 emissions to a total amount of gross emissions of 670–1430 $GtCO_2$ for the period 2018–2100 (5th–95th percentile; median 1040 $GtCO_2$). The lower end of the range is similar to what emerges from a scenario of transformative change that halves CO_2 emissions every decade from 2020 to 2050 (Rockström et al., 2017). All these estimates are above the remaining carbon budget for a two-in-three chance of limiting warming below 1.5°C without overshoot, including the low end of the hypothetical sensitivity analysis of Kriegler et al. (2018a), who assumes 75 $GtCO_2$ LUC emissions adding to a total of 575 $GtCO_2$ gross CO_2 emissions. As only limited, highly idealized cases have been identified that keep gross CO_2 emissions within the 1.5°C carbon budget and based on current understanding of the geophysical response and its uncertainties, the available evidence indicates that avoiding overshoot will require some type of CDR in a broad sense, e.g., via negative LUC CO_2 emissions. (*medium confidence*) (Table 2.2).

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

2.3.3 Emissions evolution in 1.5°C pathways

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

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

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

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

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

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

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

At the same time, by mid-century and beyond, estimates of further reductions of non-CO_2 Kyoto-GHGs, in particular CH_4 and N_2O, are hampered by the absence of mitigation options in the current generation of IAMs which are hence not able to reduce residual emissions of sources linked to livestock production and fertilizer use (Clarke et al., 2014; Gernaat et al., 2015) (Sections 2.3.1.2, 2.4.4, Supplementary Material 2.SM.1.2). Therefore, while net CO_2 emissions are projected to be markedly lower in 1.5°C-consistent compared to 2°C-consistent pathways, this is much less the case for methane (CH_4) and nitrous-oxide (N_2O) (Figures 2.6–2.7). This results in reductions of CO_2 being projected to take up the largest share of emissions reductions when moving between 1.5°C-consistent and 2°C-consistent pathways (Rogelj et al., 2015b, 2018; Luderer et al., 2018). If additional non-CO_2 mitigation measures are identified and adequately included in IAMs, they are expected to further contribute to mitigation efforts by lowering the floor of residual non-CO_2 emissions. However, the magnitude of these potential contributions has not been assessed as part of this report.

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

2.3.3.1 Emissions of long-lived climate forcers

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

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

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

N_2O emissions decline to a much lesser extent than CO_2 in currently available 1.5°C-consistent pathways (Figure 2.6). Current IAMs have limited emissions reduction potentials (Gernaat et al., 2015) (Sections 2.3.1.2, 2.4.4, Supplementary Material 2.SM.1.2), reflecting the difficulty of eliminating N_2O emission from agriculture (Bodirsky et al., 2014). Moreover, the reliance of some pathways on significant amounts of bioenergy after mid-century (Section 2.4.2) coupled to a substantial use of nitrogen fertilizer (Popp et al., 2017) also makes reducing N_2O emissions harder (for example, see pathway *S5* in Figure 2.6). As a result, sizeable residual N_2O emissions are currently projected to continue throughout the century, and measures to effectively mitigate them will be of continued relevance for 1.5°C societies. Finally, the reduction of nitrogen use and N_2O emissions from agriculture is already a present-day concern due to unsustainable levels of nitrogen pollution (Bodirsky et al., 2012). Section 2.4.4 provides a further assessment of the agricultural non-CO_2 emissions reduction potential.

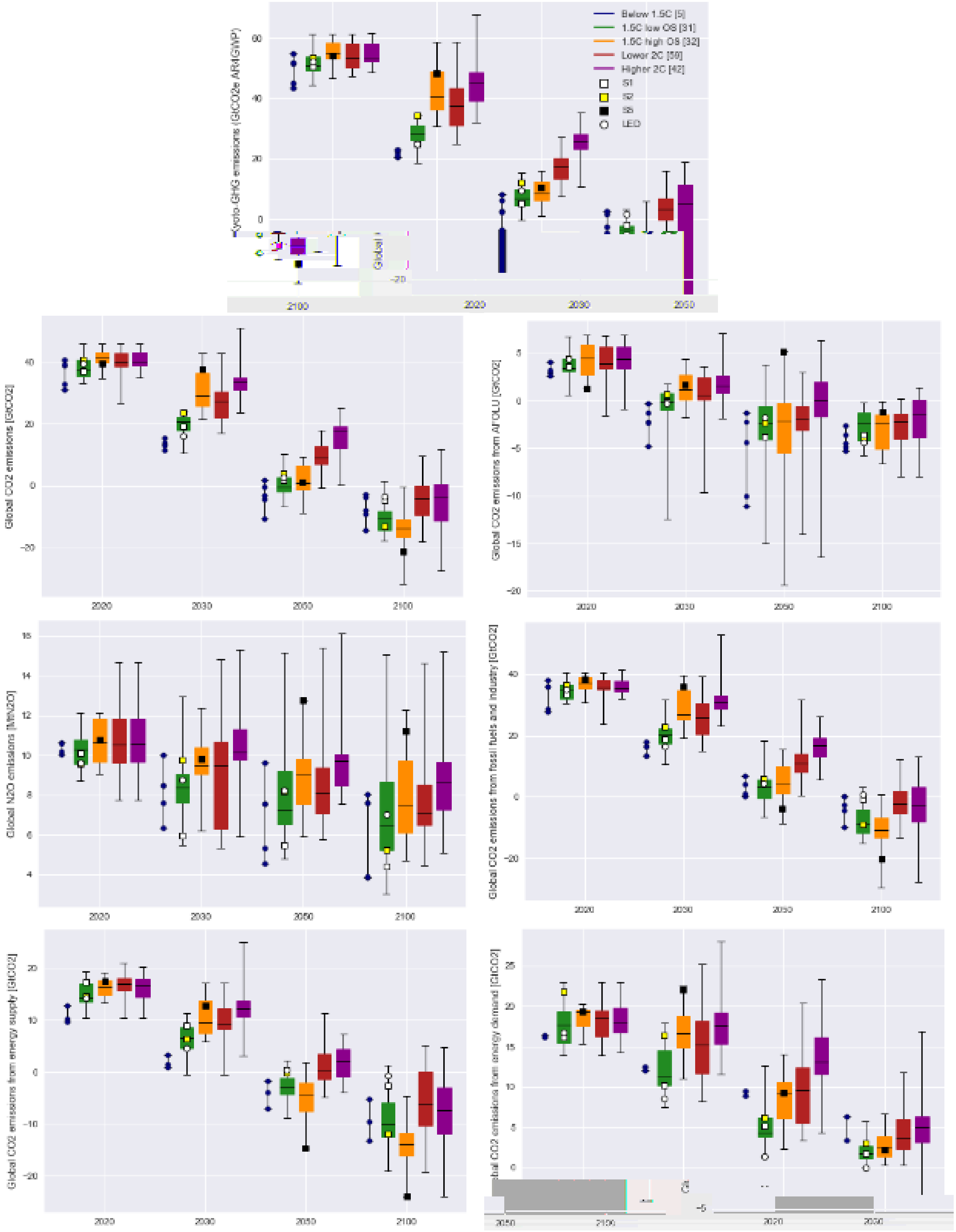

Figure 2.6: **Annual global emissions characteristics for 2020, 2030, 2050, 2100.** Data are shown for Kyoto-GHG emissions (top panel), and total CO_2 emissions, CO_2 emissions from the AFOLU sector, global N_2O emissions, and CO_2 emissions from fossil-fuel use and industrial processes. The latter is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

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

2.3.3.2 *Emissions of short-lived climate forcers and fluorinated gases*

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

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

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

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

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

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

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

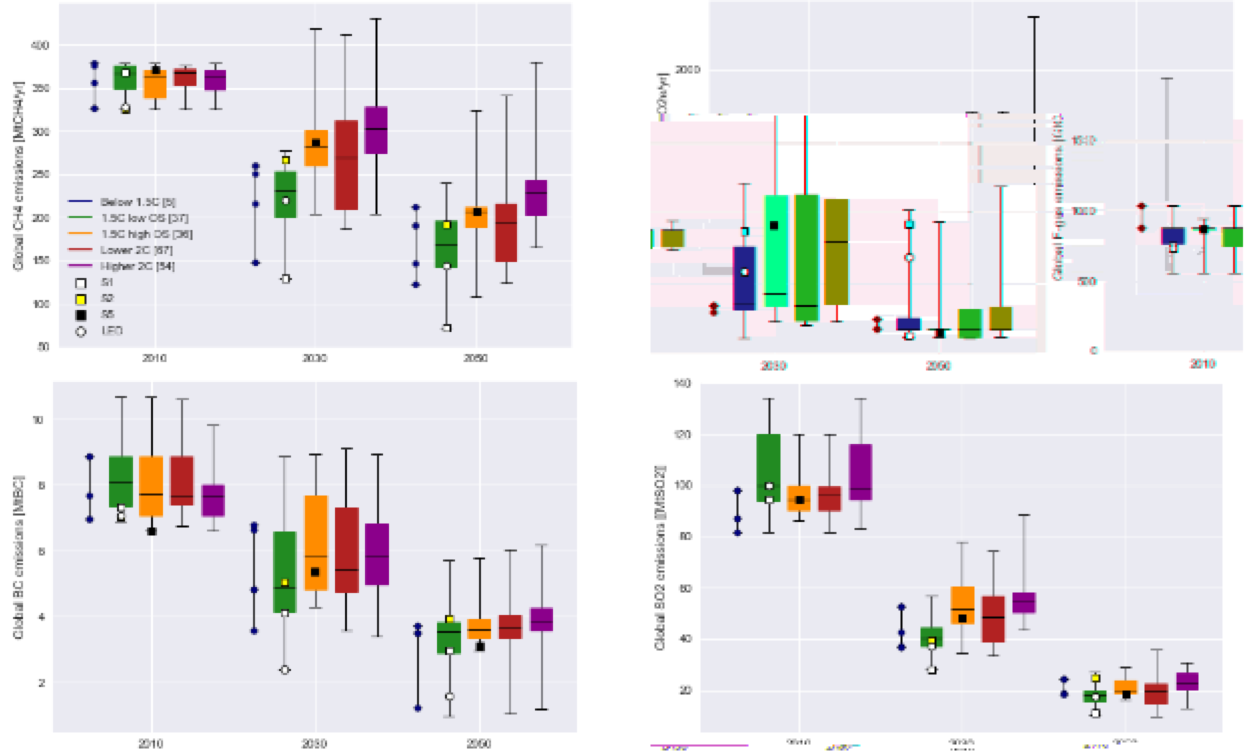

Figure 2.7: Global characteristics of a selection of short-lived non-CO_2 emissions until mid-century for five pathway classes used in this chapter. Data are shown for methane (CH_4), fluorinated gases (F-gas), black carbon (BC), and sulphur dioxide (SO_2) emissions. Boxes with different colours refer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

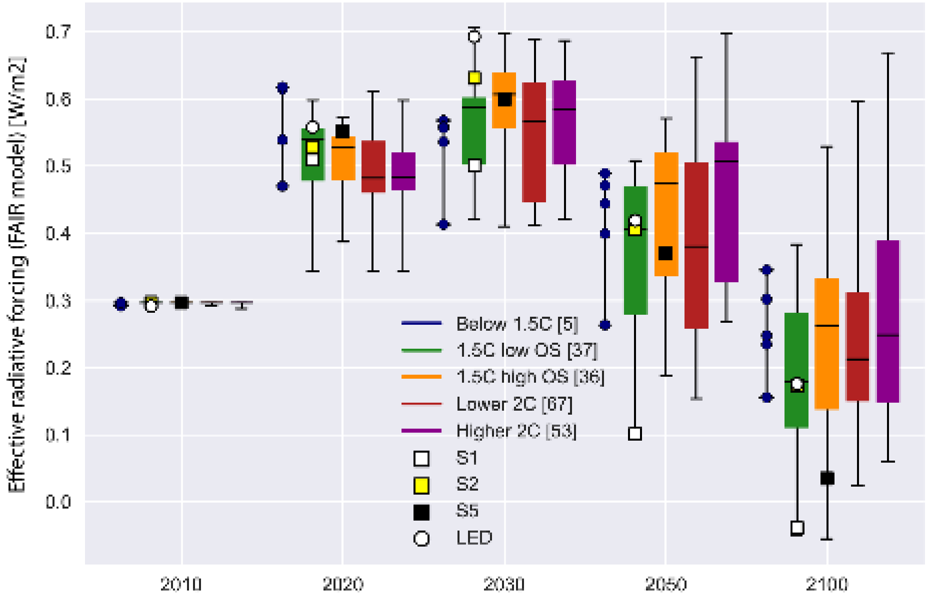

Figure 2.8: Estimated aggregated effective radiative forcing of SLCFs for 1.5°C and 2°C pathway classes in 2010, 2030, 2050, and 2100, as estimated by the FAIR model (Smith et al., 2018). Aggregated SLCF radiative forcing is estimated as the difference between total anthropogenic radiative forcing the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

2.3.4 CDR in 1.5°C-consistent pathways

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

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

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

Only some of these approaches have so far been considered in IAMs (see Section 2.3.1.2). The mitigation scenario literature up to AR5 mostly included BECCS and to a more limited extent afforestation and reforestation (Clarke et al., 2014). Since then, some 2°C and 1.5°C-consistent pathways including additional CDR measures such as DACCS (Chen and Tavoni, 2013; Marcucci et al., 2017; Lehtilä and Koljonen, 2018; Strefler et al., 2018b) and soil carbon sequestration (Frank et al., 2017) have become available. Other, more speculative approaches, in particular ocean-based CDR and removal of non-CO_2 gases, have not yet been taken up by the literature on mitigation pathways. See 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 CO_2 emissions between a baseline scenario and a 1.5°C-consistent pathway from the same model and study. However, baseline LUC emissions cannot only be reduced by CDR in the AFOLU sector, but also by measures to reduce deforestation and preserve land carbon stocks. The pathway literature and pathway data available to this assessment do not yet allow to separate the two contributions. As a conservative approximation, the additional net negative AFOLU CO_2 emissions below the baseline are taken as a proxy for AFOLU CDR in this assessment. Because this does not include CDR that was deployed before reaching net zero AFOLU emissions, this approximation is a lower-bound for terrestrial CDR in the AFOLU sector (including the factors that lead to net negative LUC emissions).

The scale and type of CDR deployment in 1.5°C-consistent pathways varies widely (Figure 2.9 and 2.10). Overall CDR deployment over the 21st century is substantial in most of the pathways, and deployment levels cover a wide range (770 [260-1170] $GtCO_2$, for median and 5th–95th percentile range). Both BECCS (560 [0 to 1000] $GtCO_2$) and AFOLU CDR measures including afforestation and reforestation (200 [0-550] $GtCO_2$) can play a major role[4], but for both cases pathways exist where they play no role at all. This shows the

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

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

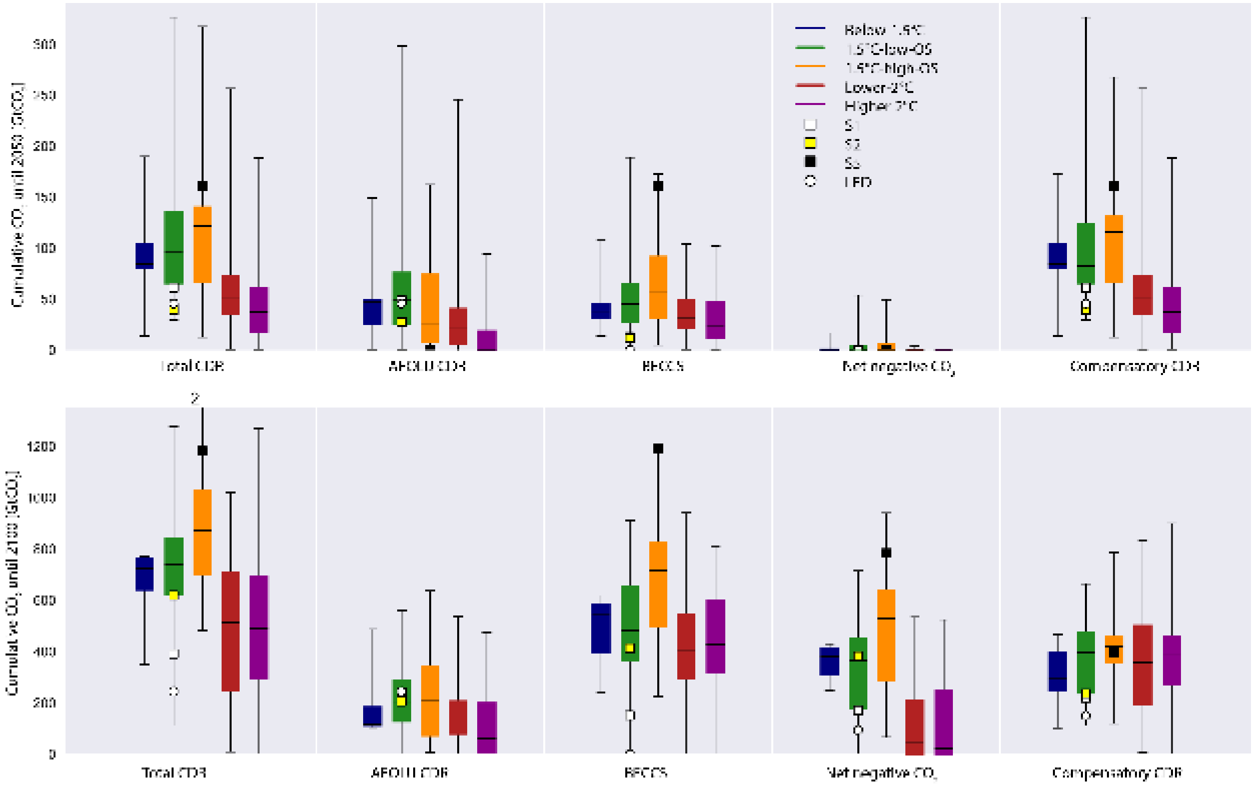

Figure 2.9: Cumulative CDR deployment in 1.5°C-consistent pathways in the literature as reported in the database collected for this assessment. Total CDR comprises all forms of CDR, including AFOLU CDR and BECCS, and in a few pathways other CDR measures like DACCS. It does not include CCS combined with fossil fuels (which is not a CDR technology as it does not result in active removal of CO_2 from the atmosphere). AFOLU CDR has not been reported directly and is hence represented by means of a proxy: the additional amount of net negative CO_2 emissions in the AFOLU sector compared to a baseline scenario (see text for a discussion). 'Compensate CO_2' depicts the cumulative amount of CDR that is used to neutralize concurrent residual CO_2 emissions. 'Net negative CO_2' describes the additional amount of CDR that is used to produce net negative emissions, once residual CO_2 emissions are neutralized. The two quantities add up to total CDR for individual pathways (not for percentiles and medians, see Footnote 4).

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

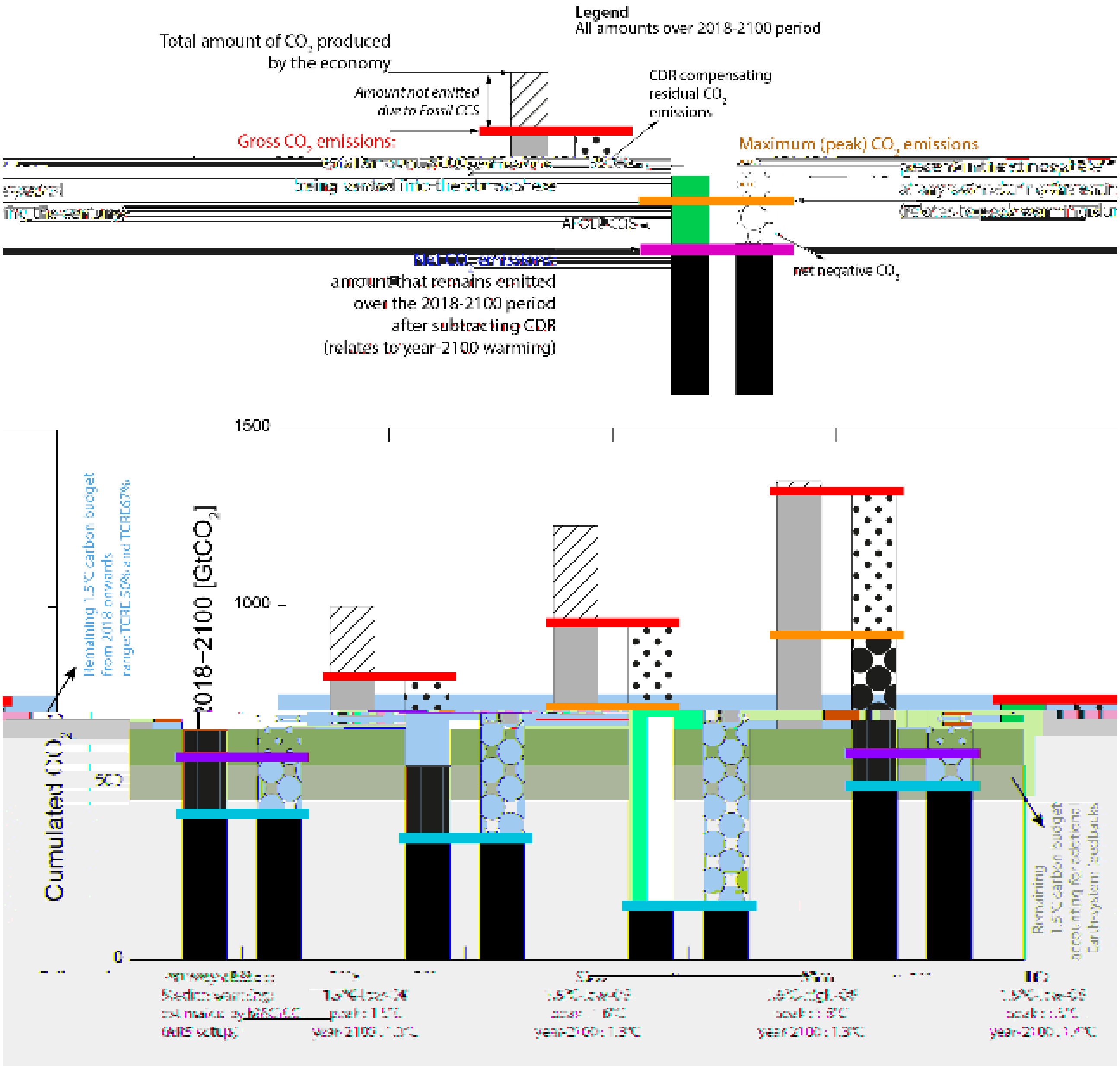

Figure 2.10: Accounting of cumulative CO_2 emissions for the four 1.5°C-consistent pathway archetypes. See top panel for explanation of the barplots. Total CDR is the difference between gross (red horizontal bar) and net (purple horizontal bar) cumulative CO_2 emissions over the period 2018–2100. Total CDR is the sum

of the BECCS (grey) and AFOLU CDR (green) contributions. Cumulative net negative emissions are the difference between peak (orange horizontal bar) and net (purple) cumulative CO_2 emissions. The blue shaded area depicts the estimated range of the remaining carbon budget for a two-in-three to one-in-two chance of staying below1.5°C. The grey shaded area depicts the range when accounting for additional Earth-system feedbacks. These remaining carbon budgets have been adjusted for the difference in starting year compared to Table 2.2

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

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

Box 2.1: Bioenergy and BECCS deployment in integrated assessment modelling

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

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

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

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

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

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

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

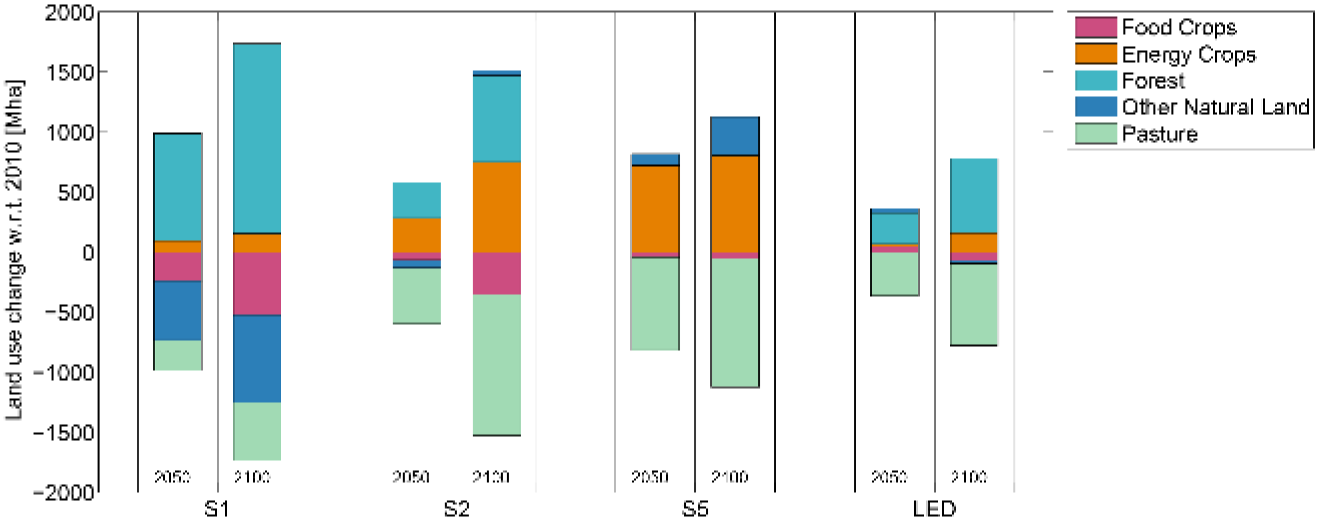

Figure 2.11: Land-use changes in 2050 and 2100 in the illustrative 1.5°C-consistent pathway archetypes (Fricko et al., 2017; Fujimori, 2017; Kriegler et al., 2017; Grubler et al., 2018; Rogelj et al., 2018).

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

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

All available 1.5°C pathways that explore consistent mitigation action from 2020 onwards peak global Kyoto-GHG emissions in the next decade and already decline Kyoto-GHG emissions to below 2010 levels by 2030. The near-term emissions development in these pathways can be compared with estimated emissions in 2030 implied by the Nationally Determined Contributions (NDCs) submitted by Parties to the Paris Agreement (Figure 2.12). Altogether, these NDCs are assessed to result in global Kyoto-GHG emissions on the order of 50–58 $GtCO_2e\ yr^{-1}$ in 2030 (for example, den Elzen et al., 2016; Fujimori et al., 2016; UNFCCC, 2016; Rogelj et al., 2017; Rose et al., 2017b; Benveniste et al., 2018; Vrontisi et al., 2018), see Cross-Chapter Box 11 in Chapter 4 for detailed assessment). In contrast, 1.5°C-consistent pathways available to this assessment show an interquartile range of about 26–38 (median 31) $GtCO_2e\ yr^{-1}$ in 2030, reducing to

26–31 (median 28) $GtCO_2e\ yr^{-1}$ if only pathways with low overshoot are taken into account[5], and still lower if pathways without overshoot are considered (Table 2.4, Section 2.3.3). Published estimates of the emissions gap between conditional NDCs and 1.5°C-consistent pathways in 2030 range from 16 (14–22) $GtCO_2e\ yr^{-1}$ (UNEP, 2017) for a greater than one-in-to chance of limiting warming below 1.5°C in 2100 to 25 (19–29) $GtCO_2e\ yr^{-1}$ (Vrontisi et al., 2018) for a greater than two-in-three chance of meeting the 1.5°C limit.

The later emissions peak and decline, the more CO_2 will have accumulated in the atmosphere. Peak cumulated CO_2 emissions and consequently also peak temperatures increase with 2030 emissions levels (Figure 2.12). Current NDCs (Cross-Chapter Box 11 in Chapter 4) are estimated to lead to CO_2 emissions of about 400–560 $GtCO_2$ from 2018 to 2030 (Rogelj et al., 2016a). Available 1.5°C- and 2°C-consistent pathways with 2030 emissions in the range estimated for the NDCs rely on an assumed swift and widespread deployment of CDR after 2030, and show peak cumulative CO_2 emissions from 2018 of about 800–1000 $GtCO_2$, above the remaining carbon budget for a one-in-two chance of remaining below 1.5°C. These emissions reflect that no pathway is able to project a phase out of CO_2 emissions starting from year-2030 NDC levels of about 40 $GtCO_2\ yr^{-1}$ (Fawcett et al., 2015; Rogelj et al., 2016a) to net zero in less than ca. 15 years. Based on the implied emissions until 2030, the high challenges of the assumed post-2030 transition, and the assessment of carbon budgets in Section 2.2.2, global warming is assessed to exceed 1.5°C if emissions stay at the levels implied by the NDCs until 2030 (Figure 2.12). The chances of remaining below 1.5°C in these circumstances remain conditional upon geophysical properties that are uncertain, but these Earth system response uncertainties would have to serendipitously align beyond current median estimates in order for current NDCs to become consistent with limiting warming to 1.5°C.

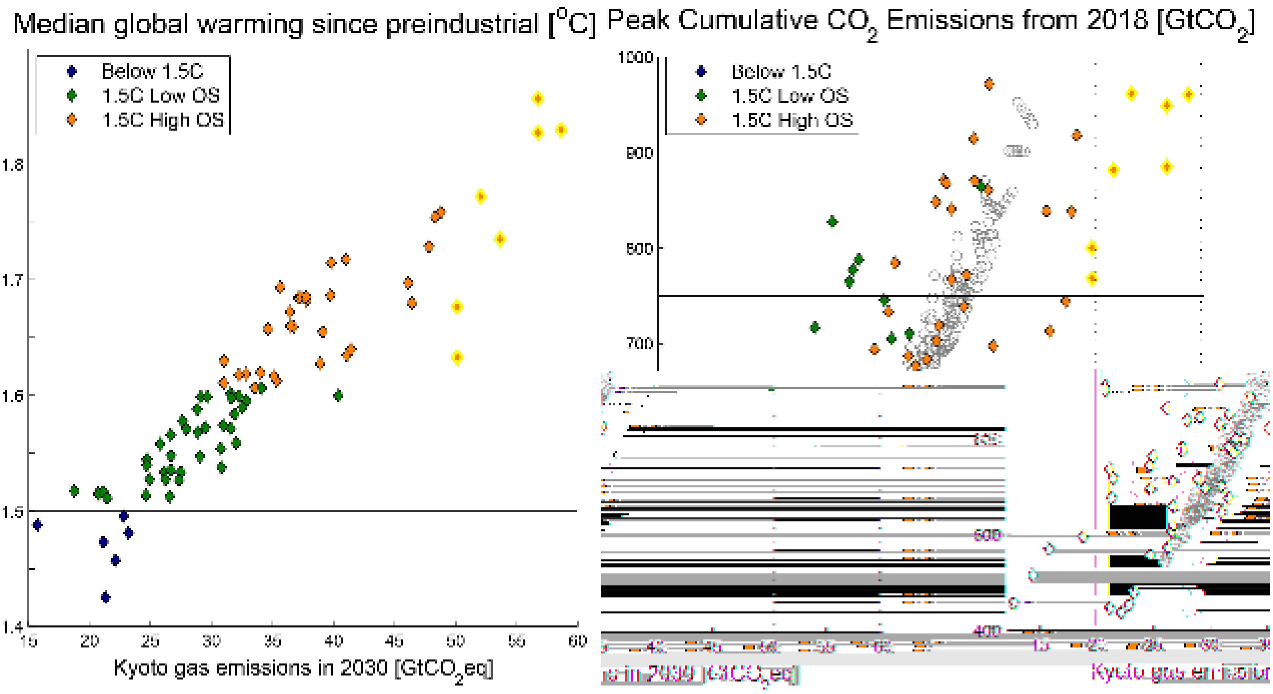

Figure 2.12: Median global warming estimated by MAGICC (left panel) and peak cumulative CO_2 emissions (right panel) in 1.5°C-consistent pathways in the SR1.5 scenario database as a function of CO_2-equivalent emissions (based on AR4 GWP-100) of Kyoto-GHGs in 2030. Pathways that were forced to go through the NDCs or a similarly high emissions point in 2030 by design are highlighted by yellow marker edges (see caption of Figure 2.13 and text for further details on the design of these pathways). The NDC range of global Kyoto-GHG emissions in 2030 assessed in Cross-Chapter Box 11 in Chapter 4 is shown by black dotted lines (adjusted to AR4 GWPs for comparison). As a second line of evidence, peak cumulative CO_2 emissions derived from a 1.5°C pathway sensitivity analysis (Kriegler et al., 2018a) are shown by grey circles in the right-hand panel. Numbers show gross fossil-fuel and industry emissions of

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[5]: Note that aggregated Kyoto-GHG emissions implied by the NDCs from Cross-Chapter Box 4.3 and Kyoto-GHG ranges from the pathway classes in Chapter 2 are only approximately comparable, because this chapter applies GWP-100 values from the IPCC Fourth Assessment Report while the NDC Cross-Chapter Box 4.3 applies GWP-100 values from the IPCC Second Assessment Report. At a global scale, switching between GWP-100 values of the Second to the Fourth IPCC Assessment Report would result in an increase in estimated aggregated Kyoto-GHG emissions of about no more than 3% in 2030 (UNFCCC, 2016).

the sensitivity cases increased by assumptions about the contributions from AFOLU (5 $GtCO_2$ yr^{-1} until 2020, followed by a linear phase out until 2040) and non-CO_2 Kyoto-GHGs (median non-CO_2 contribution from 1.5°C-consistent pathways available in the database: 10 $GtCO_2e$ yr^{-1} in 2030), and reduced by assumptions about CDR deployment until the time of net zero CO_2 emissions (limiting case for CDR deployment assumed in (Kriegler et al., 2018a) (logistic growth to 1, 4, 10 $GtCO_2$ yr^{-1} in 2030, 2040, and 2050, respectively, leading to approx. 100 $GtCO_2$ CDR by mid-century).

It is unclear whether following NDCs until 2030 would still allow global mean temperature to return to 1.5°C by 2100 after a temporary overshoot, due to the uncertainty associated with the Earth system response to net negative emissions after a peak (Section 2.2). Available IAM studies are working with reduced-form carbon cycle-climate models like MAGICC which assume a largely symmetric Earth-system response to positive and net negative CO_2 emissions. The IAM findings on returning warming to 1.5°C from NDCs after a temporary temperature overshoot are hence all conditional on this assumption. Two types of pathways with 1.5°C-consistent action starting in 2030 have been considered in the literature (Luderer et al., 2018) (Figure 2.13): pathways aiming to obtain the same end-of-century carbon budget despite higher emissions until 2030, and pathways assuming the same mitigation stringency after 2030 (approximated by using the same global price of emissions as found in least-cost pathways starting from 2020). An IAM comparison study found increasing challenges to implement pathways with the same end-of-century 1.5°C-consistent carbon budgets after following NDCs until 2030 (ADVANCE) (Luderer et al., 2018). The majority of model experiments (four out of seven) failed to produce NDC pathways that would return cumulative CO_2 emissions over the 2016–2100 period to 200 $GtCO_2$, indicating limitations to the availability and timing of CDR. The few such pathways that were identified show highly disruptive features in 2030 (including abrupt transitions from moderate to very large emissions reduction and low carbon energy deployment rates) indicating a high risk that the required post-2030 transformations are too steep and abrupt to be achieved by the mitigation measures in the models (*high confidence*). NDC pathways aiming for a cumulative 2016–2100 CO_2 emissions budget of 800 $GtCO_2$ were more readily obtained (Luderer et al., 2018), and some were classified as 1.5°C-high-OS pathways in this assessment (Section 2.1).

NDC pathways that apply a post-2030 price of emissions after 2030 as found in least-cost pathways starting from 2020 show infrastructural carbon lock-in as a result of following NDCs instead of least-cost action until 2030. A key finding is that carbon lock-ins persist long after 2030, with the majority of additional CO_2 emissions occurring during the 2030–2050 period. Luderer et al. (2018) find 90 (80–120) $GtCO_2$ additional emissions until 2030, growing to 240 (190–260) $GtCO_2$ by 2050 and 290 (200–200) $GtCO_2$ by 2100. As a result, peak warming is about 0.2°C higher and not all of the modelled pathways return warming to 1.5°C by the end of the century. There is a four sided trade-off between (i) near-term ambition, (ii) degree of overshoot, (iii) transitional challenges during the 2030–2050 period, and (iv) the amount of CDR deployment required during the century (Figure 2.13) (Holz et al., 2018b; Strefler et al., 2018b). Transition challenges, overshoot, and CDR requirements can be significantly reduced if global emissions peak before 2030 and fall below levels in line with current NDCs by 2030. For example, Strefler et al. (2018b) find that CDR deployment levels in the second half of the century can be halved in 1.5°C-consistent pathways with similar CO_2 emissions reductions rates during the 2030–2050 period if CO_2 emissions by 2030 are reduced by an additional 30% compared to NDC levels. Kriegler et al. (2018b) investigate a global roll out of selected regulatory policies and moderate carbon pricing policies. They show that additional reductions of ca. 10 $GtCO_2e$ yr^{-1} can be achieved in 2030 compared to the current NDCs. Such 20% reduction of year-2030 emissions compared to current NDCs would effectively lower the disruptiveness of post-2030 action. Strengthening of short-term policies in deep mitigation pathways has hence been identified as bridging options to keep the Paris climate goals within reach (Bertram et al., 2015b; IEA, 2015a; Spencer et al., 2015; Kriegler et al., 2018b).

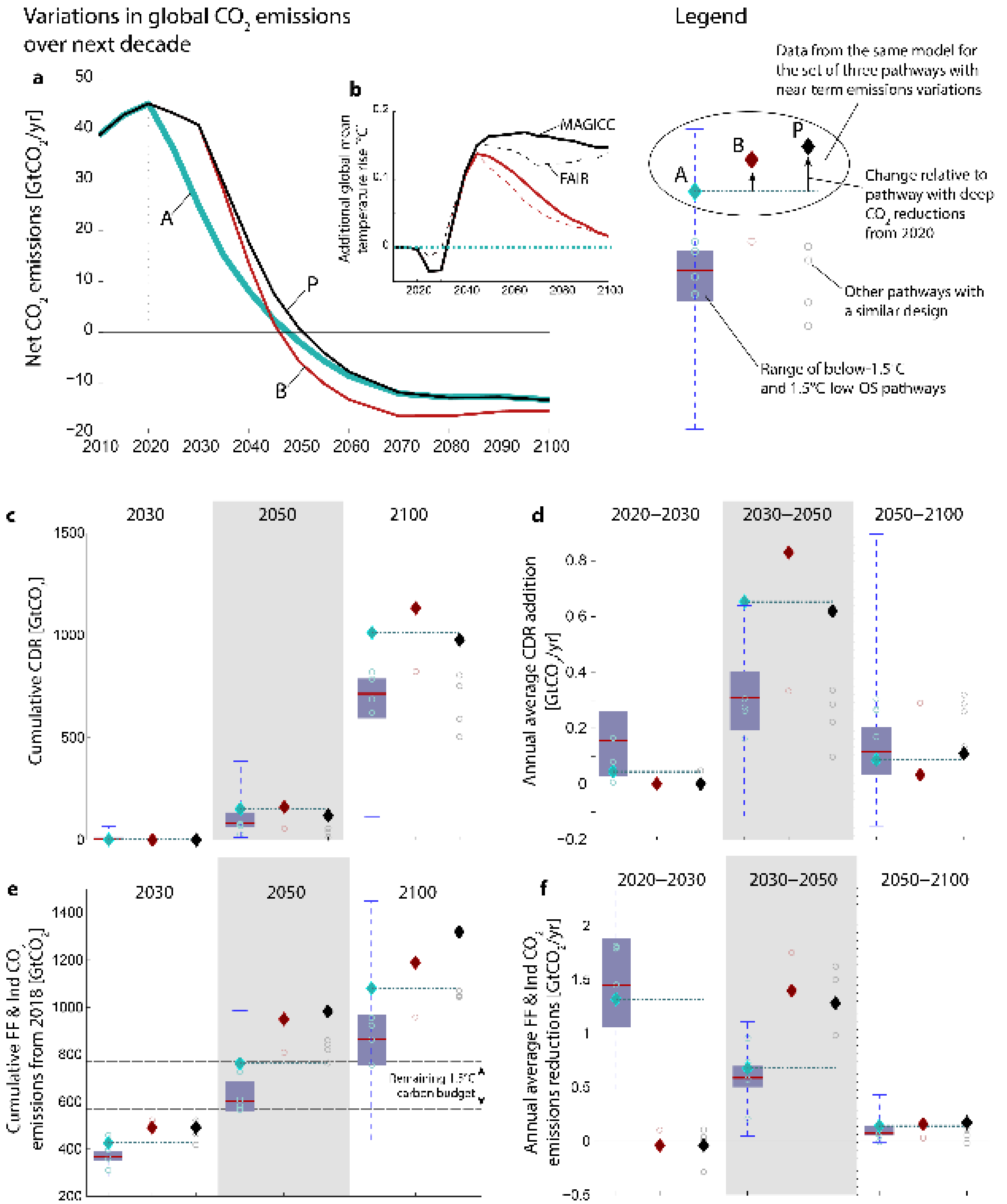

Figure 2.13: Comparison of pathways starting action for limiting warming to 1.5°C as of 2020 (A; light-blue diamonds) with pathways following the NDCs until 2030 and aiming to limit warming to 1.5°C thereafter. 1.5°C pathways following the NDCs either aim for the same cumulative CO_2 emissions by 2100 (B; red diamonds) or assume the same mitigation stringency as reflected by the price of emissions in associated least-cost 1.5°C-consistent pathways starting from 2020 (P; black diamonds)**.** Panels show the underlying emissions pathways (a), additional warming in the delay scenarios compared to 2020 action case (b), cumulated CDR (c), CDR ramp-up rates (d), cumulated gross CO_2 emissions from fossil-fuel combustion and industrial (FFI) processes over the 2018–2100 period (e), and gross FFI CO_2 emissions reductions rates (f). Scenario pairs / triplets (circles and diamonds) with 2020 and 2030 action variants were calculated by six (out of seven) models in the ADVANCE study symbols (Luderer et al., 2018) and five of them (passing near-term plausibility checks) are shown by symbols. Only two of five models could identify pathways with post-2030 action leading to a 2016–2100 carbon budget of ca. 200 $GtCO_2$ (red). The range of all 1.5°C-consistent pathways with no and low overshoot is shown by the boxplots.

2.4 Disentangling the whole-system transformation

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

Table 2.5: Overview of key characteristics of 1.5°C pathways.

1.5°C pathway characteristic	**Supporting information**	**Reference**
Rapid and profound near-term decarbonisation of energy supply	Strong upscaling of renewables and sustainable biomass and reduction of unabated (no CCS) fossil fuels, along with the rapid deployment of CCS lead to a zero-emission energy supply system by mid-century.	Section 2.4.1 Section 2.4.2
Greater mitigation efforts on the demand side	All end-use sectors show marked demand reductions beyond the reductions projected for 2°C pathways. Demand reductions from IAMs for 2030 and 2050 lie within the potential assessed by detailed sectorial bottom-up assessments.	Section 2.4.3
Switching from fossil fuels to electricity in end-use sectors	Both in the transport and the residential sector, electricity covers marked larger shares of total demand by mid-century.	Section 2.4.3.2 Section 2.4.3.3
Comprehensive emission reductions are implemented in the coming decade	Virtually all 1.5°C-consistent pathways decline net annual CO_2 emissions between 2020 and 2030, reaching carbon neutrality around mid-century. Below-1.5°C and 1.5°C-low-OS show maximum net CO2 emissions in 2030 of 18 and 28 $GtCO_2$ yr^{-1}, respectively. GHG emissions in these scenarios are not higher than 34 $GtCO_2e$ yr^{-1} in 2030.	Section 2.3.4
Additional reductions, on top of reductions from both CO2 and non-CO2 required for 2°C, are mainly from CO2	Both CO_2 and the non-CO_2 GHGs and aerosols are strongly reduced by 2030 and until 2050 in 1.5°C pathways. The greatest difference to 2°C pathways, however, lies in additional reductions of CO_2, as the non-CO_2 mitigation potential that is currently included in integrated pathways is mostly already fully deployed for reaching a 2°C pathway.	Section 2.3.1.2
Considerable shifts in investment patterns	Low-carbon investments in the energy supply side (energy production and refineries) are projected to average 1.6-3.8 trillion 2010USD yr^{-1} globally to 2050. Investments in fossil fuels decline, with investments in unabated coal halted by 2030 in most available 1.5°C-consistent projections, while the literature is less conclusive for investments in unabated gas and oil. Energy demand investments are a critical factor for which total estimates are uncertain.	Section 2.5.2
Options are available to align 1.5°C pathways with sustainable development	Synergies can be maximized, and risks of trade-offs limited or avoided through an informed choice of mitigation strategies. Particularly pathways that focus on a lowering of demand show many synergies and few trade-offs.	Section 2.5.3
CDR at scale before mid-century	By 2050, 1.5°C pathways project deployment of BECCS at a scale of 3–7 $GtCO_2yr^{-1}$ (range of medians across 1.5°C pathway classes), depending on the level of energy demand reductions and mitigation in other sectors. Some 1.5°C pathways are available that do not use BECCS, but only focus terrestrial CDR in the AFOLU sector.	Section 2.3.3, 2.3.4.1

2.4.1 Energy System Transformation

The energy system links energy supply (Section 2.4.2) with energy demand (Section 2.4.3) through final energy carriers including electricity and liquid, solid or gaseous fuels that are tailored to their end-uses. To chart energy-system transformations in mitigation pathways, four macro-level decarbonisation indicators associated with final energy are useful: limits to the increase of final energy demand, reductions in the carbon intensity of electricity, increases in the share of final energy provided by electricity, and reductions in the carbon intensity of final energy other than electricity (referred to in this section as the carbon intensity of the residual fuel mix). Figure 2.14 shows changes of these four indicators for the pathways in the scenario database (Section 2.1.3 and 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 decarbonisation of liquids, gases and solids provided to industry, residential and commercial activities, and the transport sector.

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

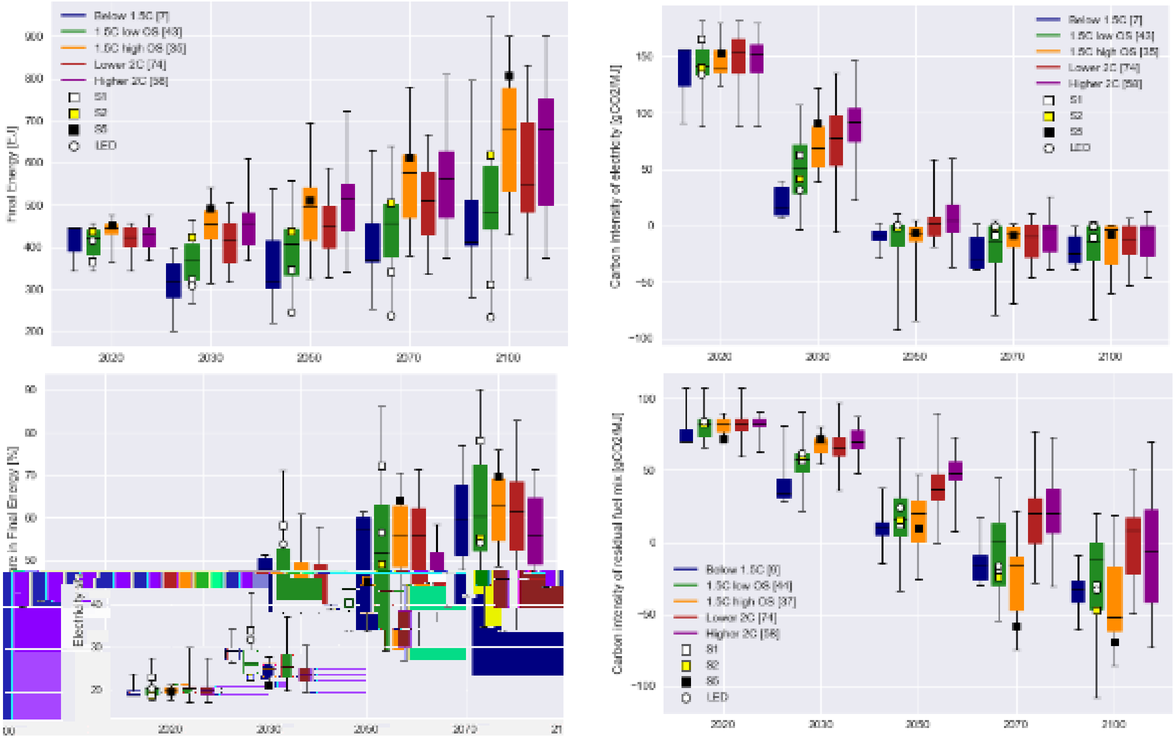

Figure 2.14: Decomposition of transformation pathways into energy demand (top left), carbon intensity of electricity (top right), the electricity share in final energy (bottom left), and the carbon intensity of the residual (non-electricity) fuel mix (bottom right). Boxplots show median, interquartile range and full range of pathways. Pathway temperature classes (Table 2.1) and illustrative pathway archetypes are indicated in the legend. Values following the class labels give the number of available pathways in each class.

2.4.2 Energy supply

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

2.4.2.1 Evolution of primary energy contributions over time

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

Renewable energy (including biomass, hydro, solar, wind, and geothermal) increases across all 1.5°C pathways with the renewable energy share of primary energy reaching 28–88% in 2050 (Table 2.6) with an interquartile range of 49–67%. The magnitude and split between bioenergy, wind, solar, and hydro differ between pathways, as can be seen in the illustrative pathway archetypes in Figure 2.15. Bioenergy is a major supplier of primary energy, contributing to both electricity and other forms of final energy such as liquid fuels for transportation (Bauer et al., 2018). In 1.5°C pathways, there is a significant growth in bioenergy used in combination with CCS for pathways where it is included (Figure 2.15).

Nuclear power increases its share in most 1.5°C pathways by 2050, but in some pathways both the absolute capacity and share of power from nuclear generators declines (Table 2.15). There are large differences in nuclear power between models and across pathways (Kim et al., 2014; Rogelj et al., 2018). One of the reasons for this variation is that the future deployment of nuclear can be constrained by societal preferences assumed in narratives underlying the pathways (O'Neill et al., 2017; van Vuuren et al., 2017b). Some 1.5°C pathways no longer see a role for nuclear fission by the end of the century, while others project over 200 EJ yr^{-1} of nuclear power in 2100 (Figure 2.15).

The share of primary energy provided by total fossil fuels decreases from 2020 to 2050 in all 1.5°C pathways, however, trends for oil, gas and coal differ (Table 2.6). By 2050, the share of primary energy from coal decreases to 0–13% across 1.5°C pathways with an interquartile range of 1–7%. From 2020 to 2050 the primary energy supplied by oil changes by –93 to +6% (interquartile range –75 to –32%); natural gas changes by –88 to +99% (interquartile range –60 to –13%), with varying levels of CCS. Pathways with higher use of coal and gas tend to deploy CCS to control their carbon emissions (see Section 2.4.2.3). As the energy transition is accelerated by several decades in 1.5°C pathways compared to 2°C pathways, residual fossil-fuel use (i.e., fossil fuels not used for electricity generation) without CCS is generally lower in 2050 than in 2°C pathways, while combined hydro, solar, and wind power deployment is generally higher than in 2°C pathways (Figure 2.15).

In addition to the 1.5°C pathways included in the scenario database (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 not necessarily developed in the context of the 1.5°C target, they explore in greater detail some options for deep reductions in GHG emissions. For example, there are analyses of transition to up to 100% renewable energy by 2050 (Creutzig et al., 2017; Jacobson et al., 2017), which describe what is entailed for a renewable energy share largely from solar and wind (and electrification) that is above the range of 1.5°C pathways available in the database, although there have been challenges to the assumptions used in high renewable analyses (e.g., Clack et al., 2017). There are also analyses that result in a large role for nuclear energy in mitigation of GHGs (Hong et al., 2015; Berger et al., 2017a, 2017b; Xiao and Jiang, 2017). BECCS could also contribute a larger share, but faces challenges related to its land use and impact on food supply (Burns and Nicholson, 2017) (assessed in greater detail in Sections 2.3.4.2, 4.3.7 and 5.4). These analyses could, provided their assumptions prove plausible, expand the range of 1.5°C pathways.

In summary, the share of primary energy from renewables increases while that from coal decreases across 1.5°C pathways (*high confidence*). This statement is true for all 1.5°C pathways in the scenario database and associated literature (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.

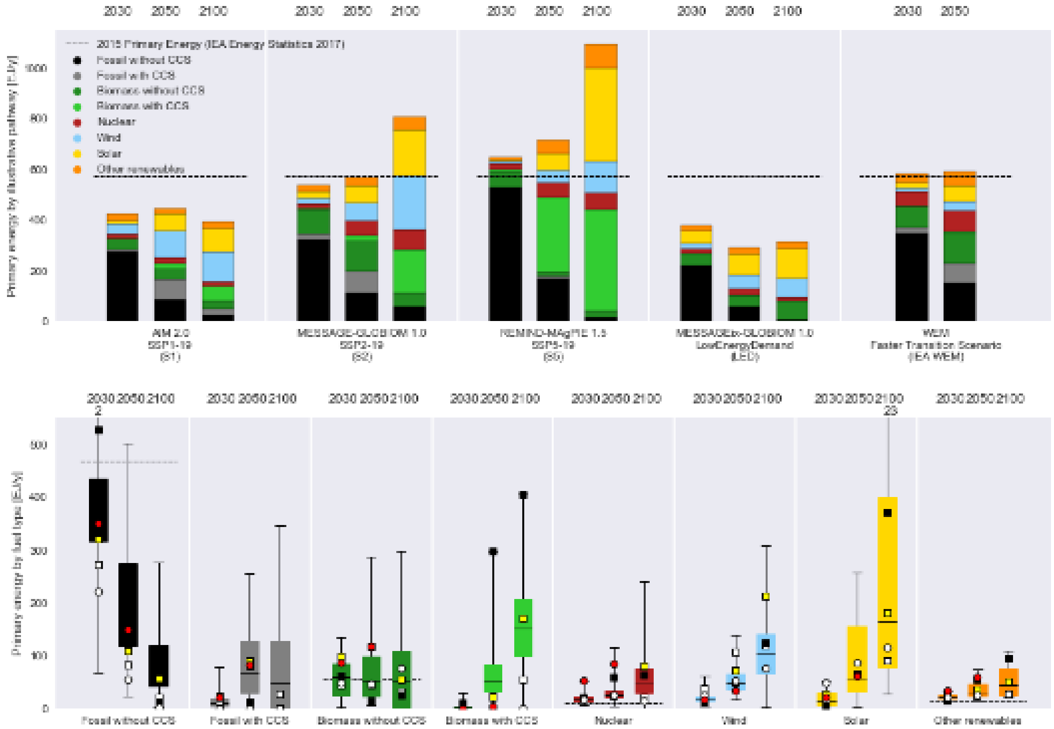

Figure 2.15: Primary energy supply for the four illustrative pathway archetypes plus the IEA's Faster Transition Scenario (OECD/IEA and IRENA, 2017) (top panel), and their relative location in the ranges for 1.5°C and 2°C pathway classes (lower panel). The category 'Other renewables' includes primary energy sources not covered by the other categories, for example, hydro and geothermal energy. The number of pathways that have higher primary energy than the scale in the bottom panel are indicated by the numbers above the whiskers. Black horizontal dashed lines indicates the level of primary energy supply in 2015 (IEA, 2017e). Boxplots in the lower panel show the minimum-maximum range (whiskers), interquartile range (box), and median (vertical thin black line). Symbols in the lower panel show the four pathway archetypes S1 (white square), S2 (yellow square), S5 (black square), LED (white disc), as well as the IEA's Faster Transition Scenario (red disc).

Table 2.6: Global primary energy supply of 1.5°C pathways from the scenario database (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].

	Primary energy supply [EJ]			**Share of primary energy [%]**		**Growth Factor**
	2020	**2030**	**2050**	**2020**	**2050**	**2020-2050**
total primary	582.12 (636.98, 483.22)	502.81 (749.05, 237.37)	580.78 (1012.50, 289.02)			0.03 (0.59, -0.51)
renewables	87.70 (101.60, 60.16)	139.48 (203.90, 87.75)	293.80 (584.78, 176.77)	15.03 (20.39, 10.60)	60.80 (87.89, 28.47)	2.62 (6.71, 0.91)
biomass	61.35 (73.03, 40.54)	75.28 (113.02, 44.42)	154.13 (311.72, 40.36)	10.27 (14.23, 7.14)	26.38 (54.10, 10.29)	1.71 (5.56, -0.42)
non-biomass	26.35 (36.58, 17.60)	61.60 (114.41, 25.79)	157.37 (409.94, 53.79)	4.40 (7.19, 2.84)	28.60 (61.61, 9.87)	4.63 (13.46, 1.38)
nuclear	10.93 (18.55, 8.52)	16.22 (41.73, 6.80)	24.48 (115.80, 3.09)	1.97 (3.37, 1.45)	4.22 (13.60, 0.43)	1.34 (7.22, -0.64)
fossil	493.44 (638.04, 376.30)	347.62 (605.68, 70.14)	199.63 (608.39, 43.87)	83.56 (114.75, 77.73)	33.58 (74.63, 7.70)	-0.58 (0.12, -0.91)
coal	147.09 (193.55, 83.23)	49.46 (176.99, 5.97)	23.84 (134.69, 0.36)	25.72 (30.82, 17.19)	4.99 (13.30, 0.05)	-0.85 (-0.30, -1.00)
gas	135.58 (169.50, 105.01)	127.99 (208.55, 17.30)	88.97 (265.66, 14.92)	23.28 (28.39, 18.09)	13.46 (34.83, 2.80)	-0.37 (0.99, -0.88)
oil	195.02 (245.15, 151.02)	175.69 (319.80, 38.94)	93.48 (208.04, 15.07)	33.79 (42.24, 28.07)	16.22 (27.30, 2.89)	-0.54 (0.06, -0.93)

Table 2.7: Global electricity generation of 1.5°C pathways from the scenarios database (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].

	Electricty generation [EJ]			**Share of electricity generation [%]**		**Growth Factor**
	2020	**2030**	**2050**	**2020**	**2050**	**2020-2050**
total electricity	100.09 (113.98, 83.53)	120.01 (177.51, 81.28)	224.78 (363.10, 126.96)			1.31 (2.55, 0.28)
renewables	26.38 (41.80, 18.26)	59.50 (111.70, 30.06)	153.72 (324.26, 84.69)	27.95 (41.84, 17.38)	77.52 (96.65, 35.58)	5.08 (10.88, 2.37)
biomass	1.52 (7.00, 0.66)	3.55 (11.96, 0.79)	16.32 (40.32, 0.21)	1.55 (7.30, 0.63)	8.02 (30.28, 0.08)	6.53 (38.14, -0.93)
non-biomass	24.48 (35.72, 17.60)	55.68 (101.90, 25.79)	136.40 (323.91, 53.79)	25.00 (40.43, 16.75)	66.75 (96.46, 27.51)	4.75 (10.64, 1.38)
nuclear	10.84 (18.55, 8.52)	15.49 (41.73, 6.80)	22.64 (115.80, 3.09)	10.91 (18.34, 8.62)	8.87 (39.61, 1.02)	1.21 (7.22, -0.64)
fossil	61.35 (76.76, 39.48)	38.41 (87.54, 2.25)	14.10 (118.12, 0.00)	61.55 (71.03, 47.26)	8.05 (33.19, 0.00)	-0.76 (0.54, -1.00)
coal	32.37 (46.20, 14.40)	10.41 (43.12, 0.00)	1.29 (46.72, 0.00)	32.39 (40.88, 17.23)	0.59 (12.87, 0.00)	-0.96 (0.01, -1.00)
gas	24.70 (41.20, 13.44)	25.00 (51.99, 2.01)	11.92 (67.94, 0.00)	24.71 (39.20, 11.80)	6.78 (32.59, 0.00)	-0.52 (1.63, -1.00)
oil	1.82 (13.36, 1.12)	0.92 (7.56, 0.24)	0.08 (8.78, 0.00)	2.04 (11.73, 1.01)	0.04 (3.80, 0.00)	-0.97 (0.98, -1.00)

2.4.2.2 Evolution of electricity supply over time

Electricity supplies an increasing share of final energy, reaching 34 to 71% in 2050, across 1.5°C pathways (Figure 2.14), extending the historical increases in electricity share seen over the past decades (Bruckner et al., 2014). From 2020 to 2050, the quantity of electricity supplied in most 1.5°C pathways more than doubles (Table 2.7). By 2050, the carbon intensity of electricity has fallen rapidly to -92 to +11 gCO_2/MJ electricity across 1.5°C pathways from a value of around 140 gCO_2/MJ (range: 88–181 gCO_2/MJ) in 2020 (Figure 2.14). A negative contribution to carbon intensity is provided by BECCS in most pathways (Figure 2.16).

By 2050, the share of electricity supplied by renewables increases from 23% in 2015 (IEA, 2017b) to 36–97% across 1.5°C pathways. Wind, solar, and biomass together make a major contribution in 2050, although the share for each spans a wide range across 1.5°C pathways (Figure 2.16). Fossil fuels on the other hand have a decreasing role in electricity supply with their share falling to 0–33% by 2050 (Table 2.7).

In summary, 1.5°C pathways include a rapid decline in the carbon intensity of electricity and an increase in electrification of energy end use (*high confidence*). This is the case across all 1.5°C pathways and their associated literature (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).

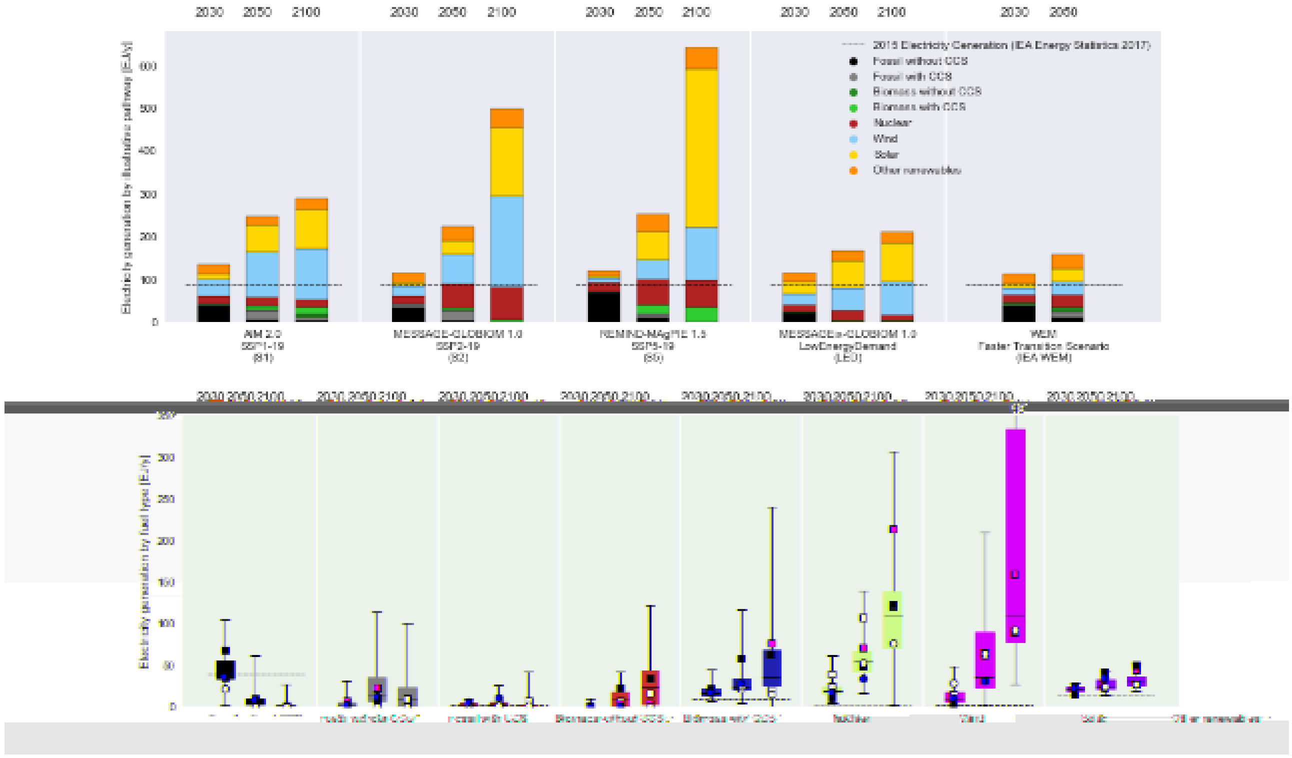

Figure 2.16: Electricity generation for the four illustrative pathway archetypes plus the IEA's Faster Transition Scenario (OECD/IEA and IRENA, 2017) (top panel), and their relative location in the ranges for 1.5°C and 2°C scenario classes (lower panel). The category 'Other renewables' includes electricity generation not covered by the other categories, for example, hydro and geothermal. The number of pathways that have higher primary energy than the scale in the bottom panel are indicated by the numbers above the whiskers. Black horizontal dashed lines indicate the level of primary energy supply in 2015 (IEA, 2017e). Boxplots in the lower panel show the minimum-maximum range (whiskers), interquartile range (box), and median (vertical thin black line). Symbols in the lower panel show the four pathway archetypes S1 (white square), S2 (yellow square), S5 (black square), LED (white disc), as well as the IEA's Faster Transition Scenario (red disc).

2.4.2.3 Deployment of Carbon Capture and Storage

Studies have shown the importance of CCS for deep mitigation pathways (Krey et al., 2014a; Kriegler et al., 2014b), based on its multiple roles to limit fossil-fuel emissions in electricity generation, liquids production, and industry applications along with the projected ability to remove CO_2 from the atmosphere when combined with bioenergy. This remains a valid finding for those 1.5°C and 2°C pathways that do not radically reduce energy demand nor offer carbon-neutral alternatives to liquids and gases that do not rely on bioenergy.

There is a wide range of CCS that is deployed across 1.5°C pathways (Figure 2.17). A few 1.5°C pathways with very low energy demand do not include CCS at all (Grubler et al., 2018). For example, the LED pathway has no CCS, whereas other pathways like the S5 pathway rely on a large amount of BECCS to get to net-zero carbon emissions. The cumulative fossil and biomass CO_2 stored through 2050 ranges from zero to 460 $GtCO_2$ across 1.5°C pathways, with zero up to 190 $GtCO_2$ from biomass captured and stored. Some pathways have very low fossil-fuel use overall, and consequently little CCS applied to fossil fuels. In 1.5°C pathways where the 2050 coal use remains above 20 EJ yr^{-1} in 2050, 33–100% is combined with CCS. While deployment of CCS for natural gas and coal vary widely across pathways, there is greater natural gas primary energy connected to CCS than coal primary energy connected to CCS in many pathways (Figure 2.17).

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

The quantity of CO_2 stored via CCS over this century in 1.5°C pathways ranges from zero to 1,900 $GtCO_2$, (Figure 2.17). The IPCC Special Report on on Carbon Dioxide Capture and Storage (IPCC, 2005) found that that, worldwide, it is *likely* that there is a technical potential of at least about 2,000 $GtCO_2$ of storage capacity in geological formations. Furthermore the IPCC (2005) recognised that there could be a much larger potential for geological storage in saline formations, but the upper limit estimates are uncertain due to lack of information and an agreed methodology. Since IPCC (2005), understanding has improved and there have been detailed regional surveys of storage capacity (Vangkilde-Pedersen et al., 2009; Ogawa et al., 2011; Wei et al., 2013; Bentham et al., 2014; Riis and Halland, 2014; Warwick et al., 2014; NETL, 2015) and improvement and standardisation of methodologies (e.g., Bachu et al. 2007a, b). Dooley (2013) synthesised published literature on both the global geological storage resource as well as the potential demand for geologic storage in mitigation pathways, and found that the cumulative demand for CO_2 storage was small compared to a practical storage capacity estimate (as defined by Bachu et al., 2007a) of 3,900 $GtCO_2$ worldwide. Differences, however, remain in estimates of storage capacity due to, e.g. the potential storage limitations of subsurface pressure build-up (Szulczewski et al., 2014) and assumptions on practices that could manage such issues (Bachu, 2015). Kearns et al. (2017) constructed estimates of global storage capacity of 8,000 to 55,000 $GtCO_2$ (accounting for differences in detailed regional and local estimates), which is sufficient at a global level for this century, but found that at a regional level, robust demand for CO_2 storage exceeds their lower estimate of regional storage available for some regions. However, storage capacity is not solely determined by the geological setting, and Bachu (2015) describes storage engineering practices that could further extend storage capacity estimates. In summary, the storage capacity of all of these global estimates is larger than the cumulative CO_2 stored via CCS of 1.5°C pathways over this century.

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

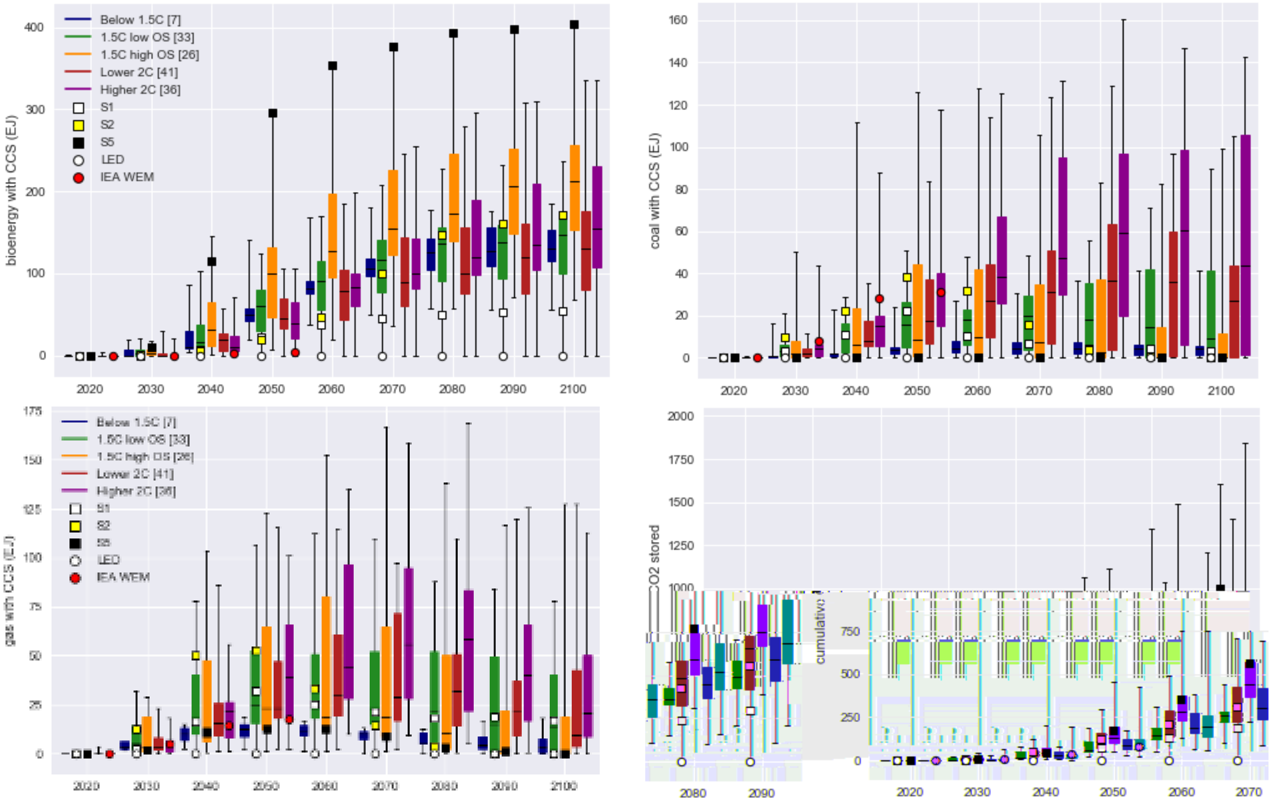

Figure 2.17: CCS deployment in 1.5°C and 2°C pathways for biomass, coal and natural gas (EJ of primary energy) and the cumulative quantity of fossil (including from, e.g., cement production) and biomass CO_2 stored via CCS (lower right in $GtCO_2$ stored). Boxplots show median, interquartile range and full range of pathways in each temperature class. Pathway temperature classes (Table 2.1), illustrative pathway archetypes, and the IEA's Faster Transition Scenario (IEA WEM) (OECD/IEA and IRENA, 2017) are indicated in the legend.

2.4.3 Energy end-use sectors

Since the power sector is almost decarbonized by mid-century in both 1.5°C and 2°C pathways, major differences come from CO_2 emission reductions in end-use sectors. Energy-demand reductions are key and common features in 1.5˚C-consistent pathways, which can be achieved by efficiency improvements and various specific demand-reduction measures. Another important feature is end-use decarbonisation including by electrification, although the potential and challenges in each end-use sector vary significantly.

In the following sections, the potential and challenges of CO_2 emission reductions towards 1.5°C and 2°C-consistent pathways are discussed for each end-use energy sector (industry, buildings, and transport sectors). For this purpose, two types of pathways are analysed and compared: IAM (integrated assessment modelling) studies and sectoral (detailed) studies. IAM data are extracted from the database that was compiled for this assessment (see 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 featured of the 1.5°C-low-OS and 1.5°C-high-OS pathways (hereafter denoted together as 1.5°C overshoot pathways or IAM-1.5DS-OS) and 2°C-consistent pathways (IAM-2DS). In order to show the diversity of IAM pathways, we again show specific data from the four illustrative pathways archetypes used throughout this chapter (see Sections 2.1 and 2.3).

IEA ETP-B2DS ('Beyond 2 Degrees') and ETP-2DS are pathways with a 50% chance of limiting temperature rise below 1.75°C and 2°C by 2100, respectively (IEA, 2017a). The IEA-66%2DS pathway keeps global-mean temperature rise below 2°C not just in 2100 but also over the course of the 21st century with a 66% chance of being below 2°C by 2100 (OECD/IEA and IRENA, 2017). The comparison of CO_2 emission trajectories between ETP-B2DS and IAM-1.5DS-OS show that these are consistent up to 2060 (Figure 2.18). IEA scenarios assume that only a very low level of BECCS is deployed to help offset emissions in difficult-to-decarbonize sectors, and that global energy-related CO_2 emissions cannot turn net-negative at any time and stay zero from 2060 to 2100 (IEA, 2017a). Therefore, although its temperature rise in 2100 is below 1.75°C rather than below 1.5°C, this scenario can give information related to 1.5°C-consistent overshoot pathway up to 2050. The trajectory of IEA-66%2DS (also referred to in other publications as IEA's 'Faster Transition Scenario') lies between IAM-1.5DS-OS and IAM-2DS pathway ranges, and IEA-2DS stays in the range of 2°C-consistent IAM pathways. The Shell-Sky scenario aims to hold the temperature rise to well-below 2°C, but it is a delayed action pathway relative to others, as can be seen in Figure 2.18.

Energy-demand reduction measures are key to reduce CO_2 emissions from end-use sectors for low-carbon pathways. The up-stream energy reductions can be several times to an order of magnitude larger than the initial end-use demand reduction. There are interdependencies among the end-use sectors and also between energy-supply and end-use sectors, which raise the importance of a wide, systematic approach. As shown in Figure 2.19, global final-energy consumption grows by 30% and 10% from 2010 to 2050 for 2°C-consistent and 1.5°C overshoot pathways from IAMs, respectively, while much higher growth of 75% is projected for reference scenarios. The ranges within a specific pathway class are due to a variety of factors as introduced in Section 2.3.1, as well as differences between modelling frameworks. The important energy efficiency improvements and energy conservation that facilitate many of the 1.5°C pathways raise the issue of potential rebound effects (Saunders, 2015), which, while promoting development, can make the achievement of low-energy demand futures more difficult than modelling studies anticipate (see Sections 2.5 and 2.6).

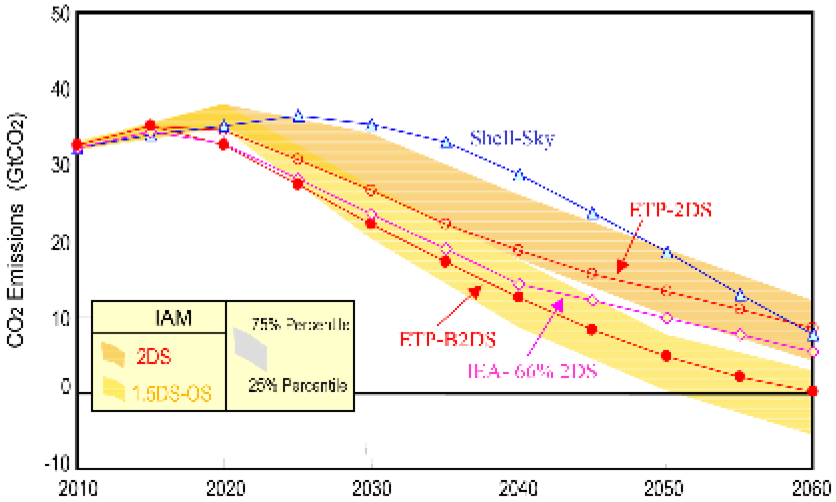

Figure 2.18: Comparison of CO_2 emission trajectories of sectoral pathways (IEA ETP-B2DS, ETP-2DS, IEA-66%2DS, Shell-Sky) with the ranges of IAM pathway (2DS are 2°C-consistent pathways and 1.5DS-OS are1.5°C-consistent overshoot pathways). The CO_2 emissions shown here are the energy-related emissions including industrial process emissions.

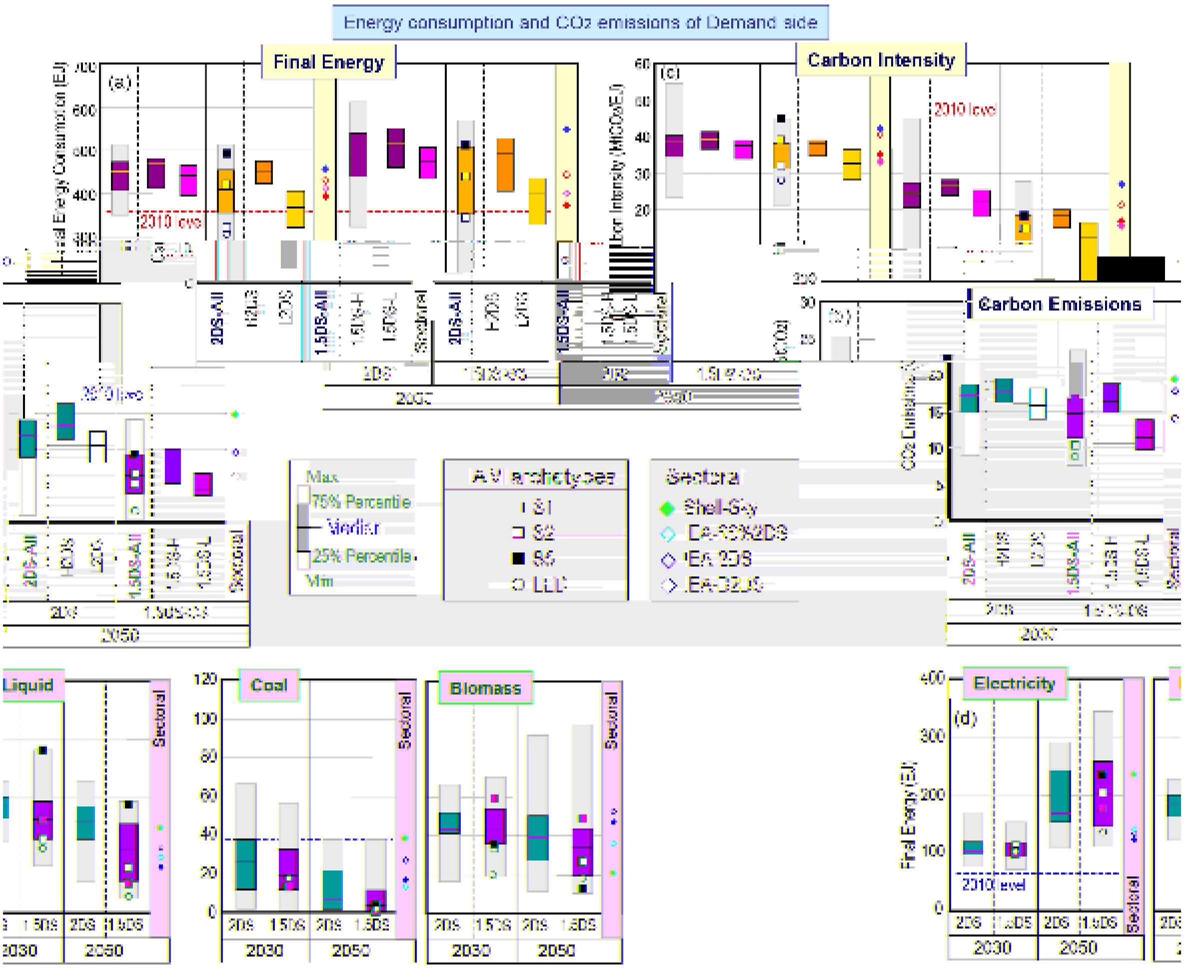

Figure 2.19: (a) Global final energy, (b) direct CO$_2$ emissions from the all energy demand sectors, (c) carbon intensity, and (d) structure of final energy (electricity, liquid fuel, coal, and biomass). The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS: Higher-2°C, L2DS: Lower-2°C, 1.5DS-H: 1.5°C-high-OS, 1.5DS-L: 1.5°C-low-OS, 1.5DS = 1.5DS-OS: 1.5°C-consistent pathways with overshoot. Section 2.1 for descriptions.

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

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

The CO$_2$ emissions[6] of end-use sectors and carbon intensity are shown in Figure 2.20. The projections of IAMs and IEA studies show rather different trends, especially in the carbon intensity. These differences come from various factors, including the deployment of CCS, the level of fuel switching and efficiency

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[6]: This section reports "direct" CO$_2$ emissions as reported for pathways in the database for the report. As shown below, the emissions from electricity are nearly zero around 2050, so the impact of indirect emissions on the whole emission contributions of each sector is very small in 2050.

improvements, and the effect of structural and behavioural changes. IAM projections are generally optimistic for the industry sectors, but not for buildings and transport sectors. Although GDP increases by a factor of 3.4 from 2010 to 2050, the total energy consumption of end-use sectors grows by only about 30% and 20% in 1.5°C overshoot and 2°C-consistent pathways, respectively. However, CO_2 emissions would need to be reduced further to achieve the stringent temperature limits. Fig. 2.20 shows that the reduction in CO_2 emissions of end-use sectors is larger and more rapid in 1.5°C overshoot than 2°C-consistent pathways, while emissions from the power sector are already almost zero in 2050 in both sets of pathways indicating that supply-side emissions reductions are almost fully exploited already in 2°C-consistent pathways (see Figure 2.20) (Rogelj et al., 2015b, 2018; Luderer et al., 2016b). The emission reductions in end-use sectors is largely made possible due to efficiency improvements, demand reduction measures and electrification, but its level differs among end-use sectors. While the carbon intensity of industry and the buildings sector decreases to a very low level of around 10 gCO_2 MJ^{-1}, the carbon intensity of transport becomes the highest of any sector by 2040 due to its higher reliance on oil-based fuels. In the following subsections, the potential and challenges of CO_2 emission reduction in each end-use sector are discussed in detail.

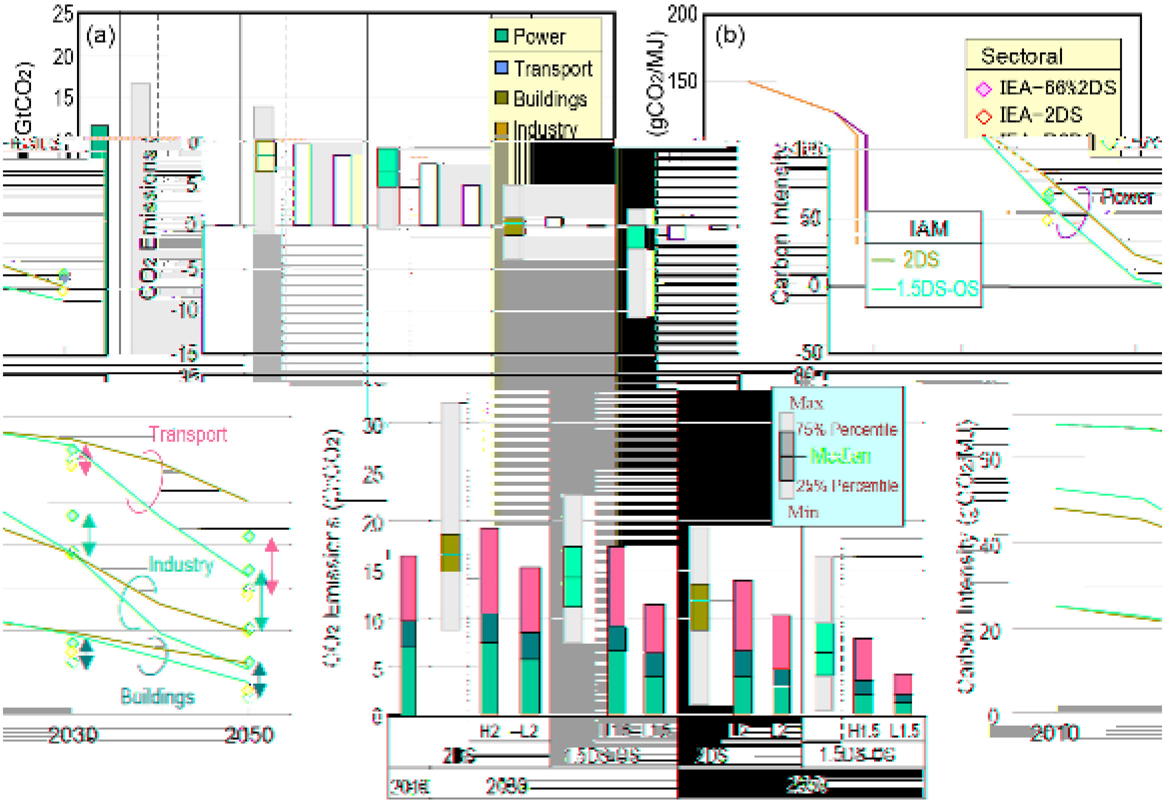

Figure 2.20: Comparison of (a) direct CO_2 emissions and (b) carbon intensity of the power and energy end-use sectors (industry, buildings, and transport sectors) between IAMs and sectoral studies (IEA-ETP and IEA/IRENA). Diamond markers in panel (b) show data for IEA-ETP scenarios (2DS and B2DS), and IEA/IRENA scenario (66%2DS). Note: for the data of IAM studies, there is rather large variation of projections for each indicator. Please see the details in the following figures in each end-use sector section.

2.4.3.1 Industry

The industry sector is the largest end-use sector both in terms of final-energy demand and GHG emissions. Its direct CO_2 emissions currently account for about 25% of total energy-related and process CO_2 emissions, and have increased with an average annual rate of 3.4% between 2000 and 2014, significantly faster than total CO_2 emissions (Hoesly et al., 2018). In addition to emissions from the combustion of fossil fuels, non-energy uses of fossil fuels in the petro-chemical industry and metal smelting, as well as non-fossil fuel process emissions (e.g., from cement production) contribute a small amount (~5%) to the sector's CO_2 emissions inventory. Material industries are particularly energy and emissions intensive: steel, non-ferrous metals, chemicals, non-metallic minerals, and pulp and paper alone accounted for close to 66% of final-energy demand, and 72% of direct industry sector emissions in 2014 (IEA, 2017a). In terms of end-uses, the bulk of energy in manufacturing industries is required for process heating and steam generation, while most electricity (but smaller shares of total final energy) is used for mechanical work (Banerjee et al., 2012; IEA, 2017a).

As shown in Figure 2.21, a major share of the additional emission reductions required for 1.5°C-overshoot pathways beyond those in 2°C-consistent pathways comes from industry. Final energy, CO_2 emissions, and carbon intensity are consistent in IAM and sectoral studies, but in IAM-1.5°C-overshoot pathways the share of electricity is higher than IEA-B2DS (40% vs. 25%) and hydrogen is also considered to have a share of about 5% vs. 0%. In 2050, final energy is increased by 30% and 5% compared with the 2010 level (red dotted line) for 1.5°C-overshoot and 2°C-consistent pathways, respectively, but CO_2 emissions are decreased by 80% and 50% and carbon intensity by 80% and 60%, respectively. This additional decarbonisation is brought by switching to low carbon fuels and CCS deployment.

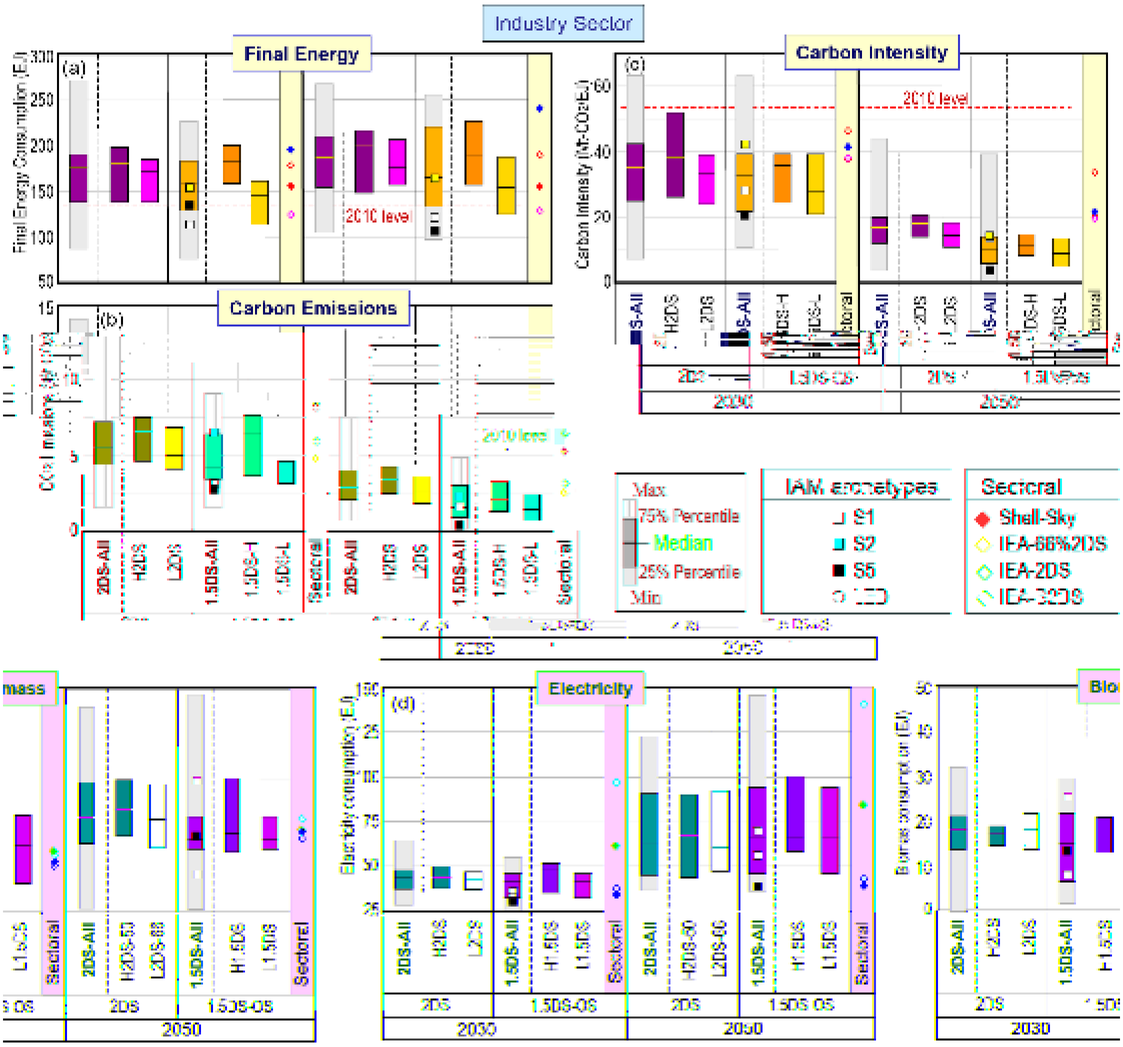

Figure 2.21: Comparison of (a) final energy, (b) direct CO_2 emissions, (c) carbon intensity, (d) electricity and biomass consumption in the industry sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS: Higher-2°C, L2DS: Lower-2°C, 1.5DS-H: 1.5°C-high-OS, 1.5DS-L: 1.5°C-low-OS, 1.5DS = 1.5DS-OS: 1.5°C-consistent pathways with overshoot. Section 2.1 for descriptions.

Broadly speaking, the industry sector's mitigation measures can be categorized in terms of the following five strategies: (i) reductions in the demand, (ii) energy efficiency, (iii) increased electrification of energy demand, (iv) reducing the carbon content of non-electric fuels, and (v) deploying innovative processes and application of CCS. IEA ETP estimates the relative contribution of different measures for CO_2 emission reduction in their B2DS scenario compared with their reference scenario in 2050 as follows: energy efficiency 42%, innovative process and CCS 37%, switching to low carbon fuels and feed-stocks 13% and material efficiency (include efficient production and use to contribute to demand reduction) 8%. The remainder of this section delves more deeply into the potential mitigation contributions of these strategies as well as their limitations.

Reduction in the use of industrial materials, while delivering similar services, or improving the quality of products could help to reduce energy demand and overall system-level CO_2 emissions. Strategies include using materials more intensively, extension of product lifetimes, increasing recycling, and increasing inter-industry material synergies, such as clinker substitution in cement production (Allwood et al., 2013; IEA, 2017a). Related to material efficiency, use of fossil-fuel feed-stocks could shift to lower-carbon feed-stocks such as oil to natural gas and biomass and end-uses could shift to more sustainable materials such as biomass-based materials, reducing the demand for energy-intensive materials (IEA, 2017a).

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

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

CO_2 emissions from industry increase by 30% in 2050 compared to 2010 in baseline scenarios. By contrast, these emissions are reduced by 80% and 50% relative to 2010 levels in 1.5°C-overshoot and 2°C-consistent pathways from IAMs, respectively (Figure 2.21). By mid-century, CO_2 emissions per unit electricity are projected to decrease to near zero in both sets of pathways (see Figure 2.20). An accelerated electrification of the industry sector thus becomes an increasingly powerful mitigation option. In the IAM pathways, the share of electricity increases up to 30% by 2050 in 1.5°C-overshoot pathways (Figure 2.21) from 20% in 2010. Some industrial fuel uses are substantially more difficult to electrify than others, and electrification would have other effects on the process, including impacts on plant design, cost and available process integration options (IEA, 2017a)[7].

In 1.5°C-overshoot pathways, the carbon intensity of non-electric fuels consumed by industry decreases to 16 $gCO_2\ MJ^{-1}$ by 2050, compared to 25 $gCO_2\ MJ^{-1}$ in 2°C-consistent pathways. Considerable carbon intensity reductions are already achieved by 2030, largely via a rapid phase-out of coal. Biomass becomes an increasingly important energy carrier in the industry sector in deep-decarbonisation pathways, but primarily in the longer term (in 2050, biomass accounts for only 10% of final energy consumption even in 1.5°C-overshoot pathways). In addition, hydrogen plays a considerable role as a substitute for fossil-based non-electric energy demands in some pathways.

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

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

CCS plays a major role in decarbonizing the industry sector in the context of 1.5°C and 2°C pathways, especially in industries with higher process emissions, such as cement, iron and steel industries. In 1.5°C-overshoot pathways, CCS in industry reaches 3 $GtCO_2$ yr^{-1} by 2050, albeit with strong variations across pathways. Given project long-lead times and the need for technological innovation, early scale-up of industry CCS is essential to achieve the stringent temperature target. Development and demonstration of such projects has been slow, however. Currently, only two large-scale industrial CCS projects outside of oil and gas processing are in operation (Global CCS Institute, 2016). The estimated current cost[8] of CO_2 avoided (in 2015-US$) ranges from $20-27 tCO_2^{-1} for gas processing and bio-ethanol production, and $60-138 tCO_2^{-1} for fossil fuel-fired power generation up to $104-188 tCO_2^{-1} for cement production (Irlam, 2017).

2.4.3.2 Buildings

In 2014, the buildings sector accounted for 31% of total global final-energy use, 54% of final-electricity demand, and 8% of energy-related CO_2 emissions (excluding indirect emission due to electricity). When upstream electricity generation is taken into account, buildings were responsible for 23% of global energy-related CO_2 emissions, with one-third of those from direct fossil fuel consumption (IEA, 2017a).

Past growth of energy consumption has been mainly driven by population and economic growth, with improved access to electricity, and higher use of electrical appliances and space cooling resulting from increasing living standards, especially in developing countries (Lucon et al., 2014). These trends will continue in the future and in 2050, energy consumption is projected to increase by 20% (50%) compared to 2010 in IAM-1.5°C-overshoot (2°C-consistent) pathways (Figure 2.22). However, sectoral studies (IEA-ETP scenarios) show different trends. Energy consumption in 2050 decreases compared to 2010 in ETP-B2DS, and the reduction rate of CO_2 emissions is higher than in IAM pathways (Figure 2.22). Mitigation options are often more widely covered in sectoral studies (Lucon et al., 2014), leading to greater reductions in energy consumption and CO_2 emissions.

Emissions reductions are driven by a clear tempering of energy demand and a strong electrification of the buildings sector. The share of electricity in 2050 is 60% in 1.5°C-overshoot pathways, compared with 50% in 2°C-consistent pathways (Figure 2.22). Electrification contributes to the reduction of direct CO_2 emissions by replacing carbon-intensive fuels, like oil and coal. Furthermore, when combined with a rapid decarbonisation of the power system (see Section 2.4.1) it also enables further reduction of indirect CO_2 emissions from electricity. Sectoral bottom-up models in general estimate lower electrification potentials for the buildings sector in comparison to global IAMs (see Figure 2.22). Besides CO_2 emissions, increasing global demand for air conditioning in buildings may also lead to increased emissions of HFCs in this sector over the next few decades. Although these gases are currently a relatively small proportion of annual GHG emissions, their use in the air conditioning sector is expected to grow rapidly over the next few decades if alternatives are not adopted. However, their projected future impact can be significantly mitigated through better servicing and maintenance of equipment and switching of cooling gases (Shah et al., 2015; Purohit and Höglund-Isaksson, 2017).

IEA-ETP (IEA, 2017a) analysed the relative importance of various technology measures toward the reduction of energy and CO_2 emissions in the buildings sector. The largest energy savings potential is in heating and cooling demand largely due to building envelope improvements and high efficiency and renewable equipment. In the ETP-B2DS, energy demand for space heating and cooling is 33% lower in 2050 than the reference scenario and these reductions account for 54% of total reductions from the reference scenario. Energy savings from shifts to high-performance lighting, appliances, and water heating equipment account for a further 24% of the total reduction. The long-term, strategic shift away from fossil-fuel use in buildings, alongside the rapid uptake of energy efficient, integrated and renewable energy technologies (with clean power generation), leads to a drastic reduction of CO_2 emissions. In ETP-B2DS, the direct CO_2 emissions are 79% lower than the reference scenario in 2050 and the remaining emissions come mainly from the continued use of natural gas.

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

The buildings sector is characterized by very long-living infrastructure and immediate steps are hence important to avoid lock-in of inefficient carbon and energy-intensive buildings. This applies both to new buildings in developing countries where substantial new construction is expected in the near future and to retrofits of existing building stock in developed regions. This represents both a significant risk and opportunity for mitigation[9]. A recent study highlights the benefits of deploying the most advanced renovation technologies, which would avoid lock-in into less efficient measures (Güneralp et al., 2017). Aside from the effect of building envelope measures, adoption of energy-efficient technologies such as heat pumps and more recently light-emitting diodes is also important for the reduction of energy and CO_2 emissions (IEA, 2017a). Consumer choices, behaviour and building operation can also significantly affect energy consumption (see Section 4.3).

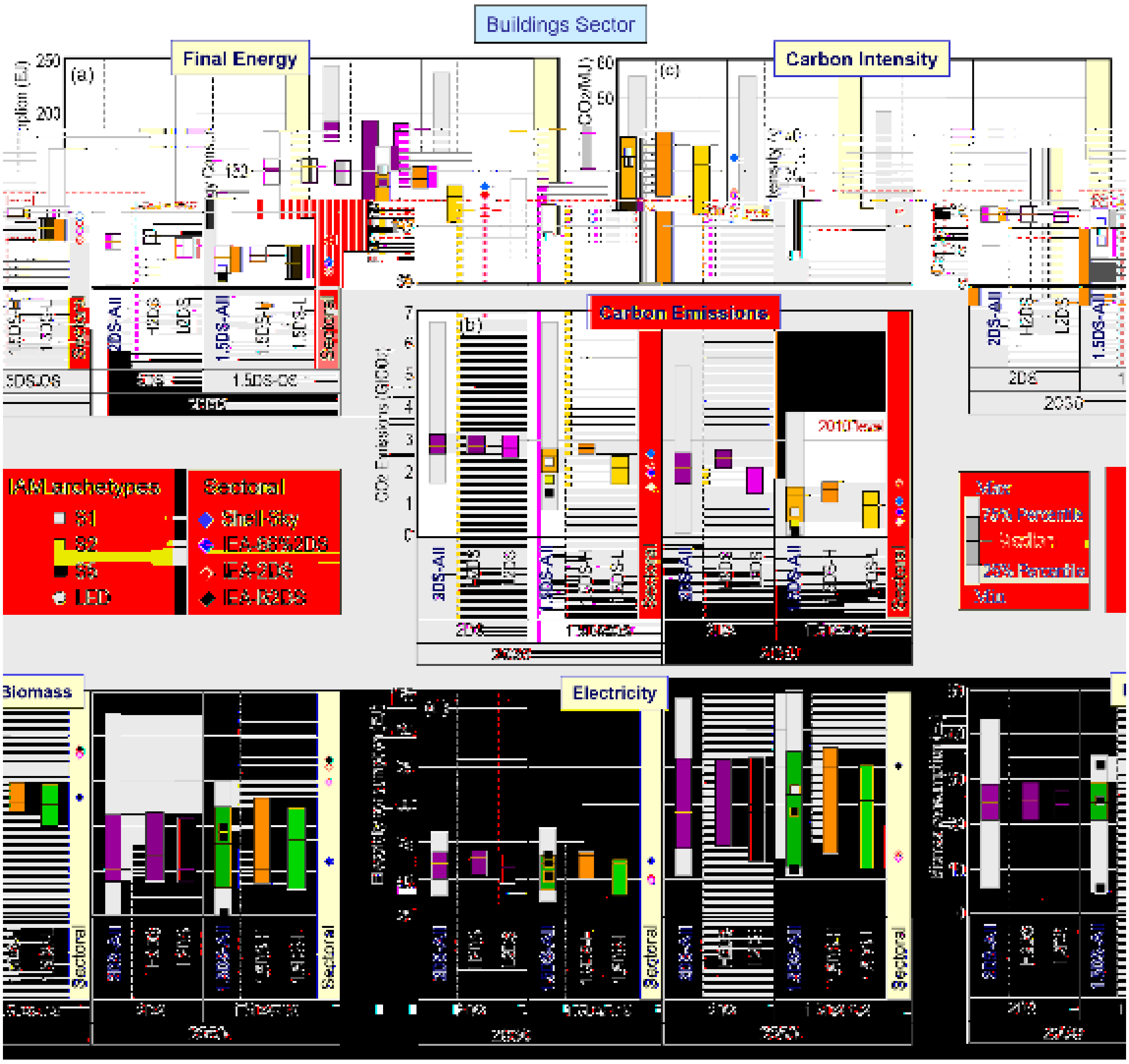

Figure 2.22: Comparison of (a) final energy, (b) direct CO_2 emissions, (c) carbon intensity, (d) electricity and biomass consumption in the buildings sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS: Higher-2°C, L2DS: Lower-2°C, 1.5DS-H: 1.5°C-high-OS, 1.5DS-L: 1.5°C-low-OS, 1.5DS = 1.5DS-OS: 1.5°C-consistent pathways with overshoot. Section 2.1 for descriptions.

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

2.4.3.3 Transport

Transport accounted for 28% of global final-energy demand and 23% of global energy-related CO_2 emissions in 2014. Emissions increased by 2.5% annually between 2010 and 2015, and over the past half century the sector has witnessed faster emissions growth than any other. The transport sector is the least diversified energy end-use sector; the sector consumed 65% of global oil final-energy demand, with 92% of transport final-energy demand consisting of oil products (IEA, 2017a), suggesting major challenges for deep decarbonisation.

Final energy, CO_2 emissions, and carbon intensity for the transport sector are shown in Figure 2.23. The projections of IAMs are more pessimistic than IEA-ETP scenarios, though both clearly project deep cuts in energy consumption and CO_2 emissions by 2050. For example, 1.5°C-overshoot pathways from IAMs project a reduction of 15% in energy consumption between 2015 and 2050, while ETP-B2DS projects a reduction of 30% (Figure 2.23). Furthermore, IAM pathways are generally more pessimistic in the projections of CO_2 emissions and carbon intensity reductions. In AR5 (Clarke et al., 2014; Sims et al., 2014), similar comparisons between IAMs and sectoral studies were performed and these were in good agreement with each other. Since the AR5, two important changes can be identified; rapid growth of electric vehicle sales in passenger cars, and more attention towards structural changes in this sector. The former contributes to reduction of CO_2 emissions and the latter reduction of energy consumption.

Deep emissions reductions in the transport sector would be achieved by several means. Technology focused measures such as energy efficiency and fuel-switching are two of these. Structural changes that avoid or shift transport activity are also important. While the former solutions (technologies) always tend to figure into deep decarbonisation pathways in a major way, this is not always the case with the latter, especially in IAM pathways. Comparing different types of global transport models, Yeh et al. (2016) find that sectoral (intensive) studies generally envision greater mitigation potential from structural changes in transport activity and modal choice. Though, even there, it is primarily the switching of passengers and freight from less- to more-efficient travel modes (e.g., cars, trucks and airplanes to buses and trains) that is the main strategy; other actions, such as increasing vehicle load factors (occupancy rates) and outright reductions in travel demand (e.g., as a result of integrated transport, land-use and urban planning), figure much less prominently. Whether these dynamics accurately reflect the actual mitigation potential of structural changes in transport activity and modal choice is a point of investigation. According to the recent IEA-ETP scenarios, the share of avoid (reduction of mobility demand) and shift (shifting to more efficient modes) measures in the reduction of CO_2 emissions from the reference to B2DS scenarios in 2050 amounts to 20% (IEA, 2017a).

The potential and strategies to reduce energy consumption and CO_2 emissions differ significantly among transport modes. In ETP-B2DS, the shares of energy consumption and CO_2 emissions in 2050 for each mode are rather different (see Table 2.8), indicating the challenge of decarbonizing heavy-duty vehicles (HDV, trucks), aviation, and shipping. The reduction of CO_2 emissions in the whole sector from the reference scenario to ETP-B2DS is 60% in 2050, with varying contributions per mode (Table 2.8). Since there is no silver bullet for this deep decarbonisation, every possible measure would be required to achieve this stringent emissions outcome. The contribution of various measures for the CO_2 emission reduction from the reference scenario to the IEA-B2DS in 2050 can be decomposed to efficiency improvement (29%), biofuels (36%), electrification (15%), and avoid/shift (20%) (IEA, 2017a). It is noted that the share of electrification becomes larger compared with older studies, reflected by the recent growth of electric vehicle sales worldwide. Another new trend is the allocation of biofuels to each mode of transport. In IEA-B2DS, the total amount of biofuels consumed in the transport sector is 24EJ[10] in 2060, and allocated to LDV (light-duty vehicles, 17%), HDV (35%), aviation (28%), and shipping (21%), that is, more biofuels is allocated to the difficult-to-decarbonize modes (see Table 2.8).

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

Table 2.8: Transport sector indicators by mode in 2050 (IEA, 2017a). Share of Energy consumption, biofuel consumption, CO_2 emissions, and reduction of energy consumption and CO_2 emissions from 2014. (CO_2 emissions are Well-to-Wheel emissions, including the emission during the fuel production.), LDV: Light Duty Vehicle, HDV: Heavy Duty Vehicle

	Share of each mode (%)			**Reduction from 2014 (%)**	
	Energy	**Biofuel**	**CO_2**	**Energy**	**CO_2**
LDV	36	17	30	51	81
HDV	33	35	36	8	56
Rail	6		-1	-136	107
Aviation	12	28	14	14	56
Shipping	17	21	21	26	29

In road transport, incremental vehicle improvements (including engines) are relevant, especially in the short to medium term. Hybrid electric vehicles (HEVs) are also instrumental to enabling the transition from ICEs (internal combustion engine vehicles) to electric vehicles, especially plug-in hybrid electric vehicles (PHEVs). Electrification is a powerful measure to decarbonize short-distance vehicles (passenger cars and two and three wheelers) and the rail sector. In road freight transport (trucks), systemic improvements (e.g., in supply chains, logistics, and routing) would be effective measures with efficiency improvement of vehicles. Shipping and aviation are more challenging to decarbonize, while their demand growth is projected to be higher than other transport modes. Both modes would need to pursue highly ambitious efficiency improvements and use of low-carbon fuels. In the near and medium term, this would be advanced biofuels while in the long term it could be hydrogen as direct use for shipping or an intermediate product for synthetic fuels for both modes (IEA, 2017a).

The share of low-carbon fuels in the total transport fuel mix increases to 10% (16%) by 2030 and to 40% (58%) by 2050 in 1.5°C-overshoot pathways from IAMs. The IEA-B2DS scenario is on the more ambitious side, especially in the share of electricity. Hence, there is wide variation among scenarios, including the IAM pathways, regarding changes in the transport fuel mix over the first half of the century. As seen in Figure 2.23, the projections of energy consumption, CO_2 emissions, and carbon intensity are quite different between IAM and ETP scenarios. These differences can be explained by more weight on efficiency improvements and avoid/shift decreasing energy consumption, and the higher share of biofuels and electricity accelerating the speed of decarbonisation in ETP scenarios. Although biofuel consumption and electric vehicle sales have increased significantly in recent years, the growth rates projected in these pathways would be unprecedented and far higher than has been experienced to date.

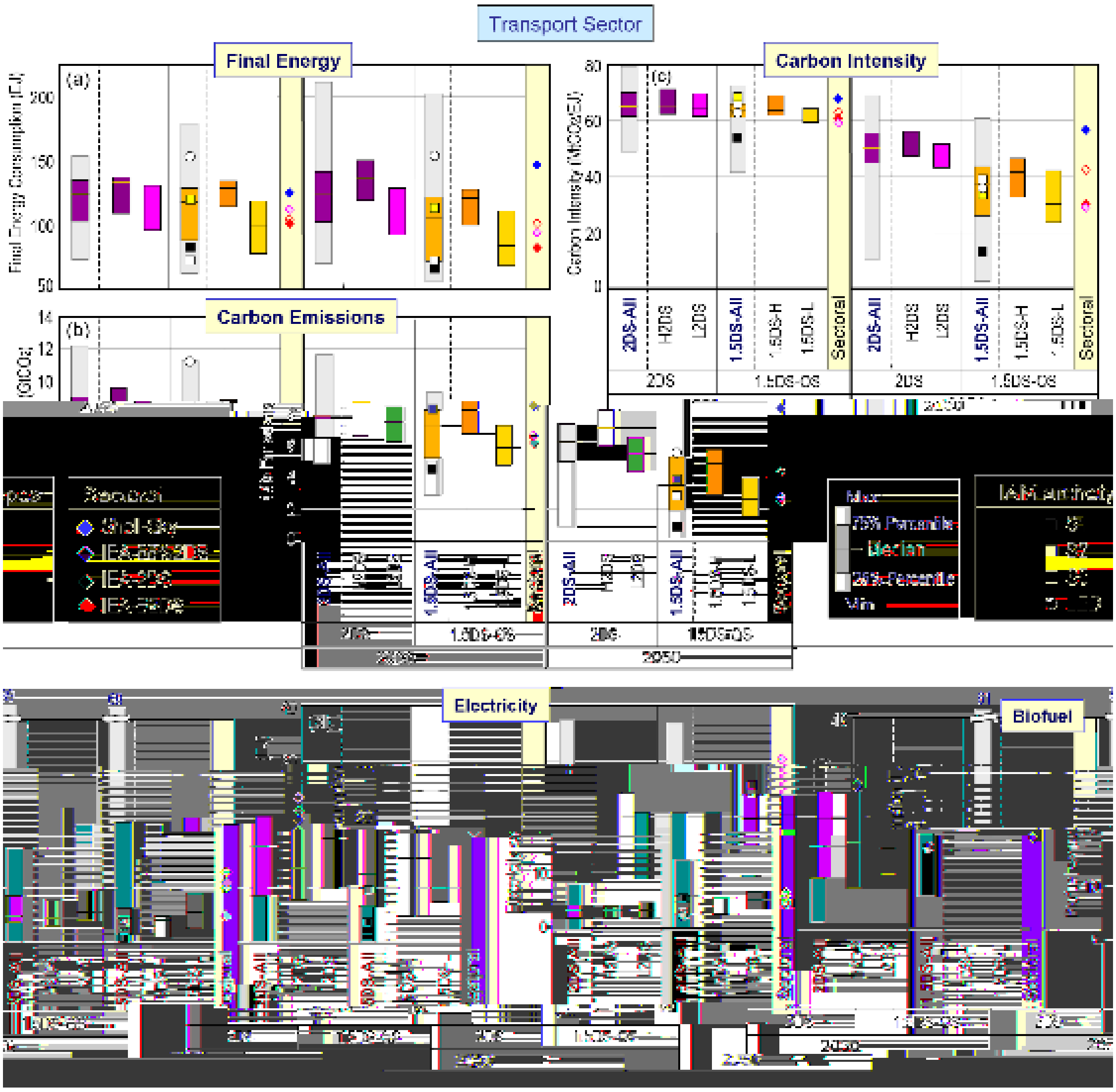

Figure 2.23: Comparison of (a) final energy, (b) direct CO₂ emissions, (c) carbon intensity, (d) electricity and biofuel consumption in the transport sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red 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, 1.5DS = 1.5DS-OS: 1.5°C-consistent pathways with overshoot. Section 2.1 for descriptions.

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

2.4.4 Land-use transitions and changes in the agricultural sector

The agricultural and land system described together under the umbrella of the AFOLU (Agriculture, Forestry, and Other Land Use) sector plays an important role in 1.5°C pathways (Clarke et al., 2014; Smith and Bustamante, 2014; Popp et al., 2017). On the one hand, its emissions need to be limited over the course of this century to be in line with pathways limiting warming to 1.5°C (see Sections 2.2-3). On the other hand, the AFOLU system is responsible for food and feed production, for wood production for pulp and construction, for the production of biomass that is used for energy, CDR or other uses, and for the supply of non-provisioning (ecosystem) services (Smith and Bustamante, 2014). Meeting all demands together requires changes in land use, as well as in agricultural and forestry practices, for which a multitude of potential options have been identified (Smith and Bustamante, 2014; Popp et al., 2017) (see also 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 1.1), including for the AFOLU sector (Popp et al., 2017; Riahi et al., 2017). The SSP pathway ensemble hence allows for a structured exploration of AFOLU transitions in the context of climate change mitigation in line with 1.5°C, taking into account technological and socio-economic aspects. Other considerations, like food security, livelihoods and biodiversity, are also of importance when identifying AFOLU strategies. These are at present only tangentially explored by the SSPs. Further assessments of AFOLU mitigation options are provided in other parts of this report and in the IPCC AR6 Special Report on Climate Change and Land (SRCCL). Chapter 4 provides an assessment of bioenergy (including feedstocks, see Section 4.3.1), livestock management (Section 4.3.1), reducing rates of deforestation and other land-based mitigation options (as mitigation and adaptation option, see Section 4.3.2), and BECCS, Afforestation and Reforestation options (including the bottom-up literature of their sustainable potential, mitigation cost and side effects, Section 4.3.7). Chapter 3 discusses impacts land-based CDR (Cross-Chapter Box 7 in Chapter 3). Chapter 5 assesses the sustainable development implications of AFOLU mitigation, including impacts on biodiversity (Section 5.4). Finally, the SRCCL will undertake a more comprehensive assessment of land and climate change aspects. For the sake of complementarity, this section focusses on the magnitude and pace of land transitions in 1.5°C pathways, as well as on the implications of different AFOLU mitigation strategies for different land types. The interactions with other societal objectives and potential limitations of identified AFOLU measures link to these large-scale evolutions, but these are assessed elsewhere (see above).

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

As a consequence of other land use changes, pasture land is generally projected to be reduced compared to both baselines in which no climate change mitigation action is undertaken and 2°C-consistent pathways. Furthermore, cropland for food and feed production decreases in most 1.5°C pathways, both compared to a no-climate baseline and relative to 2010. These reductions in agricultural land for food and feed production are facilitated by intensification on agricultural land and in livestock production systems (Popp et al., 2017), as well as changes in consumption patterns (Frank et al., 2017; Fujimori, 2017) (see also 4.3.2 for an assessment of these mitigation options). For example, in a scenario based on rapid technological progress (Kriegler et al., 2017), global average cereal crop yields in 2100 are assumed to be above 5 tDM/ha.yr in mitigation scenarios aiming at limiting end-of-century radiative forcing to 4.5 or 2.6 W/m^2, compared to 4 tDM/ha.yr in the SSP5 baseline to ensure the same food production. Similar improvements are present in 1.5°C variants of such scenarios. Historically, cereal crop yields are estimated at 1 tDM/ha.yr and ca. 3 tDM/ha.yr in 1965 and 2010, respectively (calculations based on FAOSTAT, 2017). For aggregate energy crops, models assume 4.2-8.9 tDM/ha.yr in 2010, increasing to about 6.9-17.4 tDM/ha.yr in 2050, which fall within the range found in the bottom-up literature yet depend on crop, climatic zone, land quality, and plot size (Searle and Malins, 2014).

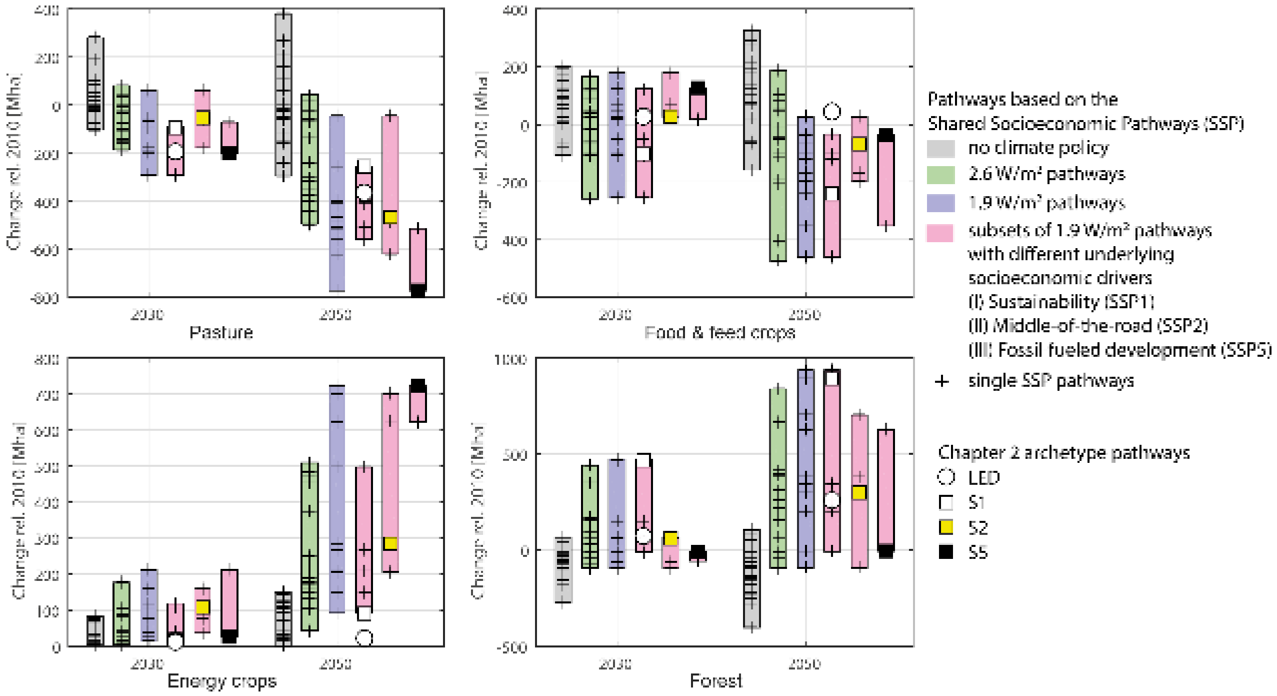

Figure 2.24: Overview of land-use change transitions in 2030 and 2050, relative to 2010 based on pathways based on the Shared Socioeconomic Pathways (SSP) (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Grey: no-climate-policy baseline; green: 2.6 W/m^2 pathways; blue: 1.9 W/m^2 pathways. Pink: 1.9 W/m^2 pathways grouped per underlying socioeconomic assumption (from left to right: SSP1 sustainability, SSP2 middle-of-the-road, SSP5 fossil-fuelled development). Ranges show the minimum-maximum range across the SSPs. Single pathways are shown with plus signs. Illustrative archetype pathways are highlighted with distinct icons. Each panel shows the changes for a different land type. 1.9 and 2.6 W/m^2 are taken as proxies for 1.5°C and 2°C pathways, respectively. 2.6 W/m^2 pathways are mostly consistent with the Lower-2°C and Higher-2°C pathway classes. 1.9 W/m^2 pathways are consistent with the 1.5°C-low-OS (mostly SSP1 and SSP2) and 1.5°C-high-OS (SSP5) pathway classes. In 2010, pasture was estimated to cover about 3-3.5 10^3 Mha, food and feed crops about 1.5-1.6 10^3 Mha, energy crops about 0-14 Mha and forest about 3.7-4.2 10^3 Mha, across the models that reported SSP pathways (Popp et al., 2017).

The pace of projected land transitions over the coming decades can differ strongly between 1.5°C and baseline scenarios without climate change mitigation and from historical trends (Table 2.9). However, there is uncertainty in the sign and magnitude of these future land-use changes (Prestele et al., 2016; Popp et al., 2017; Doelman et al., 2018). The pace of projected cropland changes overlaps with historical trends over the past four decades, but in several cases also goes well beyond this range. By the 2030-2050 period, the projected reductions in pasture and potentially strong increases in forest cover imply a reversed dynamic compared to historical and baseline trends. For forest increases, this suggests that distinct policy and government measures would be needed to achieve this, particularly in a context of projected increased bioenergy use.

Table 2.9: Annual pace of land-use change in baseline, 2°C and 1.5°C pathways. All values in Mha/yr. 2.6 W/m^2 pathways are mostly consistent with the Lower-2°C and Higher-2°C pathway classes. 1.9 W/m^2 pathways are broadly consistent with the 1.5°C-low-OS (mostly SSP1 and SSP2) and 1.5°C-high-OS (SSP5) pathway classes. Baseline projections reflect land-use developments projected by integrated assessment models under the assumptions of the Shared Socioeconomic Pathways (SSP) in absence of climate policies (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Values give the full range across SSP scenarios. According to the Food and Agriculture Organization of the United Nations (FAOSTAT, 2017), 4.9 billion hectares (approximately 40% of the land surface) was under agricultural use in 2005, either as cropland (1.5 billion hectares) or pasture (3.4 billion hectares). FAO data in the table are equally from FAOSTAT (2017).

Annual pace of land-use change [Mha yr^{-1}] **Land type**	**Pathway**	**Time window**		**Historical**	
		2010-2030	**2030-2050**	**1970-1990**	**1990-2010**
Pasture	1.9 W m^{-2}	[-14.6/3.0]	[-28.7/-5.2]	8.7 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]		

Changes of the AFOLU sector are driven by three main factors: demand changes, efficiency of production, and policy assumptions (Smith et al., 2013; Popp et al., 2017). Demand for agricultural products and other land-based commodities is influenced by consumption patterns (including dietary preferences and food waste affecting demand for food and feed) (Smith et al., 2013; van Vuuren et al., 2018), demand for forest products for pulp and construction (including less wood waste), and demand for biomass for energy production (Lambin and Meyfroidt, 2011; Smith and Bustamante, 2014). Efficiency of agricultural and forestry production relates to improvements in agricultural and forestry practices (including product cascades, by-products as well as more waste- and residue-based biomass for energy production), agricultural and forestry yield increases as well as intensification of livestock production systems leading to higher feed efficiency and changes in feed composition (Havlík et al., 2014; Weindl et al., 2015). Policy assumptions relate to the level of land protection, the treatment of food waste, policy choices about the timing of mitigation action (early vs late), the choice and preference of land-based mitigation options (for example, the inclusion of afforestation and reforestation as mitigation options), interactions with other sectors (Popp et al., 2017) and trade (Schmitz et al., 2012; Wiebe et al., 2015).

A global study (Stevanović et al., 2017) reported similar GHG reduction potentials for production (agricultural production measures in combination with reduced deforestation) and consumption side (diet change in combination with lower shares of food waste) measures of in the order of 40% in 2100[11] (compared to a baseline scenario without land-based mitigation). Lower consumption of livestock products by 2050 could also substantially reduce deforestation and cumulative carbon losses (Weindl et al., 2017). On

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[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.

the supply side, minor productivity growth in extensive livestock production systems is projected to lead to substantial CO_2 emission abatement, but the emission saving potential of productivity gains in intensive systems is limited, mainly due to trade-offs with soil carbon stocks (Weindl et al., 2017). In addition, even within existing livestock production systems, a transition from extensive to more productive systems bears substantial GHG abatement potential, while improving food availability (Gerber et al., 2013; Havlík et al., 2014). Many studies highlight the capability of agricultural intensification for reducing GHG emissions in the AFOLU sector or even enhancing terrestrial carbon stocks (Valin et al., 2013; Popp et al., 2014a; Wise et al., 2014). Also the importance of immediate and global land-use regulations for a comprehensive reduction of land-related GHG emissions (especially related to deforestation) has been shown by several studies (Calvin et al., 2017; Fricko et al., 2017; Fujimori, 2017). Ultimately, there are also interactions between these three factors and the wider society and economy, for example, if CDR technologies that are not land based are deployed (like direct air capture – DACCS, see Chapter 4, Section 4.3.7) or if other sectors over- or underachieve their projected mitigation contributions (Clarke et al., 2014). Variations in these drivers can lead to drastically different land-use implications (Popp et al., 2014b) (Figure 2.24).

Stringent mitigation pathways inform general GHG dynamics in the AFOLU sector. First, CO_2 emissions from deforestation can be abated at relatively low carbon prices if displacement effects in other regions (Calvin et al., 2017) or other land-use types with high carbon density (Calvin et al., 2014; Popp et al., 2014a; Kriegler et al., 2017) can be avoided. However, efficiency and costs of reducing rates of deforestation strongly depend on governance performance, institutions and macroeconomic factors (Wang et al., 2016). Secondly, besides CO_2 reductions, the land system can play an important role for overall CDR efforts (Rogelj et al., 2018) via BECCS, afforestation and reforestation, or a combination of options. The AFOLU sector also provides further potential for active terrestrial carbon sequestration, e.g., via land restoration, improved management of forest and agricultural land (Griscom et al., 2017), or biochar applications (Smith, 2016) (see also Section 4.3.7). These options have so far not been extensively integrated in the mitigation pathway literature (see 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-CO_2 emissions of CH_4 and N_2O play an important role for temperature stabilisation pathways and their relative importance increases in stringent mitigation pathways in which CO_2 is reduced to net zero emissions globally (Gernaat et al., 2015; Popp et al., 2017; Stevanović et al., 2017; Rogelj et al., 2018), for example, through their impact on the remaining carbon budget (Section 2.2). Although agricultural non-CO_2 emissions show marked reduction potentials in 2°C-consistent pathways, complete elimination of these emission sources does not occur in IAMs based on the evolution of agricultural practice assumed in integrated models (Figure 2.25) (Gernaat et al., 2015). CH_4 emissions in 1.5°C pathways are reduced through improved agricultural management (e.g., improved management of water in rice production, manure and herds, and better livestock quality through breeding and improved feeding practices) as well as dietary shifts away from emissions-intensive livestock products. Similarly, N_2O emissions decrease due to improved N-efficiency and manure management (Frank et al., 2018). However, high levels of bioenergy production can also result in increased N_2O emissions (Kriegler et al., 2017) highlighting the importance of appropriate management approaches (Davis et al., 2013). Residual agricultural emissions can be further reduced by limiting demand for GHG-intensive foods through shifts to healthier and more sustainable diets (Tilman and Clark, 2014; Erb et al., 2016b; Springmann et al., 2016) and reductions in food waste (Bajželj et al., 2014; Muller et al., 2017; Popp et al., 2017) (see also Chapter 4, and SRCCL). Finally, several mitigation measures that could affect these agricultural non-CO_2 emissions are not, or only to a limited degree, considered in the current integrated pathway literature (see 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.

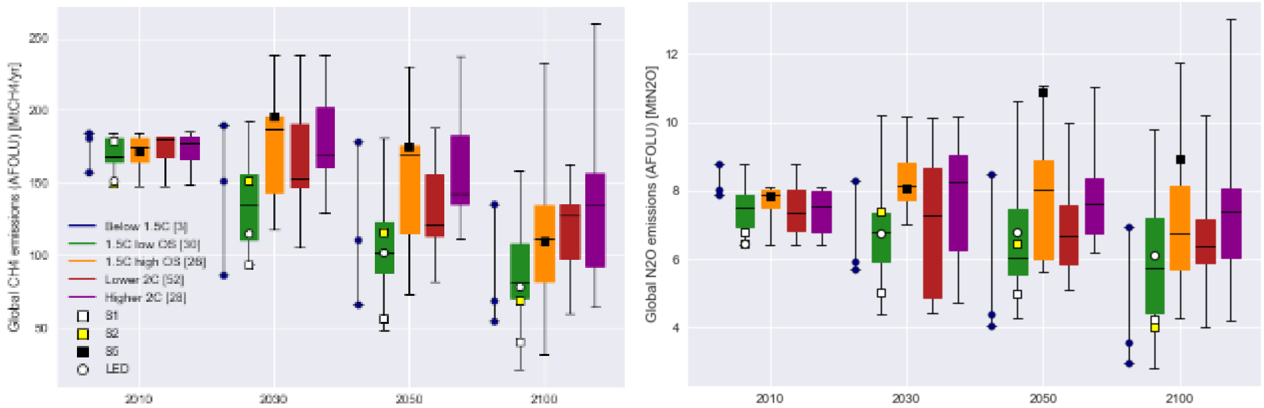

Figure 2.25: Agricultural emissions in transformation pathways. Global agricultural CH_4 (left) and N_2O (right) emissions. Boxplots show median, interquartile range and full range. Classes are defined in Section 2.1.

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

The choice of strategy or mitigation portfolio impacts the GHG dynamics of the land system and other sectors (see Section 2.3), as well as the synergies and trade-offs with other environmental and societal objectives (see Section 2.5.3 and Section 5.4). For example, AFOLU developments in 1.5°C pathways range from strategies that differ almost an order of magnitude in their projected land requirements for bioenergy (Figure 2.24), and some strategies would allow an increase in forest cover over the 21st century compared to strategies under which forest cover remains approximately constant. High agricultural yields and application of intensified animal husbandry, implementation of best-available technologies for reducing non-CO_2 emissions, or lifestyle changes including a less-meat-intensive diet and less CO_2-intensive transport modes, have been identified to allow for such a forest expansion and reduced footprints from bioenergy without compromising food security (Frank et al., 2017; Doelman et al., 2018; van Vuuren et al., 2018).

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

Despite the limitations of current modelling approaches, there is *high agreement* and *robust evidence* across models and studies that the AFOLU sector plays an important role in stringent mitigation pathways. The findings from these multiple lines of evidence also result in *high confidence* that AFOLU mitigation strategies can vary significantly based on preferences and policy choices, facilitating the exploration of strategies that can achieve multiple societal objectives simultaneously (see also Section 2.5.3). At the same time, given the many uncertainties and limitations, only *low to medium confidence* can be attributed by this assessment to the more extreme AFOLU developments found in the pathway literature, and *low to medium confidence* to the level of residual non-CO_2 emissions.

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

2.5 Challenges, opportunities and co-impacts of transformative mitigation pathways

This section examines aspects other than climate outcomes of 1.5°C mitigation pathways. Focus is given to challenges and opportunities related to policy regimes, price of carbon and co-impacts, including sustainable development issues, which can be derived from the existing integrated pathway literature. Attention is also given to uncertainties and critical assumptions underpinning mitigation pathways. The challenges and opportunities identified in this section are further elaborated Chapter 4 (e.g., policy choice and implementation) and Chapter 5 (e.g., sustainable development). The assessment indicates unprecedented policy and geopolitical challenges.

2.5.1 Policy frameworks and enabling conditions

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

The available literature indicates that mitigation pathways in line with 1.5°C-consistent pathways would require stringent and integrated policy interventions (*very high confidence*). Higher policy ambition often takes the form of stringent economy-wide emission targets (and resulting peak-and-decline of emissions), larger coverage of NDCs to more gases and sectors (e.g., land-use, international aviation), much lower energy and carbon intensity rates than historically seen, carbon prices much higher than the ones observed in real markets, increased climate finance, global coordinated policy action, and implementation of additional initiatives (e.g., by non-state actors) (Sections 2.3, 2.4 and 2.5.2). The diversity (beyond carbon pricing) and effectiveness of policy portfolios are of prime importance, particularly in the short-term (Mundaca and Markandya, 2016; Kuramochi et al., 2017; OECD, 2017; Kriegler et al., 2018b; Michaelowa et al., 2018). For instance, deep decarbonisation pathways in line with a 2˚C target (covering 74% of global energy-system emissions) include a mix of stringent regulation (e.g., building codes, minimum performance standards), carbon pricing mechanisms and R&D (research and development) innovation policies (Bataille et al., 2016a). Carbon pricing, direct regulation and public investment to enable innovation are critical for deep decarbonisation pathways (Grubb et al., 2014). Effective planning (including compact city measures) and integrated regulatory frameworks are also key drivers in the IEA-ETP B2DS study for the transport sector (IEA, 2017a). Effective urban planning can reduce GHG emissions from urban transport between 20% and 50% (Creutzig, 2016). Comprehensive policy frameworks would be needed if the decarbonisation of the power system is pursued while increasing end-use electrification (including transport) (IEA, 2017a). Technology policies (e.g., feed-in-tariffs), financing instruments, carbon pricing and system integration management driving the rapid adoption of renewable energy technologies are critical for the decarbonisation of electricity generation (Bruckner et al., 2014; Luderer et al., 2014; Creutzig et al., 2017; Pietzcker et al., 2017). Likewise, low-carbon and resilient investments are facilitated by a mix of coherent policies including fiscal and structural reforms (e.g., labour markets), public procurement, carbon pricing, stringent standards, information schemes, technology policies, fossil-fuel subsidy removal, climate risk disclosure, and land-use and transport planning (OECD, 2017). Pathways in which CDR options are restricted emphasise the strengthening of near-term policy mixes (Luderer et al., 2013; Kriegler et al., 2018b). Together with the decarbonisation of the supply side, ambitious policies targeting fuel switching and energy efficiency improvements on the demand side play a major role across mitigation pathways (Clarke et al., 2014; Kriegler et al., 2014b; Riahi et al., 2015; Kuramochi et al., 2017; Brown and Li, 2018; Rogelj et al., 2018; Wachsmuth and Duscha, 2018).

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

SSP-based modelling studies underline that socio-economic and climate policy assumptions strongly influence mitigation pathway characteristics and the economics of achieving a specific climate target (Bauer et al., 2017; Guivarch and Rogelj, 2017; Riahi et al., 2017; Rogelj et al., 2018) (*very high confidence*). SSP assumptions related to economic growth and energy intensity are critical determinants of projected CO_2 emissions (Marangoni et al., 2017). A multi-model inter-comparison study found that mitigation challenges in line with a 1.5˚C target vary substantially across SSPs and policy assumptions (Rogelj et al., 2018). Under SSP1-SPA1 (sustainability) and SSP2-SPA2 (middle-of-the-road), the majority of IAMs were capable of producing 1.5˚C pathways. On the contrary, none of the IAMs contained in the SR1.5 database could produce a 1.5°C pathway under SSP3-SPA3 assumptions. Preventing elements include, for instance, climate policy fragmentation, limited control of land-use emissions, heavy reliance on fossil fuels, unsustainable consumption and marked inequalities (Rogelj et al., 2018). Dietary aspects of the SSPs are also critical: climate-friendly diets were contained in 'sustainability' (SSP1) and meat-intensive diets in SSP3 and SSP5 (Popp et al., 2017). CDR requirements are reduced under 'sustainability' related assumptions (Strefler et al., 2018b). These are major policy-related factors for why SSP1-SPA1 translates into relatively low mitigation challenges whereas SSP3-SPA3 and SSP5-SPA5 entail futures that pose the highest socio-technical and economic challenges. SSPs/SPAs assumptions indicate that policy-driven pathways that encompass accelerated change away from fossil fuels, large-scale deployment of low-carbon energy supplies, improved energy efficiency and sustainable consumption lifestyles reduce the risks of climate targets becoming unreachable (Clarke et al., 2014; Riahi et al., 2015, 2017; Marangoni et al., 2017; Rogelj et al., 2017, 2018; Strefler et al., 2018b).

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

Whereas the policy frameworks and enabling conditions identified above pertain to the 'idealised' dimension of mitigation pathways, aspects related to 1.5°C mitigation pathways in practice are of prime importance. For example, issues related to second-best stringency levels, international cooperation, public acceptance, distributional consequences, multi-level governance, non-state actions, compliance levels, capacity building, rebound effects, linkages across highly heterogeneous policies, sustained behavioural change, finance and intra- and inter-generational issues need to be considered (Somanthan et al., 2014; Bataille et al., 2016a; Mundaca and Markandya, 2016; Baranzini et al., 2017; van den Bergh, 2017; Vogt-Schilb and Hallegatte, 2017; Chan et al., 2018; Holz et al., 2018a; Klinsky and Winkler, 2018; Michaelowa et al., 2018; Patterson et al., 2018) (see Section 4.4). Furthermore, policies interact with a wide portfolio of pre-existing policy instruments that address multiple areas (e.g., technology markets, economic growth, poverty alleviation, climate adaptation) and deal with various market failures (e.g., information asymmetries) and behavioural aspects (e.g., heuristics) that prevent or hinder mitigation actions (Kolstad et al., 2014; Mehling and Tvinnereim, 2018). The socio-technical transition literature points to multiple complexities in real-world settings that prevent reaching 'idealised' policy conditions but at the same time can still accelerate transformative change through other co-evolutionary processes of technology and society (Geels et al., 2017; Rockström et al., 2017). Such co-processes are complex and go beyond the role of policy (including carbon pricing) and comprise the role of citizens, businesses, stakeholder groups or governments, as well as the interplay of institutional and socio-political dimensions (Michaelowa et al., 2018; Veland et al., 2018). It is argued that large system transformations, similar to those in 1.5°C pathways, require prioritizing an evolutionary and behavioural framework in economic theory rather than an optimization or equilibrium framework as is common in current IAMs (Grubb et al., 2014; Patt, 2017). Accumulated know-how, accelerated innovation and public investment play a key role in (rapid) transitions (Geels et al., 2017; Michaelowa et al., 2018) (see Sections 4.2 and 4.4).

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

[START CROSS CHAPTER BOX 5 HERE]

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

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Two approaches have been commonly used to assess alternative emissions pathways: **cost-effectiveness analysis (CEA)** and **cost-benefit analysis (CBA)**. **CEA** aims at identifying emissions pathways minimising the total mitigation costs of achieving a given warming or GHG limit (Clarke et al., 2014). **CBA** has the goal to identify the optimal emissions trajectory minimising the discounted flows of abatement expenditures and monetised climate change damages (Boardman, 2006; Stern, 2007). A third concept, the **Social Cost of Carbon (SCC)** measures the total net damages of an extra metric ton of CO_2 emissions due to the associated climate change (Nordhaus, 2014; Pizer et al., 2014; Rose et al., 2017a). Negative and positive impacts are monetised, discounted and the net value is expressed as an equivalent loss of consumption today. The SCC can be evaluated for any emissions pathway under policy consideration (Rose, 2012; NASEM, 2016, 2017).

Along the optimal trajectory determined by CBA, the SCC equals the discounted value of the marginal abatement cost of a metric ton of CO_2 emissions. Equating the present value of future damages and marginal abatement costs includes a number of critical value judgments in the formulation of the social welfare function (SWF), particularly in how non-market damages and the distribution of damages across countries and individuals and between current and future generations are valued (Kolstad et al., 2014). For example, since climate damages accrue to a larger extent in the farther future and can persist for many years, assumptions and approaches to determine the social discount rate (normative 'prescriptive' vs. positive 'descriptive') and social welfare function (e.g., discounted utilitarian SWF vs. undiscounted prioritarian SWF) can heavily influence CBA outcomes and associated estimates of SCC (Kolstad et al., 2014; Pizer et al., 2014; Adler and Treich, 2015; Adler et al., 2017; NASEM, 2017; Nordhaus, 2017; Rose et al., 2017a).

In CEA, the marginal abatement cost of carbon is determined by the climate goal under consideration. It equals the shadow price of carbon associated with the goal which in turn can be interpreted as the willingness to pay for imposing the goal as a political constraint. Emissions prices are usually expressed in carbon (equivalent) prices using the GWP-100 metric as the exchange rate for pricing emissions of non-CO_2 GHGs controlled under internationally climate agreements (like CH_4, N_2O and fluorinated gases, see Cross-Chapter Box 1.2)[13]. Since policy goals like the goals of limiting warming to 1.5°C or well below 2°C do not directly result from a money metric trade-off between mitigation and damages, associated shadow prices can differ from the SCC in a CBA. In CEA, value judgments are to a large extent concentrated in the choice of climate goal and related implications, while more explicit assumptions about social values are required to perform CBA. For example, assumptions about the social discount rate no longer affect the overall abatement levels now set by the climate goal, but the choice and timing of investments in individual measures to reach these levels.

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

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

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

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[13]: Also other metrics to compare emissions have been suggested and adopted by governments nationally (Kandlikar, 1995; Marten et al., 2015; Shindell, 2015; Interagency Working Group on Social Cost of Greenhouse Gases, 2016).

An important question is how results from CEA- and CBA-type approaches can be compared and synthesised. Such synthesis needs to be done with care, since estimates of the shadow price of carbon under the climate goal and SCC estimates from CBA might not be directly comparable due to different tools, approaches and assumptions used to derive them. Acknowledging this caveat, the SCC literature has identified a range of factors, assumptions and value judgements that support SCC values above \$100 tCO_2^{-1} that are also found as net present values of the shadow price of carbon in 1.5°C pathways. These factors include accounting for tipping points in the climate system (Lemoine and Traeger, 2014; Cai et al., 2015; Lontzek et al., 2015), a low social discount rate (Nordhaus, 2005; Stern, 2007) and inequality aversion (Schmidt et al., 2013; Dennig et al., 2015; Adler et al., 2017).

The SCC and the shadow price of carbon are not merely theoretical concepts but used in regulation (Pizer et al., 2014; Revesz et al., 2014; Stiglitz et al., 2017). As stated by the report of the High-Level Commission on Carbon Pricing (Stiglitz et al., 2017), in the real world there is a distinction to be made between the implementable and efficient explicit carbon prices and the implicit (notional) carbon prices to be retained for policy appraisal and the evaluation of public investments, as is already done in some jurisdictions such as the USA, UK and France. Since 2008, the U.S. government has used SCC estimates to assess the benefits and costs related to CO_2 emissions resulting from federal policymaking (NASEM, 2017; Rose et al., 2017a).

The use of the SCC for policy appraisals is however not straightforward in an SDG context. There are suggestions that a broader range of polluting activities than only CO_2 emissions, for example emissions of air pollutants, and a broader range of impacts than only climate change, such as impacts on air quality, health and sustainable development in general (see Chapter 5 for a detailed discussion), would need to be included in social costs (Sarofim et al., 2017; Shindell et al., 2017a). Most importantly, a consistent valuation of the SCC in a sustainable development framework would require accounting for the SDGs in the social welfare formulation (see Chapter 5).

[END CROSS CHAPTER BOX 5 HERE]

2.5.2 Economic and financial implications of 1.5°C Pathways

2.5.2.1 Price of carbon emissions

The price of carbon assessed here is fundamentally different from the concepts of optimal carbon price in a cost-benefit analysis, or the social cost of carbon (see Cross-Chapter Box 5 in this Chapter and Section 3.5.2). Under a cost-effective analysis (CEA) modelling framework, prices for carbon (mitigation costs) reflect the stringency of mitigation requirements at the margin (i.e., cost of mitigating one extra unit of emission).

Based on data available for this special report, the price of carbon varies substantially across models and scenarios, and their value increase with mitigation efforts (see Figure 2.26) (*high confidence*). For instance, undiscounted values under a Higher-2˚C pathway range from 10–200 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2030, 45–960 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2050, 120–1000 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2070 and 160–2125 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2100. On the contrary, estimates for a Below-1.5˚C pathway range from 135–5500 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2030, 245–13000 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2050, 420–17500 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2070 and 690–27000 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2100. One can also observe that values for 1.5°C-low-OS pathway are relatively higher than 1.5°C-high-OS pathway in 2030, but the difference decreases over time. This is because in 1.5°C-high-OS pathways there is relatively less mitigation activity in the first half of the century, but more in the second half. *LED* exhibits the lowest values across the illustrative pathway archetypes. As a whole, the average discounted price of emissions across 1.5˚C- and 2˚C pathways differs by a factor of four across models (assuming a 5% annual discount rate). If values from 1.5˚C-high-OS pathways (with peak warming 0.1–0.4°C higher than 1.5°C) or pathways with very large land-use sinks are kept in the 1.5˚C pathway superclass, the differential value is reduced to a limited degree, from a factor 4 to a factor 3. The increase in carbon prices between 1.5°C- and 2°C-consistent pathways is based on a direct comparison of pathway pairs from the same model and the same study in which the 1.5°C-consistent pathway assumes a significantly smaller carbon budget compared to the 2°C-consistent pathway (e.g., 600 $GtCO_2$ smaller in the CD-LINKS and ADVANCE studies). This assumption is the main driver behind the increase in the price of carbon (Luderer et al., 2018; McCollum et al., 2018).[14] Considering incomplete and uncertain information, an optimal price of carbon of the magnitude estimated in modelling studies needs to be compared with what is politically and institutionally feasible (see Section 4.4.5.2).

The wide range of values depends on numerous aspects, including methodologies, projected energy service demands, mitigation targets, fuel prices and technology availability (Clarke et al., 2014; Kriegler et al., 2015b; Rogelj et al., 2015c; Riahi et al., 2017; Stiglitz et al., 2017) (*high confidence*). The characteristics of the technology portfolio, particularly in terms of investment costs and deployment rates play a key role (Luderer et al., 2013, 2016a; Clarke et al., 2014; Bertram et al., 2015a; Riahi et al., 2015; Rogelj et al., 2015c). Models that encompass a higher degree of technology granularity and that entail more flexibility regarding mitigation response, often produce relatively lower mitigation costs than those that show less flexibility from a technology perspective (Bertram et al., 2015a; Kriegler et al., 2015a). Pathways providing high estimates often have limited flexibility of substituting fossil fuels with low-carbon technologies and the associated need to compensate fossil-fuel emissions with CDR. Emission prices are also sensitive to the non-availability of BECCS (Bauer et al., 2018). Furthermore, and due to the treatment of future price anticipation, recursive-dynamic modelling approaches (with ‘myopic anticipation’) exhibit higher prices in the short term but modest increases in the long term compared to optimisation modelling frameworks with ‘perfect foresight’ that show exponential pricing trajectories (Guivarch and Rogelj, 2017). The chosen social discount rate in CEA studies (range of 2–8% per year in the reported data, varying over time and sectors) can also affect the choice and timing of investments in mitigation measures (Clarke et al., 2014; Kriegler et al., 2015b; Weyant, 2017). However, the impacts of varying discount rates on 1.5°C (and 2˚C) mitigation strategies can only be assessed to a limited degree. The above highlights the importance of sampling bias in pathway analysis ensembles towards outcomes derived from models which are more flexible, have more mitigation options and cheaper cost assumptions and thus can provide feasible pathways in contrast to other who are unable to do so (Tavoni and Tol, 2010; Clarke et al., 2014; Bertram et al., 2015a; Kriegler et al., 2015a; Guivarch and Rogelj, 2017). All CEA-based IAM studies reveal no unique carbon pricing path (Bertram et al., 2015a; Kriegler et al., 2015b; Akimoto et al., 2017; Riahi et al., 2017).

Socio-economic conditions and policy assumptions also influence the price of carbon (Bauer et al., 2017; Guivarch and Rogelj, 2017; Hof et al., 2017; Riahi et al., 2017; Rogelj et al., 2018) (*very high confidence*). A multi-model study (Riahi et al., 2017) estimated the average discounted price of carbon (2010-2100, 5% discount rate) for a 2˚C target to be nearly three times higher in the SSP5 marker than in the SSP1 marker. Another multi-model study (Rogelj et al., 2018) estimated average discounted carbon prices (2020-2100, 5%) to be 35–65% lower in SSP1 compared to SSP2 in 1.5˚C pathways. Delayed near-term mitigation policies and measures, including the limited extent of international global cooperation, increases total economic mitigation costs, and corresponding prices of carbon (Luderer et al., 2013; Clarke et al., 2014). This is because stronger efforts are required in the period after the delay to counterbalance the higher emissions in the near term. Staged accession scenarios also produce higher carbon prices than immediate action mitigation scenarios under the same stringency level of emissions (Kriegler et al., 2015b). In addition, the revenue recycling effect of carbon pricing can reduce mitigation costs by displacing distortionary taxes (Baranzini et al., 2017; OECD, 2017; McFarland et al., 2018; Sands, 2018; Siegmeier et al., 2018) and the reduction of capital tax (compared to a labour tax) can yield greater savings in welfare costs (Sands, 2018). The effect on public budgets is particularly important in the near term, however it can decline in the long term as carbon neutrality is achieved (Sands, 2018).

It has been long argued that carbon pricing (whether via a tax or cap-and-trade scheme) can theoretically achieve cost-effective emission reductions (Nordhaus, 2007; Stern, 2007; Aldy and Stavins, 2012; Goulder and Schein, 2013; Somanthan et al., 2014; Weitzman, 2014; Tol, 2017). Whereas the integrated assessment literature is mostly focused on the role of carbon pricing to reduce emissions (Clarke et al., 2014; Riahi et al., 2017; Weyant, 2017) there is an emerging body of studies (including bottom-up approaches) that focuses on the interaction and performance of various policy mixes (e.g., regulation, subsidies, standards). Assuming global implementation of a mix of regionally existing best practice policies (mostly regulatory policies in the electricity, industry, buildings, transport and agricultural sectors) and moderate carbon pricing (between 5–

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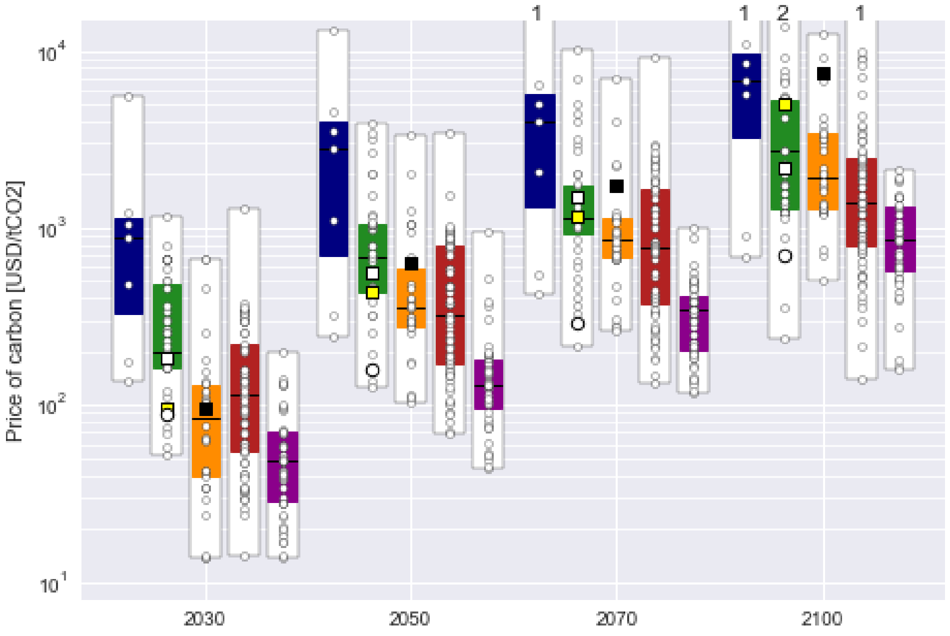
[14]: Unlike AR5, which only included cost-effective scenarios for estimating discounted average carbon prices for 2015-2100 (also using a 5% discount rate) (see Clarke et al., 2014, p.450), please note that values shown in Figure 2.26 (panel b) include delays or technology constraint cases (see Sections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

20 USD$_{2010}$ tCO$_2^{-1}$ in 2025 in most world regions and average prices around 25 USD$_{2010}$ tCO$_2^{-1}$ in 2030), early action mitigation pathways are generated that reduce global CO$_2$ emissions by an additional 10 GtCO$_2$e in 2030 compared to the NDCs (Kriegler et al., 2018b) (see Section 2.3.5). Furthermore, a mix of stringent energy efficiency policies (e.g., minimum performance standards, building codes) combined with a carbon tax (rising from 10 USD$_{2010}$ tCO$_2^{-1}$ in 2020 to 27 USD$_{2010}$ tCO$_2^{-1}$ in 2040) is more cost-effective than a carbon tax alone (from 20 to 53 USD$_{2010}$ tCO$_2^{-1}$) to generate a 1.5˚C pathway for the U.S. electric sector (Brown and Li, 2018). Likewise, a policy mix encompassing a moderate carbon price (7 USD$_{2010}$ tCO$_2^{-1}$ in 2015) combined with a ban on new coal-based power plants and dedicated policies addressing renewable electricity generation capacity and electric vehicles reduces efficiency losses compared with an optimal carbon pricing in 2030 (Bertram et al., 2015b). One study estimates the price of carbon in high energy-intensive pathways to be 25–50% higher than in low energy-intensive pathways that assume ambitious regulatory instruments, economic incentives (in addition to a carbon price) and voluntary initiatives (Méjean et al., 2018). A bottom-up approach shows that stringent minimum performance standards (MEPS) for appliances (e.g., refrigerators) can effectively complement carbon pricing, as tightened MEPS can achieve ambitious efficiency improvements that cannot be assured by carbon prices of 100 USD$_{2010}$ tCO$_2^{-1}$ or higher (Sonnenschein et al., 2018). The literature indicates that the pricing of emissions is relevant but needs to be complemented with other policies to drive the required changes in line with 1.5°C-consistent cost-effective pathways (Stiglitz et al., 2017; Mehling and Tvinnereim, 2018; Méjean et al., 2018; Michaelowa et al., 2018) (*low to medium evidence, high agreement*) (see Section 4.4.5).

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



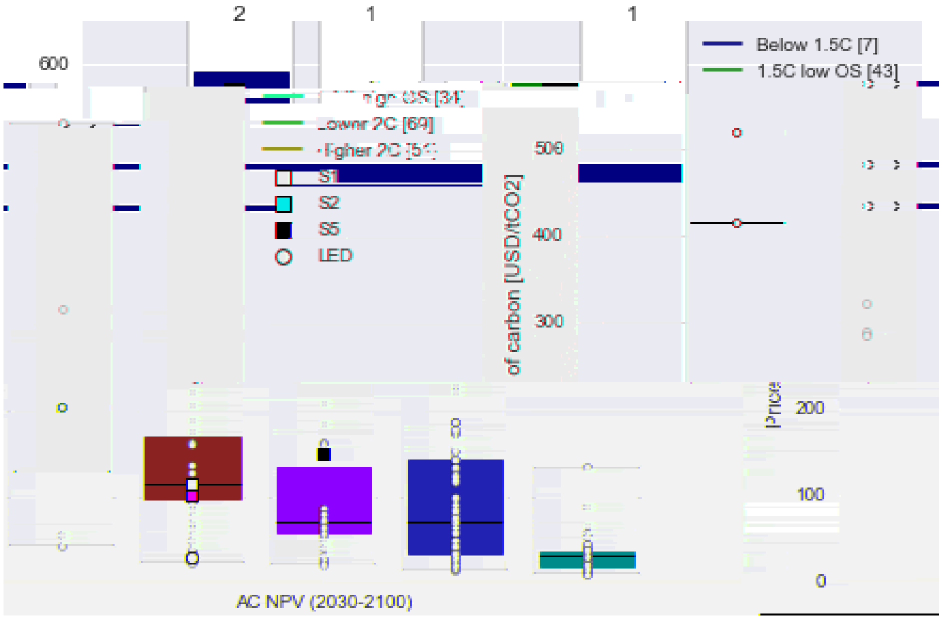


Figure 2.26: Global price of carbon emissions consistent with mitigation pathways. Panels show undiscounted price of carbon (2030-2100) (top panel) and average price of carbon (2030-2100) discounted at a 5% discount rate (lower panel). AC: Annually compounded. NPV: Net present value. Median values in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

2.5.2.2 Investments

Realising the transformations towards a 1.5°C world requires a major shift in investment patterns (McCollum et al., 2018). Literature on global climate-change mitigation investments is relatively sparse, with most detailed literature having focused on 2°C pathways (McCollum et al., 2013; Bowen et al., 2014; Gupta and Harnisch, 2014; Marangoni and Tavoni, 2014; OECD/IEA and IRENA, 2017).

Global energy-system investments in the year 2016 are estimated at approximately 1.7 trillion USD_{2010} (approximately 2.2% of global GDP and 10% of gross capital formation), of which 0.23 trillion USD_{2010} was for incremental end-use energy efficiency and the remainder for supply-side capacity installations (IEA, 2017c). There is some uncertainty surrounding this number because not all entities making investments report them publicly, and model-based estimates show an uncertainty range of about ± 15% (McCollum et al., 2018). Notwithstanding, the trend for global energy investments has been generally upward over the last two decades: increasing about threefold between 2000 and 2012, then levelling off for three years before declining in both 2015 and 2016 as a result of the oil price collapse and simultaneous capital cost reductions for renewables (IEA, 2017c).

Estimates of demand-side investments, either in total or for incremental efficiency efforts, are more uncertain, mainly due to a lack of reliable statistics and definitional issues about what exactly is counted towards a demand-side investment and what the reference should be for estimating incremental efficiency (McCollum et al., 2013). Grubler and Wilson (2014) use two working definitions (a broader and a narrower one) to provide a first-order estimate of historical end-use technology investments in total. The broad definition defines end-use technologies as the technological systems purchasable by final consumers in order to provide a useful service, for example, heating and air conditioning systems, cars, freezers, or aircraft. The narrow definition sets the boundary at the specific energy-using components or subsystems of the larger end-use technologies (e.g., compressor, car engine, heating element). Based on these two definitions, demand-side energy investments for the year 2005 were estimated about 1–3.5 trillion USD_{2010} (central estimate 1.7 trillion USD_{2010}) using the broad definition and 0.1–0.6 trillion USD_{2010} (central estimate 0.3 trillion USD_{2010}) using the narrower definition. Due to these definitional issues, demand-side investment projections are uncertain, often underreported, and difficult to compare. Global IAMs often do not fully and explicitly represent all the various measures that could improve end-use efficiency.

Research carried out by six global IAM teams found that 1.5°C-consistent climate policies would require a marked upscaling of energy system supply-side investments (resource extraction, power generation, fuel conversion, pipelines/transmission, and energy storage) between now and mid-century, reaching levels of between 1.6–3.8 trillion USD_{2010} yr^{-1} globally on average over the 2016-2050 timeframe (McCollum et al., 2018) (Figure 2.27). How these investment needs compare to those in a policy baseline scenario is uncertain: they could be higher, much higher, or lower. Investments in the policy baselines from these same models are 1.6–2.7 trillion USD_{2010} yr^{-1}. Much hinges on the reductions in energy demand growth embodied in the 1.5°C pathways, which require investing in energy efficiency. Studies suggest that annual supply-side investments by mid-century could be lowered by around 10% (McCollum et al., 2018) and in some cases up to 50% (Grubler et al., 2018) if strong policies to limit energy demand growth are successfully implemented. However, the degree to which these supply-side reductions would be partially offset by an increase in demand-side investments is unclear.

Some trends are robust across scenarios (Figure 2.27). First, pursuing 1.5°C mitigation efforts requires a major reallocation of the investment portfolio, implying a financial system aligned to mitigation challenges. The path laid out by countries' current NDCs until 2030 will not drive these structural changes; and despite increasing low-carbon investments in recent years (IEA, 2016b; Frankfurt School-UNEP Centre/BNEF, 2017), these are not yet aligned with 1.5°C. Specifically, annual investments in low-carbon energy are projected to average 0.8–2.9 trillion USD_{2010} yr^{-1} globally to 2050 in 1.5 °C pathways, overtaking fossil investments globally already by around 2025 (McCollum et al., 2018). The bulk of these investments are projected to be for clean electricity generation, particularly solar and wind power (0.09–1.0 trillion USD_{2010} yr^{-1} and 0.1–0.35 trillion USD_{2010} yr^{-1}, respectively) as well as nuclear power (0.1–0.25 trillion USD_{2010} yr^{-1}). The precise apportioning of these investments depends on model assumptions and societal preferences related to mitigation strategies and policy choices (see Sections 2.1 and 2.3). Investments for electricity transmission and distribution and storage are also scaled up in 1.5°C pathways (0.3–1.3 trillion USD_{2010} yr^{-1}), given their widespread electrification of the end-use sectors (see Section 2.4). Meanwhile, 1.5°C pathways see a reduction in annual investments for fossil-fuel extraction and unabated fossil electricity generation (to 0.3–0.85 trillion USD_{2010} yr^{-1} on average over the 2016–2050 period). Investments in unabated coal are halted by 2030 in most 1.5°C projections, while the literature is less conclusive for investments in unabated gas (McCollum et al., 2018). This illustrates how mitigation strategies vary between models, but in the real world should be considered in terms of their societal desirability (see Section 2.5.3). Furthermore, some fossil investments made over the next few years – or those made in the last few – will likely need to be retired prior to fully recovering their capital investment or before the end of their operational lifetime (Bertram et al., 2015a; Johnson et al., 2015; OECD/IEA and IRENA, 2017). How the pace of the energy transition will be affected by such dynamics, namely with respect to politics and society, is not well captured by global IAMs at present. Modelling studies have, however, shown how the reliability of institutions influences investment risks and hence climate mitigation investment decisions (Iyer et al., 2015), finding that a lack of regulatory credibility or policy commitment fails to stimulate low-carbon investments (Bosetti and Victor, 2011; Faehn and Isaksen, 2016).

Low-carbon supply-side investment needs are projected to be largest in OECD countries and those of developing Asia. The regional distribution of investments in 1.5°C pathways estimated by the multiple models in (McCollum et al., 2018) are the following (average over 2016-2050 timeframe): 0.30-1.3 trillion USD_{2010} yr^{-1}(ASIA), 0.35–0.85 trillion USD_{2010} yr^{-1} (OECD), 0.08–0.55 trillion USD_{2010} yr^{-1} (MAF), 0.07–0.25 trillion USD_{2010} yr^{-1} (LAM), and 0.05–0.15 trillion USD_{2010} yr^{-1} (REF) (regions are defined consistent with their use in AR5 WGIII, see Table A.II.8 in Krey et al., 2014b).

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

Assumptions in modelling studies indicate a number of challenges. For instance, access to finance and mobilisation of funds are critical (Fankhauser et al., 2016; OECD, 2017). In turn, policy efforts need to be effective in re-directing financial resources (UNEP, 2015; OECD, 2017) and reduce transaction costs for bankable mitigation projects (i.e. projects that have adequate future cash-flow, collateral, etc. so lenders are willing to finance it), particularly on the demand side (Mundaca et al., 2013; Brunner and Enting, 2014; Grubler et al., 2018). Assumptions also imply that policy certainty, regulatory oversight mechanisms and fiduciary duty need to be robust and effective to safeguard credible and stable financial markets and de-risk mitigation investments in the long term (Clarke et al., 2014; Mundaca et al., 2016; EC, 2017; OECD, 2017). Importantly, the different time horizons that actors have in the competitive finance industry are typically not explicitly captured by modelling assumptions (Harmes, 2011). See Section 4.4.5 for details of climate finance in practice.

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

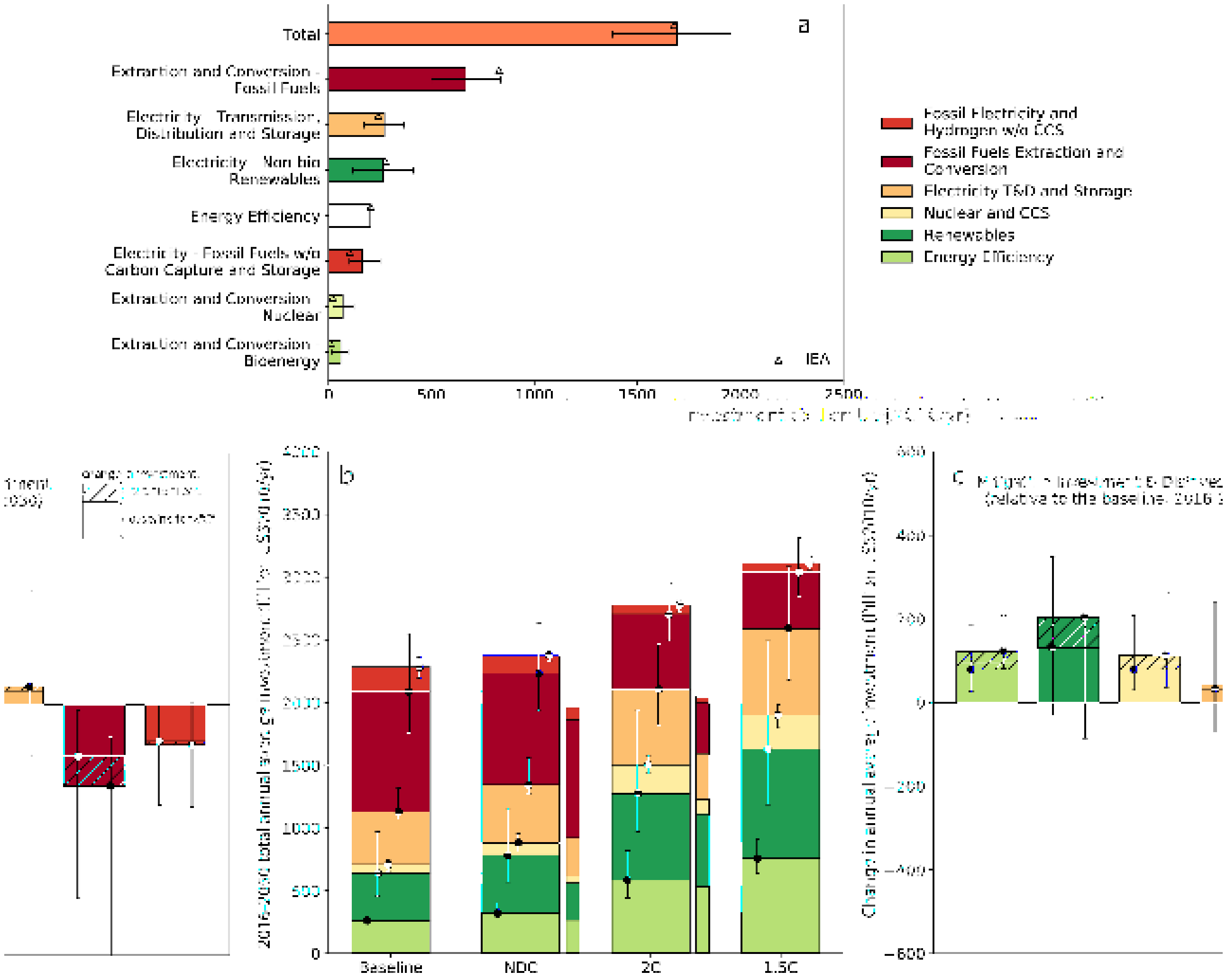


Figure 2.27: Historical and projected global energy investments. (a) Historical investment estimates across six global models from (McCollum et al., 2018) (bars = model means, whiskers full model range) compared to historical estimates from IEA (International Energy Agency (IEA) 2016) (triangles). (b) Average annual investments over the 2016–2050 period in no-climate policy ‘baselines’, scenarios which implement the NDCs (‘NDC’), scenarios consistent with the Lower-2°C pathway class (‘2°C’), and scenarios in line with the 1.5°C-low-OS pathway class (‘1.5°C’). Whiskers show the range of models; wide bars show the multi-model means; narrow bars represent analogous values from individual IEA

scenarios (OECD/IEA and IRENA, 2017). (c) Average annual mitigation investments and disinvestments for the 2016–2030 periods relative to the baseline. The solid bars show the values for '2°C' pathways, while the hatched areas show the additional investments for the pathways labelled with '1.5°C'. Whiskers show the full range around the multi-model means. T&D stands for transmission and distribution, and CCS stands for carbon capture and storage. Global cumulative carbon dioxide emissions, from fossil fuels and industrial processes (FF&I) but excluding land use, over the 2016-2100 timeframe range from 880 to 1074 $GtCO_2$ (multi-model mean: 952 $GtCO_2$) in the '2°C' pathway and from 206 to 525 $GtCO_2$ (mean: 390 $GtCO_2$) in the '1.5°C' pathway.

2.5.3 Sustainable development features of 1.5°C pathways

Potential synergies and trade-offs between 1.5°C mitigation pathways and different sustainable development (SD) dimensions (see Cross-Chapter Box 4) are an emerging field of research. Section 5.4 assesses interactions between individual mitigation measures with other societal objectives, as well as the Sustainable Development Goals (SGDs) (Table 5.1). This section synthesized the Chapter 5 insights to assess how these interactions play out in integrated 1.5°C pathways, and the four illustrative pathway archetypes of this chapter in particular (see Section 2.1). Information from integrated pathways is combined with the interactions assessed in Chapter 5 and aggregated for each SDG, with a level of confidence attributed to each interaction based on the amount and agreement of the scientific evidence (see Chapter 5).

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

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

At the same time, the literature on climate-SDG interactions is still an emergent field of research and hence there is *low to medium confidence* in the precise magnitude of the majority of these interactions. Very limited literature suggests that achieving co-benefits are not automatically assured but result from conscious and carefully coordinated policies and implementation strategies (Shukla and Chaturvedi, 2012; Clarke et al., 2014; McCollum et al., 2018). Understanding these mitigation-SDG interactions is key for selecting mitigation options that maximise synergies and minimize trade-offs towards the 1.5°C and sustainable development objectives (van Vuuren et al., 2015; Hildingsson and Johansson, 2016; Jakob and Steckel, 2016; von Stechow et al., 2016; Delponte et al., 2017).

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

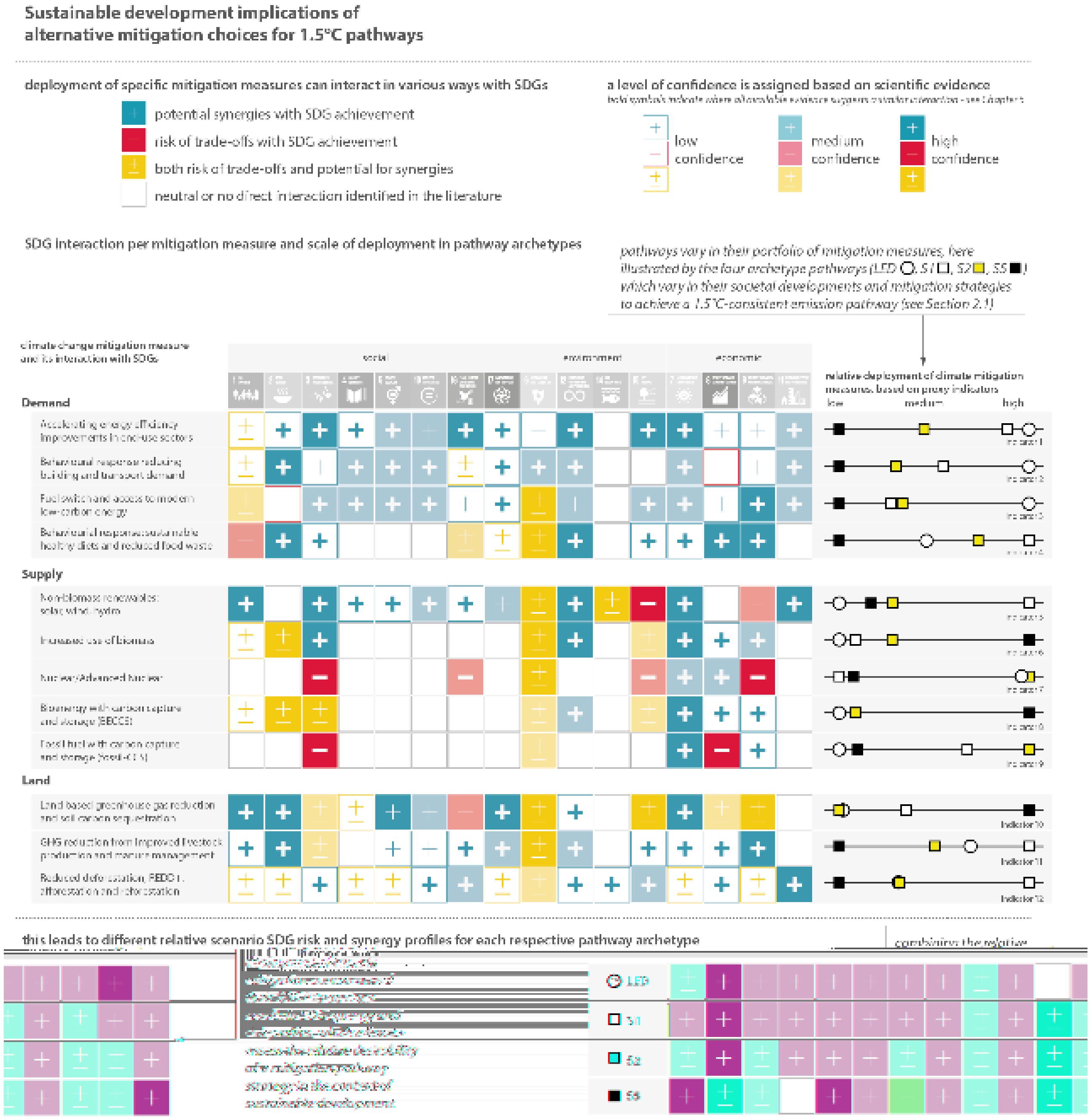


Figure 2.28: Interactions of individual mitigation measures and alternative mitigations portfolios for 1.5°C with Sustainable Development Goals (SDGs). The assessment of interactions between mitigation measures and individual SDGs is based on the assessment of Section 5.4. Proxy indicators and synthesis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

2.6 Knowledge gaps

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

2.6.1 Geophysical understanding

Knowledge gaps are associated with the carbon-cycle response, the role of non-CO_2 emissions and on the evaluation of an appropriate historic baseline.

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

The future emissions of short-lived climate forcers and their temperature response are a large source of uncertainty in 1.5°C pathways, having a greater relative uncertainty than in higher CO_2 emission pathways. Their global emissions, their sectorial and regional disaggregation and their climate response are generally less well quantified than for CO_2 (Sections 2.2 and 2.3). Emissions from the agricultural sector including land-use based mitigation options in 1.5°C pathways constitute the main source of uncertainty here and are an important gap in understanding the potential achievement of stringent mitigation scenarios (Sections 2.3 and 2.4). This also includes uncertainties surrounding the mitigation potential of the long-lived GHG nitrous oxide. (Sections 2.3 and 2.4)

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

The pathway classification employed in this Chapter employs results from the MAGICC model with its AR5 parameter sets. The alternative representation of the relationship between emissions and effective radiative forcing and response in the FAIR model would lead to a different classification that would make 1.5°C targets more achievable (Section 2.2 and 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 that would act to increase the temperature response (Section 2.2). For this assessment report, any possible bias in MAGICC setup applied in this and earlier reports is not established enough in the literature to change the classification approach. However, we only place *medium confidence* in the classification adopted by the chapter.

2.6.2 Integrated assessment approaches

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

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

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

While the representation of renewable energy resource potentials, technology costs and system integration in IAMs has been updated since AR5, bottom-up studies find higher mitigation potentials in the industry, buildings, and transport sector in that realized by selected pathways from IAMs, indicating the possibility to strengthen sectorial decarbonisation strategies compared to the IAM 1.5°C pathways assessed in this chapter (Section 2.1).

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

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

2.6.3 Carbon Dioxide Removal (CDR)

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

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

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

There is substantial uncertainty about the adverse effects of large-scale CDR deployment on the environment and societal sustainable development goals. It is not fully understood how land use and land management choices for large-scale BECCS will affect various ecosystem services and sustainable development, and further translate into indirect impacts on climate including GHG emissions other than $CO_{2.}$ (Section 2.3, Section 2.5.3)

Frequently Asked Questions

FAQ 2.1: What kind of pathways limit warming to 1.5°C and are we on track?

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

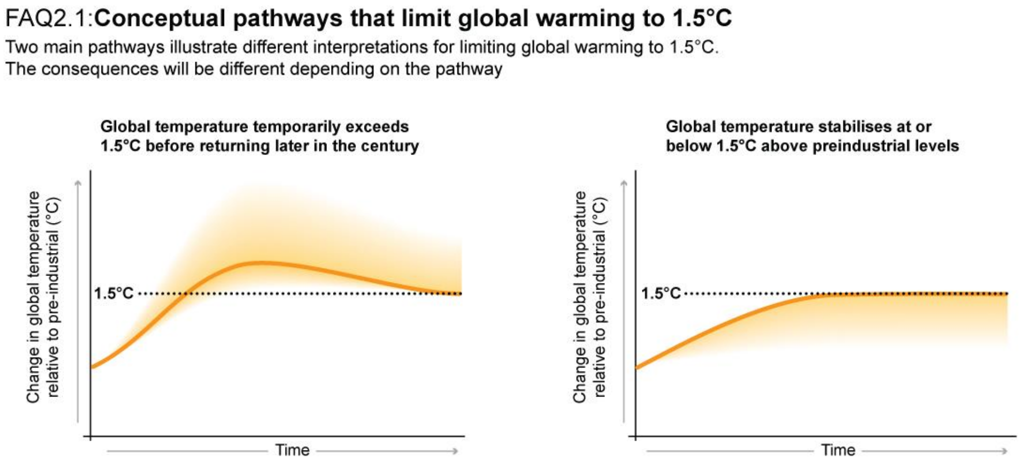
Scientists use computer models to simulate the emissions of greenhouse gases that would be consistent with different levels of warming. The different possibilities are often referred to as 'greenhouse gas emission pathways'. There is no single, definitive pathway to limiting warming to 1.5°C.

This IPCC special report identifies two main pathways that explore global warming of 1.5°C. The first involves global temperature stabilising at or below before 1.5°C above preindustrial levels. The second pathway sees warming exceed 1.5°C around mid-century, remain above 1.5°C for a maximum duration of a few decades, and return to below 1.5°C before 2100. The latter is often referred to as an 'overshoot' pathway. Any alternative situation in which global temperature continues to rise, exceeding 1.5°C permanently until the end of the 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 CO_2 from the atmosphere, on top of reducing the sources of emissions (mitigation). Such ideas for CO_2 removal have not been proven to work at scale and, therefore, run the risk of being less practical, effective or economical than assumed. There is also the risk that the use of CO_2 removal techniques ends up competing for land and water and if these trade-offs are not appropriately managed, they can adversely affect sustainable development. Additionally, a larger and longer overshoot increases the risk for irreversible climate impacts, such as the onset of the collapse of polar ice shelves and accelerated sea level rise.

Countries that formally accept or 'ratify' the Paris Agreement submit pledges for how they intend to address climate change. Unique to each country, these pledges are known as Nationally Determined Contributions (NDCs). Different groups of researchers around the world have analysed the combined effect of adding up all the NDCs. Such analyses show that current pledges are not on track to limit global warming to 1.5°C above pre-industrial levels. If current pledges for 2030 are achieved but no more, researchers find very few (if any) ways to reduce emissions after 2030 sufficiently quickly to limit warming to 1.5°C. This, in turn, suggests that with the national pledges as they stand, warming would exceed 1.5°C, at least for a period of time, and practices and technologies that remove CO_2 from the atmosphere at a global scale would be required to return warming to 1.5°C at a later date.

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



FAQ2.1: **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

Global temperature temporarily exceeds 1.5°C before returning later in the century

Global temperature stabilises at or below 1.5°C above preindustrial levels

FAQ2.1, Figure 1: Two main pathways for limiting global temperature rise to 1.5°C above pre-industrial levels are discussed in this Special Report. These are: stabilising global temperature at, or just below, 1.5°C (left) and global temperature temporarily exceeding 1.5°C before coming back down later in the century (right). Temperatures shown are relative to pre-industrial but pathways are illustrative only, demonstrating conceptual not quantitative characteristics.

FAQ 2.2: What do energy supply and demand have to do with limiting warming to 1.5°C?

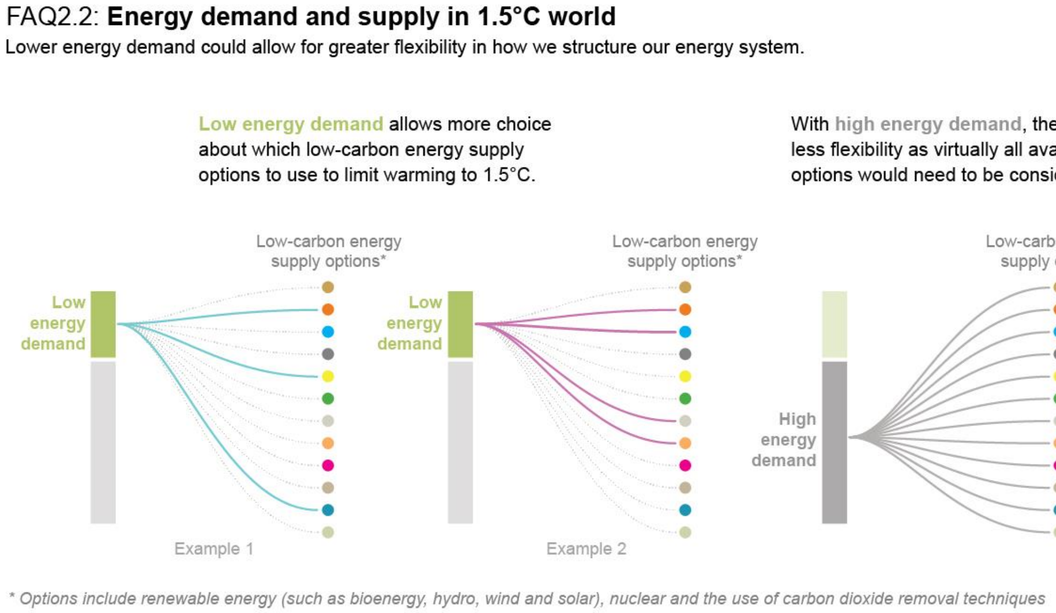
***Summary**: Limiting global warming to 1.5°C above pre-industrial levels would require major reductions in greenhouse gas emissions in all sectors. But different sectors are not independent of each other and making changes in one can have implications for another. For example, if we as a society use a lot of energy, then this could mean we have less flexibility in the choice of mitigation options available to limit warming to 1.5°C. If we use less energy, the choice of possible actions is greater. For example we could be less reliant on technologies that remove carbon dioxide (*CO_2*) from the atmosphere.*

To stabilise global temperature at any level, ‘net’ CO_2 emissions would need to be reduced to zero. This means the amount of CO_2 entering the atmosphere must equal the amount that is removed. Achieving a balance between CO_2 ‘sources’ and ‘sinks’ is often referred to as ‘net zero’ emissions or ‘carbon neutrality’. The implication of net zero emissions is that the concentration of CO_2 in the atmosphere would slowly decline over time until a new equilibrium is reached, as CO_2 emissions from human activity are redistributed and taken up by the oceans and the land biosphere. This would lead to a near-constant global temperature over many centuries.

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

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

Making changes in one sector can have consequences for another, as they are not independent of each other. In other words, the choices that we make now as a society in one sector can either restrict or expand our options later on. For example, a high demand for energy could mean we would need to deploy almost all known options to reduce emissions in order to limit global temperature rise to 1.5°C above pre-industrial levels, with the potential for adverse side-effects. For example, a high-demand pathway increases our reliance on practices and technologies that remove CO_2 from the atmosphere. As of yet, such techniques have not been proven to work on a large scale and, depending on how they are implemented, could compete for land and water. By leading to lower overall energy demand, effective demand-side measures could allow for greater flexibility in how we structure our energy system. However, demand-side measures are not easy to implement and barriers have prevented the most efficient practices being used in the past.



FAQ2.2, Figure 1: Having a lower energy demand increases the flexibility in choosing options for supplying energy. A larger energy demand means many more low carbon energy supply options would need to be used.

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