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

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Executive Summary

This chapter examines mitigation pathways consistent with limiting warming to 1.5°C above preindustrial levels. In doing so, it explores the following key questions: What is the remaining budget of CO$_2$ emissions to stay below 1.5°C? To what extent do 1.5°C scenarios involve overshooting and returning to below 1.5°C by 2100? {2.2, 2.6} How is the carbon budget affected by non-CO$_2$ emissions? {2.2, 2.3, 2.4, 2.6} What do 1.5°C pathways imply about transitions in energy, land use and sustainable development? {2.3, 2.4} How do policies in the near term affect the ability to limit warming to 1.5°C? {2.3, 2.5} What are the strengths and limitations of current modelling tools? {2.6}

There is very high risk that under current emission trajectories or current national pledges the Earth will warm more than 1.5°C above preindustrial levels. Limiting warming to 1.5°C would require a rapid phase out of net global carbon dioxide (CO$_2$) emissions and deep reductions in non-CO$_2$ drivers of climate change such as methane. Such ambitious mitigation pathways are put at risk by high population growth, low economic development, and limited efforts to reduce energy demand. In comparison to a 2°C limit, required transformations are qualitatively similar but more pronounced and rapid over the next decades *(high confidence)* {2.3.1, 2.3.5, 2.5.1}.

It is possible to define consistency with limiting warming to 1.5°C in different ways, including pathways that keep global average temperature below 1.5°C and those that overshoot 1.5°C and return later in the century. These different types of pathways come with very different implications and risks, including for sustainable development. For the purposes of this chapter, any scenario (non-overshoot and overshoot) with a greater than 50% probability of limiting warming to 1.5°C in 2100 is referred to as a “1.5°C scenario”, with variations highlighted where appropriate. {2.3.1, 2.2.3, 2.5.3}

This assessment evaluates the temperature outcome from quantitative model descriptions of emissions associated with the energy system, land use and the economy. While such model results provide insight into the consequences of policy options and their interplay with socio-economic and technological development, the models are constrained by multiple underlying assumptions. For this reason, their results are complemented in this assessment with other types of studies and evidence. {2.1.3, 2.2.1, 2.6.1, 2.6.2}

Remaining Carbon Budgets of 1.5°C pathways

This assessment explores two types of remaining carbon budgets. The first is the Threshold Peak Budget (TPB), defined as cumulative CO$_2$ emissions from 1 January 2016 until global mean temperature peaks. The second is the Threshold Return Budget (TRB), defined as cumulative CO$_2$ emissions until global mean temperature returns to 1.5 or 2°C after a temporary temperature overshoot. Budgets are computed assuming that warming is limited to 1.5 or 2°C with either 50% likelihood or 66% likelihood, and accounting for non-CO$_2$ drivers. Current emissions are ~40 GtCO$_2$ yr^{-1}, which means budgets from 2019 onwards will be ~120 GtCO$_2$ lower than counting from the start of 2016. The range accompanying budget calculations are based on available scenarios and cover physical uncertainty as well as variations in non-CO$_2$ emissions. Values are presented in Table ES1. {2.2.2}

Table ES1: Median and likely range of Threshold Return Budget *(medium confidence)* and Threshold Peak Budget *(high confidence)* in GtCO$_2$ compatible with 1.5°C or 2°C for 1st January 2016 onwards. N/A: not available {Table 2.4}

	Risk Preference	**Threshold Return Budgets (TRB)**	**Threshold Peak Budgets (TPB)**
Limiting warming to 1.5°C	50% likelihood	590 (420—880)	580 (490—640)
	66% likelihood	390 (200—730)	N/A
Limiting warming to 2°C	50% likelihood	960 (570—1460)	1450 (1330—1550)
	66^{t}% likelihood	910 (570—1210)	1180 (1050—1380)

In the 5% of pathways that experience the greatest warming due to non-CO$_2$ drivers there is a 3% risk that the TPB for 1.5°C is already exhausted, and a 25% risk that the TRB for 1.5°C is exhausted. In the 5% of pathways with the most ambitious mitigation of non-CO$_2$ drivers, the latter risk is reduced to less than 1% *(medium confidence)*. Pathways consistent with keeping warming below 1.5°C in 2100 maintain net zero or net negative CO$_2$ emissions after mid-century, neutralizing residual emissions of other long-lived greenhouse gases (predominantly nitrous oxide from agriculture). Such pathways also reduce emissions of short-lived climate forcers (particularly methane) as much as possible. {2.2.2}

Remaining uncertainties in the Earth system, including feedbacks and radiative forcings, primarily increase rather than decrease the risk of exceeding 1.5°C of warming *(medium confidence)*. Uncertainties in radiative forcing and revisions in methane forcing allow only medium confidence in the assessed likely range. Most uncertainties in the Earth system, including permafrost feedbacks and the saturation of carbon uptake by the biosphere, are expected to reduce available carbon budgets and, therefore, increase the risk of exceeding 1.5°C of warming. In addition, budgets are sensitive to uncertainties in estimating temperature change since preindustrial times, current land-use emissions, climate sensitivity, and the impact of non-CO_2 forcers (especially aerosols). {2.2.2, 2.6.2}

The risk of passing 1.5°C and the requirements for urgent action

Even with emissions reductions in line with countries' pledges under the Paris Agreement, known as Nationally-Determined Contributions (NDCs), a large share of the TPB would be exhausted by 2030 (median confidence). This means there is high risk that warming will exceed 1.5°C during the 21st century and remain above it by 2100 if emissions are reduced only to the level of current commitments, or remain above them. Current NDCs are estimated to result in greenhouse gas emissions of ~49-56 $GtCO_2$-eq yr^{-1} in 2030. In contrast, 1.5°C scenarios available to this assessment show an interquartile range of 14 to 48 $GtCO_2$-eq yr^{-1} in 2030. If current pledges are followed to 2030, there are no model scenarios in which average warming is kept below 1.5°C. The large majority of models also fail to return warming to below 1.5°C by the end of the 21st century if global emissions reduce in line with NDCs but no further. There is a high risk, therefore, that even if current NDCs are met, the post-2030 transformations that would be required to limit warming to 1.5°C are too steep and abrupt to be achieved even by the large portfolio of mitigation options that is considered in models *(high confidence)*. {2.3.1.1, 2.3.5, Table 2.7, Cross-chapter Box 4.1}

Delayed action or weak near-term policies increase the risk of exceeding 1.5°C and stranded investment in fossil-based capacity, leading to higher long-term mitigation challenges *(high confidence)*. Historical emissions and policies already mean that pathways with at least a 66% likelihood of holding global warming below 1.5°C are out of the reach of models (*medium confidence*; Table ES1). Failure to achieve near-term emissions reductions would mean faster rates of change afterwards to stay consistent with 1.5°C, as well as generally higher cumulative CO_2 emissions until carbon neutrality is reached (global net zero CO_2 emissions). This, in turn, implies a larger requirement for carbon dioxide removal (CDR), and a higher and longer exceedance of the 1.5°C temperature limit. A lack of near-term policy commitment and regulatory credibility hinders mitigation investments and increases abatement costs. *(high confidence)* {2.1.3, 2.3.2, 2.5.1, 2.5.2}

Strong carbon pricing mechanisms are necessary in 1.5°C scenarios to achieve the most cost-effective emissions reductions *(high confidence)*. Discounted carbon prices for limiting warming to 1.5°C are three to seven times higher compared to 2°C, depending on models and socioeconomic assumptions *(medium confidence)*. Carbon pricing can be usefully complemented by other policy instruments in the real world. For example, technology policies can also have an important role in the near term. {2.5.1, 2.5.2}

Adopting a 1.5°C rather than 2°C pathway implies faster socio-technical transitions and deployment of mitigation measures. The shift from 2°C to 1.5°C also implies more ambitious, internationally cooperative and transformative policy environments in the short term that target both supply and demand *(very high confidence)*. To keep the target of limiting warming to 1.5°C within reach, the stringency and effectiveness of policy portfolios is critical, as well as their diversity beyond carbon pricing. Pathways that assume stringent demand-side policies, and thus lower energy intensity and limited energy demand, reduce the risks of exceeding 1.5°C. {2.5, 2.5.1, 2.5.2}

Limiting warming to 1.5°C requires a marked shift in investment patterns *(high confidence)*, implying a financial system aligned with mitigation challenges. Studies reveal a gap between current investment patterns and those compatible with 1.5°C (or 2°C) scenarios. Whereas uncertainties exist regarding the extent of required investments (1.4–3.8 trillion USD annually on the supply side for 2016-2050), studies suggest a need for policies that re-direct existing financial resources towards mitigation investments and reduce transaction costs for bankable low-carbon energy technology projects, particularly on the demand side. Limiting warming to 1.5°C carries the risk of fossil-based asset stranding, indicating the need for financial stress tests for future energy infrastructure. {2.5.2}

The role of CO_2 emissions and Carbon Dioxide Removal (CDR)

1.5°C scenarios require deep reductions in CO_2, reaching carbon neutrality around mid-century, or shortly after *(high confidence)*. Rapid and stringent mitigation as well as upscaling of CDR deployment occur simultaneously. Compared to 2°C pathways, 1.5°C pathways generally rely more on additional emissions reductions than on additional CDR, reflecting limitations in scaling up CDR. This leads to only modest CDR deployment increases over the century in 1.5°C pathways compared to 2°C pathways. In particular, compared to 2°C pathways, additional mitigation measures account for around two thirds of the ca. 600 $GtCO_2$ CO_2 reductions by the end of the century, and CDR for the remaining third (~180 $GtCO_2$ for the median).{ 2.3.1, 2.3.4}

All 1.5°C pathways analysed use CDR to some extent, to neutralize emissions for which no mitigation measures can be identified or to achieve net negative emissions to draw down any excess in carbon emissions beyond the carbon budget during the second half of the century *(high confidence)*. About 25-85% of cumulative CDR over the 21st century is used to neutralize emissions for which no mitigation measures can be identified. The scale of net CDR in 1.5°C scenarios after carbon neutrality depends on the pace of emissions reductions in the next decades and the degree to which emissions exceed the TPB for 1.5°C. Quantifying how the carbon cycle responds to negative emissions is an important gap in understanding of negative emission pathways. {2.3.1, 2.6.4}

The total amount of CDR projected in 1.5°C scenarios is of the order of 380-1130 $GtCO_2$ over the 21st century. The scale and type of CDR deployment varies widely across 1.5°C pathways. Some 1.5°C pathways rely predominantly on terrestrial CDR measures, such as afforestation, and others relying predominantly on bioenergy with CCS. CDR deployed at scale is unproven and reliance on such technology is assessed to be a major risk in the ability to limit warming to 1.5°C. {2.3.1, 2.6.4}

Biomass energy with carbon capture and storage (BECCS) and afforestation are considered in most 1.5°C pathways as a cost-effective way to achieve CDR. Such scenarios deploy BECCS at about 0.1 $GtCO_2\ yr^{-1}$ in 2030, but other scenarios do not use BECCS at all. ***(high confidence)*** Scenarios without BECCS instead focus on land-based CDR methods, such as afforestation. These scenarios also assume strongly bounded energy and resource demand, as well as the phasing-out of CO_2-producing infrastructure. Other CDR options, such as direct air capture and storage, are currently not by default included in model scenarios for limiting warming to 1.5°C. {2.3.1, 2.3.4}

Different CDR measures, and their deployment, have fundamentally different consequences for achieving sustainable development objectives. *(medium confidence)* Bioenergy demand is substantial in 1.5°C pathways due to its multiple energy uses and CDR potential. Both BECCS and afforestation require land to produce sustainable biomass and to store CO_2 through the growth of trees (certain). Across 1.5°C pathways, bioenergy supplies nearly as much energy as wind and solar combined, and nearly half as much as total fossil fuel energy in 2050. The scale of bioenergy and BECCS deployment depends on its cost development as well as on related policy choices, such as land and water use or reductions in energy demand. More BECCS is required in 1.5°C scenarios when fossil fuels are phased-out more slowly. {2.3.3, 2.4.2, 2.5.3} Land-use change dynamics associated with bioenergy and BECCS do not generally differ markedly between 1.5°C and 2°C pathways, although there remains deep uncertainty linked to societal and technological developments. In general, the stronger mitigation requirements for 1.5°C increase pressure on land and the potential for trade-offs with sustainable development. {2.4.4}

The role of non-CO_2 emissions and targeted policies

There is a high risk that global temperature will pass 1.5°C even with the most stringent CO_2 mitigation, unless emissions of non-CO_2 warming agents are also strongly reduced *(medium*

confidence). Since some non-CO_2 warming agents are emitted alongside CO_2, particularly in the energy and transport sectors, non-CO_2 emissions can be addressed through CO_2 mitigation as well as through specific measures, for example to target agricultural methane, black carbon from kerosene lamps or HFCs (such as the Kigali Amendment). *(high confidence)* Every tenth of a degree of warming that comes from non-CO_2 emissions reduces the remaining carbon budget for 1.5°C by ~150 $GtCO_2$, increasing the risk of exceeding 1.5°C *(medium confidence)*. Mitigating non-CO_2 emissions can carry large benefits for public health and sustainable development, particularly through improved air quality. *(high confidence)* {2.2.2, 2.3.1, 2.4.2, 2.5.1}

Properties of transitions in mitigation pathways before mid-century

In 1.5°C scenarios, mitigation options are deployed more rapidly, at greater scale, and with a greater portfolio of options than in 2°C scenarios. Key technical and behavioural options are sector and region specific but generally include efficiency improvements, reduction in demand and switching to lower-carbon sources of energy (including renewables and/or nuclear) *(high confidence)*. End-use electrification replacing fossil fuels plays a major role in the buildings, industry and transportation sectors. {2.3.4, 2.4.1, 2.4.2, 2.4.3}

1.5°C scenarios include rapid electrification of energy end use (about two thirds of final energy by 2100 alongside rapid decreases in the carbon intensity of electricity and of the residual fuel mix *(high confidence)*. The electricity sector is fully decarbonized by mid-century in 1.5°C pathways, a feature shared with 2°C pathways. Additional emissions reductions compared to 2°C pathways come predominantly from energy end use sectors (transport, buildings, industry). Pathways that hold warming to below 1.5°C show markedly faster transitions until 2030 and 2050 compared to pathways that temporarily overshoot 1.5°C and return by 2100. {2.3.3}

The share of primary energy from renewables increases rapidly in 1.5°C scenarios, becoming the dominant source of energy by 2050 in most pathways. On average, the share of low-carbon energy (including renewable energy, sustainable biomass and nuclear) accounts for one third of primary energy in 2030 (15-87% across the full range of model scenarios), and about two thirds (36-97%) in 2050. Coal usage is phased out rapidly in mitigation pathways consistent with 1.5°C, with annual reduction rates of 4-5% until the middle of the century. In cases where coal use is not completely phased out by 2050, 40-100% is combined with Carbon Capture and Storage (CCS). The result is that in most 1.5°C scenarios, virtually no primary energy from unabated coal use remains in 2050 (~2 EJ yr^{-1}, on average). For other fossil fuels, the mid-century picture is more differentiated. Scenarios indicate slowly declining use of oil and a wide range of natural gas usage, with varying levels of CCS. {2.3.3}

Demand-side mitigation and behavioural changes

A number of demand-side measures and behavioural changes are critical elements of 1.5°C scenarios. These include: large reductions of per capita energy demand in areas with high consumption; substantial decreases in livestock and private vehicle transportation demand per capita; reductions in food waste and deforestation; and improvements in end-use efficiency (e.g. appliances, industrial processes, insulation, lighter vehicles) *(medium confidence)*. By 2030, all end-use sectors (including building, transport, and industry) show significant demand reductions in modelled 1.5°C pathways, beyond those projected in 2°C pathways. Sectorial models confirm demand reductions for 2030 and 2050 projected by Integrated Assessment Models that underlie global mitigation pathways, and suggest some potential further reductions based on emerging demand-side options. *(medium confidence)* {2.3.4, 2.4}

Final energy demand in 2100 is generally 20-60% above 2014 levels (interquartile range across available 1.5°C scenarios). Scenarios show, however, that energy demand levels lower than today can be achieved alongside strong economic growth until the end of the century through shifts to more sustainable energy, material and food consumption patterns *(medium to high confidence)*.{2.4.3}

Links between 1.5°C pathways and sustainable development

Limiting warming to 1.5°C by 2100 is easier in a world where policies focus on sustainable

development and with lifestyles that limit population growth as well as energy, resource and food demand. ***(medium confidence)*****. Under conditions of high population growth (and associated low educational attainment for females), low economic development, and limited efforts to reduce energy demand, no 1.5°C pathways have been identified**. In many parts of the world, limiting warming to 1.5°C can be achieved synergistically with poverty alleviation, improved energy security and public health. Some risk of trade-offs exist, however. For example, increased biomass production and its use has the potential to increase pressure on land and water resources, food production, biodiversity, and to reduce air-quality improvements. The risk of trade-offs is smaller and more easily avoided in a world where policies focus on sustainable development. The transition to net zero or negative CO_2 emissions within the energy sector is also less expensive in a sustainability-focused world. *(medium confidence)* {2.5.2, 2.5.3}

Recent years have seen substantial progress in coordinating scenario development and Integrated Assessment Modelling (IAM). This has resulted in a better characterization of the influence of various factors on the transition to climate stabilisation. Nevertheless, major limitations of integrated mitigation studies remain with respect to climate damages and avoided impacts, for example. Societal co-benefits of the modelled transformations also remain largely unaccounted for, while rapid technological changes and uncertainties about input data present continuous challenges. *(high confidence)* {2.5.1, 2.6.4}

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 compatible 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 1.3), this chapter focuses on geophysical, technological, and economic dimensions, with social and institutional dimensions covered in Chapter 4.

Mitigation scenarios are typically designed to reach a target defined by climate impacts alone. Economic optimization, considering mitigation expenditures and their influence on gross domestic product (GDP) but not climate-related damages, defines these least-cost pathways to the desired climate target (see Box 2.2 for additional discussion). However, there are co-impacts of mitigation on multiple other sustainable development goals (see Section 1.1 and Chapter 5) which 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 useful 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 (Clarke et al., 2014). This chapter thus presents both the pathways and an initial discussion of their context within sustainable development objectives (Section 2.5), with the latter analysed in more detail in Chapter 5.

As described in Chapter 1 (see Cross-Chapter Box 1.1), scenarios are comprehensive, plausible and integrated descriptions of possible futures based on specified underlying assumptions, with pathways often used to describe the clear temporal evolution of specific scenario aspects. For example, often the emissions pathway in line with a given scenario is referred to, and we follow these usages here.

2.1.1 *Mitigation Pathways compatible 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, and institutions are all required to generate scenarios. 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.

Plausible developments need to be anticipated in many facets of the key sectors of energy and land use. Within energy, these consider energy resources (e.g., 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 discussed incorporate regional differentiation in sectoral and policy development. Discussion of these assumptions within recently developed 1.5°C scenarios is given in Section 2.3.2. 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 (see Sections 2.2 and 2.6).

Emission pathways such as those based on current legislation or the pledges incorporated into current national contributions (INDCs and NDCs) likely exceed the 1.5°C peak carbon budget before 2030 (UN Environment, 2017); see also Section 2.3), hence we examine strengthened mitigation pathways consistent with 1.5°C (pathways that remain below the 1.5°C limit or return to it after temporarily exceeding it; see Section 1.2.4). For this chapter we will use the term “integrated pathways” to refer to those developed with process based integrated assessment modelling covering all sectors and regions over the 21st century. Those integrated pathways can be directly linked to climate outcomes and their consistency with the 1.5°C goal evaluated. Pathways generated from individual sectorial or regional modelling frameworks are assessed in relation to integrated 1.5°C pathways as they cannot be direct linked to 1.5°C by themselves. Mitigation scenarios are compared with reference cases as a way to measure the potential policy impact in multiple dimensions (e.g., emissions change, climate response, mitigation costs, etc.).

The temperature response to a given emission pathway is uncertain and therefore quantified in terms of a probabilistic outcome. Hence a scenario that is consistent with 1.5°C may still miss that target (in either direction, see Section 1.2.4.4). Natural variations such as volcanic eruptions or solar output changes could also affect trajectories. Here, however, we only evaluate the anthropogenic component of future temperature change, starting from Chapter 1's estimate of the anthropogenic component of historical warming through 2015 of . Additionally, this means consistency with a target temperature must be defined probabilistically, with threshold values selected based on risk avoidance preferences. Stabilization scenarios limit peak warming below a threshold with a maximum allowed exceedance probability. Overshoot scenarios temporarily exceed the threshold (with more than some low probability p) and return below afterwards (with higher than some probability 1–p). Various lengths of overshoot are possible (e.g., measured in terms of expected degree years). Timing of initially reaching a warming likely above 1.5°C and of returning to a level likely below 1.5°C can be evaluated, for example, as the time when exceedance probability passes 50% or 90%, or when it drops below 33%. The date at which these limits are passed can be a way to characterize overshoot scenarios (incorporating duration). As in Chapter 1, continued warming scenarios that exceed 1.5°C are not considered consistent with 1.5°C.

The global mean temperature response to the various scenarios explored here is assessed via use of simple geophysically-based models that do not incorporate internal variability and exclude future natural variations as these cannot be reliably projected (see Sections 2.2.1 and 2.6). Impacts beyond global mean temperature are not typically evaluated in such models and are assessed in Chapter 3.

2.1.2 *The Use of Scenarios to Answer Particular Questions*

Variations in scenario assumptions and design define to a large degree which questions can be addressed, for example, the exploration of implications of delayed climate mitigation action. In this assessment, we have identified the following classes of scenarios which are of particular interest to the topics addressed in this chapter: (a) scenarios with the same target in 2100 but varying socio-economic assumptions; (b) pairs of scenarios with similar socio-economic assumptions but with forcing targets aimed at 1.5°C and 2°C; (c) scenarios that follow the INDCs/NDCs until 2030with much more stringent mitigation action thereafter.

Mitigation scenarios generated with IAMs and related models 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). Characteristics of these scenarios 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 being "required" for 1.5°C, unless a targeted scenario analysis is available that specifically asked whether there could be pathways without the characteristics in question. Such targeted analyses have become available since AR5, for example asking when pathways have to obtain a peak in emissions to still limit warming below 2°C, or which technologies are important to keep the 2°C target within reach. In this assessment, we will distinguish between consistent and the much stronger concept of required characteristics of 1.5°C pathways wherever possible.

Ultimately, it is unrealistic that any pathway developed today will be exactly followed until the end of the century. 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 (Clarke et al., 2014; Luderer et al., 2013; Rogelj et al., 2013). Not knowing what adaptations might be put in place in the future, however, and due to limited studies, in this report we primarily examine prospective (fixed) rather than adaptive (e.g., greater emissions reductions under high climate sensitivity) pathways. Currently available scenarios may also be used to evaluate progress, and indeed this is part of the rationale for the Parties to the UNFCCC for requesting this Special Report, and as such the societal choices illustrated by these scenarios could influence what futures are envisioned as possible or desirable and hence whether those come into being (Beck and Mahoney, 2017).

2.1.3 *New scenario information since AR5*

In this chapter, we focus on an extension of 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 2.2.2 and 2.6.2.

This report relies on the integrated scenario literature for its pathway assessment, which the AR5 mainly discussed in Chapter 6 of Working Group III (Clarke et al., 2014). Since then, several new integrated multi-model studies have appeared in the literature that explore specific characteristics of scenarios markedly more stringent than the lowest scenario category assessed in AR5. Those scenarios explore 1.5°C pathways from multiple perspectives, 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; see Cross-Chapter Box 1.1)
- near term climate policies until 2020 and 2030 describing different levels of strengthening the NDCs
- the availability of technology options such as bioenergy and carbon dioxide removal technologies

A large number of these scenarios were collected in a scenario database established for the assessment of this Special Report. Scenarios were classified by three factors: threshold value, non-overshoot or overshoot, and likelihood. Specifically, they were put into groups that either kept surface temperatures below a given threshold (according to the definitions of Chapter1 and Section 2.1.1) throughout the 21st century (Below 1.5°C and Below 2°C) or returned the value below 1.5°C by 2100 after overshoot (Return 1.5°C). ‘Below’ and ‘Return’ groups were further separated based on the probability of being below the threshold (Table 2.1). Scenarios are uniquely classified, with ‘Return 1.5°C’ given higher priority than ‘Below 2°C’ in cases where a scenario would be applicable to either class. No scenarios were available that remained below the 1.5°C limit with at least 66% probability or remained below the 2°C limit with at least 90% probability.
These scenarios draw largely from a set of integrated scenarios exercises with multiple modelling teams – the lowest category of scenarios in the framework of the SSPs (see Cross-Chapter Box 1.1 and (Rogelj et al., 2017b) and scenarios developed within the framework of the ADVANCE project (Luderer et al., 2016b), the CD-LINKS project (Roelfsema et al., 2017) and the EMF33 project (Bauer et al., 2017b)– combined with individual scenarios from single model studies, like the International Energy Agency (IEA) Perspectives for the Energy Transition (IEA / IRENA, 2017) (see Table 2.2). Results from non-IAM and single sector (e.g., 100% renewable electricity) studies are discussed further in Sections 2.3 and 2.4.

The scenario ensemble collected as part of the IPCC SR1.5 process represents an ensemble of opportunity. The submitted scenarios cover a wide range of scenario types and thus allow exploration of a wide range of questions. For this to be possible, however, critical scenario selection based on scenario assumptions and setup is required.

Scenario Class	***Likelihood ranges: number of scenarios***
Below 1.5°C 66%	*66–90%: 0*
Below 1.5°C 50%	*50–66%: 10*
Return 1.5°C 66%	*66–90%: 68*
Return 1.5°C 50%	*50–66%: 40*
Below 2°C 66%	*66–90%: 98*
Below 2°C 50%	*50–66%: 68*

Values of exactly 66% are included in the 66–90% category.

Table 2.1: Classification of scenarios this chapter draws upon

Study/model name	**Key focus**	**Reference papers**
Multi-model studies		
SSPx-1.9	Development of new community scenarios based on the full SSP framework limiting end-of-century radiative forcing to 1.9 W m^{-2}.	Riahi et al. 2017; Rogelj et al. 2017a
ADVANCE	Aggregate effect of the INDCs, comparison to optimal 2°C/1.5°C scenarios ratcheting up after 2020.	Vrontisi et al. 2017a
	Decarbonisation bottlenecks and the effects of following the INDCs until 2030 as opposed to ratcheting up to optimal ambition levels after 2020 in terms of additional emissions locked in.	Luderer et al. 2017c
CD-LINKS	Exploring interactions between climate and sustainable development policies with the aim to identify robust integral policy packages to achieve all objectives.	Krey et al. 2017
	Evaluating implications of short term policies on the mid-century transition in 1.5°C pathways linking the national to the global scale.	Roelfsema et al. 2017a; Kriegler et al. 2017e
EMF-30	Study of the contribution of short-lived climate forcers in deep mitigation scenarios.	Harmsen et al. 2017
EMF-33	Study of the bioenergy contribution in deep mitigation scenarios.	Bauer et al. 2017b
Single-model studies		
IMAGE 1.5	Understanding the dependency of 1.5°C pathways on negative emissions, and exploring whether they are essential.	van Vuuren et al. 2017d
IIASA LED (MESSAGEix)	A global scenario of Low Energy Demand (LED) for Sustainable Development below 1.5°C without Negative Emission Technologies.	Grubler et al. 2017
GENeSYS-MOD	Application of the Open-Source Energy Modelling System to the question of 1.5°C and 2°C pathways.	Löffler et al., 2017
TIAM-Grantham	The role of advanced technologies and energy demand reduction in achieving ambitious carbon budgets.	Napp et al., 2017
IEA WEO	World Energy Outlook.	OECD/IEA and IRENA, 2017a
OECD/IEA ETP	Energy Technology Perspectives.	IEA, 2017a
PIK CEMICS (REMIND)	Study of CDR requirements and portfolios in 1.5°C pathways.	Strefler et al., 2017
PIK PEP (REMIND-MAgPIE)	Exploring short-term policies as entry points to global 1.5°C pathways.	Kriegler et al., 2017d
PIK SD (REMIND-MAgPIE)	Targeted policies to compensate risk to sustainable development in 1.5°C scenarios.	Bertram et al., 2017
AIM	Socio-economic factors and future challenges of the goal of limiting the increase in global average temperature to 1.5°C.	Liu et al., 2017
C-Roads	Interactions between emissions reductions and carbon dioxide removal.	Holz et al., 2017
MERGE-ETL	The role of Direct Air Capture and Storage (DACS) in 1.5°C pathways.	Marcucci et al., 2017

Table 2.2: Recent studies this chapter draws upon and their key foci indicating which questions can be explored by the scenarios of each study

2.2 Geophysical relationships and constraints

2.2.1 *Linking geophysical characteristics to mitigation pathways*

Emissions pathways can be characterised by various geophysical relationships such as radiative forcing (Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; van Vuuren et al., 2011b), atmospheric concentrations (Clarke et al., 2014; van Vuuren et al., 2011a; Van Vuuren et al., 2007) and associated temperature outcomes (Luderer et al., 2013; Meinshausen et al., 2009; Rogelj et al., 2011). These latter can be used to derive the cumulative CO_2 emissions until a given warming threshold also known as carbon budgets (Meinshausen et al. 2009; Friedlingstein et al. 2014; Rogelj et al. 2016) which is a useful geophysical constraints to characterise mitigation pathways compatible with 1.5°C or 2°C. Other geophysical relationships linking the short-lived climate forcers (i.e., non-CO_2 greenhouse gases and aerosols such as methane and black carbon) to the remaining carbon budget (Bowerman et al. 2011; Rogelj et al. 2014, 2015b, 2016; Shindell et al. 2012a) or to the temperature outcomes (Bowerman et al., 2013; Lamarque et al., 2011) are also assessed in this section. In the following, we use the working definition of Chapter 1 for carbon emissions and global warming which relate to those attributed to human activities.

The geophysical scenario characteristics used in this chapter are derived from simulations using a reduced complexity carbon-cycle, atmospheric composition and climate model (MAGICC) (Meinshausen et al., 2011b). For each mitigation pathway, MAGICC simulations provide a probabilistic estimate of atmospheric concentrations, radiative forcing and global temperature outcomes across the century. For the purpose of this report, and to facilitate comparison with previous scenarios assessment performed in AR5, the range of the key climate parameters for MAGICC are identical to those used in AR5 Working Group III (WGIII) (Clarke et al., 2014). MAGICC and its sensitivity to key parameters are assessed in Section 2.6. The assessed likely range of response (18–83%) is taken as the 5–95% range from the MAGICC model as the MAGICC setup underestimates some uncertainties, see Section 2.6.2 for further details.

2.2.2 *The 1.5°C and 2°C carbon budget*

2.2.2.1 *Carbon budget computations*

Since the AR5, several approaches have been proposed to estimate carbon budgets compatible with 1.5°C or 2°C. Most of those approaches indirectly rely on the approximate linear relationship between peak temperature and cumulative emissions of carbon (the transient climate response to cumulative emission, (TCRE, Collins et al. 2013; Friedlingstein et al. 2014; Rogelj et al. 2016), see Chapter 1), whereas others based their estimates on equilibrium climate sensitivity (e.g., Schneider et al. 2017a). As shown in Figure 2.1, carbon budgets depend on the budget definition that is used, for example, the emissions when the global mean temperature reaches, exceeds, avoids, or peaks at a given warming level with a given probability.

Two approaches were employed in AR5 to determine carbon budgets. Working Group I (WGI) reported Threshold Exceedance Budgets (TEB, Figure 2.1a) that correspond to the amount of cumulative CO_2 emissions at the time a specific temperature threshold is exceeded with a given probability in a particular multi-gas and aerosol emission scenario. Working Group III (WGIII) used Threshold Avoidance Budgets (TAB, Figure 2.1b) that correspond to the cumulative CO_2 emissions over a given time period of a subset of multi-gas and aerosol emission scenarios in which global mean temperature stays below a specific temperature threshold with a given probability. The TEB and TAB budgets and their limitations and assessed below for comparison with AR5. However, we focus our assessment on two alternative computations of the carbon budget that are more suitable to the context of this report. The Threshold Peak Budget (TPB, Figure 2.1c) and the Threshold Return Budget (TRB, Figure 2.1d) that are estimated from the amount of cumulative CO_2 emissions over a given time period of a multi-gas and aerosols emission scenario until the time that the global mean temperature peaks or returns after a temperature overshoot, respectively, to a given warming threshold with a given probability (Herrington and Zickfeld, 2014; MacDougall et al., 2015; Matthews et al., 2017). TPBs are conceptually close to TEBs, while TRBs display different features, especially for 1.5°C limits, due to the presence of net carbon dioxide removal and the path-dependency of the climate system's and carbon cycle's response to declining emissions (Gasser et al.; Jones et al., 2016; Séférian et al., 2017;

Zickfeld et al., 2016) (see Section 2.6). In a situation where the pathways do not involve the reversibility of the climate system, which is the case for non-overshooting scenarios, the TRB and TPB are identical.

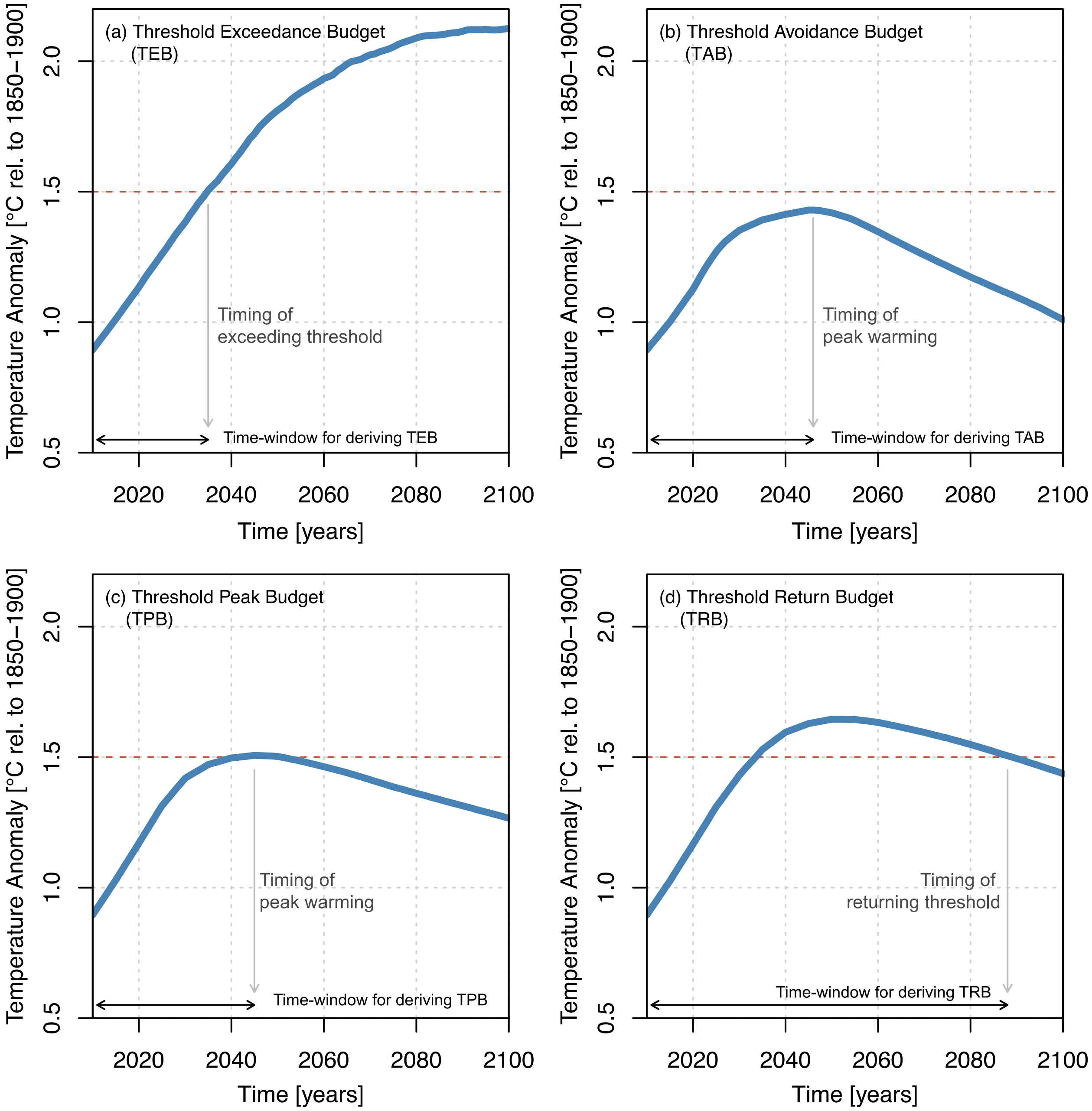


Figure 2.1: Definition of various carbon budgets relative to 2016 as function of the median temperature (relative to 1850–1900) as a function of threshold peak carbon budgets (TPB, relative to 2016). Threshold exceedance budget (a), avoidance budget (b), Threshold peak budget (c) and Threshold return budget are defined by the temperature outcomes exceeds, avoids, peaks or returns below a warming threshold. In this conceptual figure, the warming threshold is 1.5°C and is indicated by a red dashed line. The vertical grey arrow indicates the timing at which the median temperature exceeds, avoids, peaks or returns the 1.5°C warming threshold pending on the carbon budget definition. The horizontal arrows indicated the time span during which cumulative CO_2 emissions are computed to estimate the carbon budget compatible with 1.5°C.

Budget type	**AR5**			**This report**		
	Notes	1.5°C GtCO$_2$	2°C GtCO$_2$	Notes	1.5°C	2°C
TEB (WGI)	From 2011 relative to 1861–1880; non-CO$_2$ GHG and aerosols as in RCP8.5	2250	2900; 3700 CO$_2$only budget	From 2011 based on scenario database pathways	810 (670–970)	1530 (1320–1900)
TAB (WGIII)	Either from 2011–2050 or from 2011–2100	90–310for the 2011–2100 period (> 50% likelihood limited studies)	150–1300 for the 2011–2050 period 630–1180 for the 2011–2100 period	From 2011 based on scenario database pathways	NA	1130 (790–1500)

Table 2.3: Median and assessed likely range (the 5–95% MAGICC range) of for different types of TEB and TAB carbon budgets compared to AR5. Quoted budget is compatible with 1.5°C or 2°C for the 66th quantile of the global mean temperature unless otherwise specified. Budgets are quoted in GtCO$_2$. NA: not available

When comparing to AR5 an important consideration stems from the fact that AR5 TEB and TAB were derived for different time periods and employed a different subset of multi-gas and aerosol emission scenarios as indicated in Table 2.3. WGI computed TEBs from 2011 onwards for 1.5°C and 2°C relative to the 1861–1880 period using all available scenarios whereas WGIII estimated TABs from pathways that have a >50% probability to exceed 1.5°C by mid-century and returns to 1.5°C in 2100.

Another important consideration when comparing literature values arises from the fact that TEB and TAB can be derived from CO$_2$-only scenarios or 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; IPCC, 2013a). However, because non-CO$_2$ climate forcing is projected to be more positive in the future than that of CO$_2$ alone, CO$_2$-only carbon budgets overestimate the total net cumulative carbon emissions compatible with 1.5°C or 2°C (Friedlingstein et al., 2014a; Matthews et al., 2017; Mengis et al.; Rogelj et al., 2016b; Tokarska et al.). For a 66% likelihood to stay below 2°C relative to the 1861–1880 period, AR5 WGI estimated a CO$_2$-only carbon budget of 3700 GtCO$_2$. Over a similar period, the carbon budget compatible with 2°C is reduced by 800 GtCO$_2$ when accounting for all CO$_2$, non-CO$_2$ GHG and aerosols as in RCP8.5. Both CO$_2$-only and multi-forcer estimates of carbon budgets are informative to understand how both CO$_2$ and non-CO$_2$ greenhouse gases and aerosols affect the amounts of total net cumulative CO$_2$ emissions compatible with a given temperature limit over a given time period.

In order to hold warming below 1.5°C between 2016 and 2100 with a 66% likelihood, median TEB for 1.5°C estimated from 578 mitigation pathways is 590 GtCO$_2$ with a likely range of 450–750 GtCO$_2$ when accounting for warming induced by all multi-gas and aerosols climate forcers. For the same budget definition but for 2°C, 378 mitigation pathways exceed 2°C and lead to mean TEB of 1300 GtCO$_2$ with a likely range of 1090–1660 GtCO$_2$. TABs for 2°C estimated from 215 mitigation pathways are 900 (570–1270) GtCO$_2$. For 1.5°C, TABs that result in a 50% likelihood of avoiding to cross 1.5°C add up to 500 (440–700) GtCO$_2$ estimated from only 10 mitigation pathways. These values are larger than the initial estimates in AR5 but remain smaller than some published estimates, that is to say., 750–920 for the 33–66% percentile range of the CMIP5 models under RCP85 multi-gas and aerosol scenarios (Millar et al., 2017), 660–1060 for the 33–66% percentile range under RCP4.5 and RCP8.5 multi-gas and aerosol scenarios (Tokarska et al.) or 750–800 for the 33–66% percentile range of the CMIP5 simulations when constrained with available observations (Goodwin et al., 2017). The differences between the various estimates for carbon budgets compatible with 1.5°C or 2°C arise from a suite of methodological approaches and physical uncertainties that are assessed in the following Section 2.2.2.2.

Budget type	**Threshold Return Budgets**		**Threshold Peak Budgets**	
Abbreviation	**TRB**		**TPB**	
Climate forcers	CO_2-only	Multi-gas and aerosols	CO_2-only	Multi-gas and aerosols
Compatible with 1.5°C				
50th quantile of temperature	920 (550–1350)	590 (420–880)	1390 (1290–1470)	580 (490–640)
66th quantile of temperature	790 (520–980)	390 (200–730)	1000 (960–1080)	NA
90th quantile of temperature	260 (140–570)	190 (170–210)	500 (360–700)	NA
Compatible with 2°C				
50th quantile of temperature	960 (550–1530)	960 (570–1460)	2760 (2650–2810)	1450 (1330–1550)
66th quantile of temperature	920 (520–1480)	910 (570–1210)	2150 (2020–2250)	1180 (1050–1380)
90th quantile of temperature	710 (450–950)	560 (280–800)	960 (860–1030)	660 (590–800)

Table 2.4: Median and assessed likely range(the 5–95% MAGICC range) of Threshold Return Budget (TRB) and Threshold Peak Budget (TPB) compatible with 1.5°C or 2°C for a given probability. All carbon budgets are derived from all mitigation pathways available in the SR15 database and (median) 50th, 66th and the 90th percentile temperature outcomes from MAGICC from the 1st January 2016 onwards. The assessed likely range is indicated in brackets for each carbon budget. TRBs have medium confidence and TPBs have high confidence. NA: not available.

Precise comparison of TRBs and TPBs is complicated due to their different definitions. For example, TRBs and TPBs are not determined over the same time period. For a 1.5°C warming threshold, TPBs estimates are determined at time points that range between 2035 and 2060, whereas TRBs are derived from time points ranging between 2035 and 2100. Furthermore, because of their definition, their ranges are not determined by neither the same nor the same number of mitigation pathways. For a warming threshold of 1.5°C with a likelihood of 50%, TPBs are determined from an ensemble of 40 mitigation pathways whereas TRBs are determined from 118. This difference in mitigation pathways used for estimating carbon budgets remains large for a warming threshold of 2°C for which TRBs are derived from 273 scenarios where only 27 are used for estimating TPBs. Such differences ultimately complicate the assessment of those carbon budgets. It is however, possible to map key characteristics of those carbon budgets. For example, TRBs are generally smaller than TPB for the same level of warming with a given likelihood because the inertia of the Earth system conducts the temperature to return below 1.5°C or 2°C when net CO_2 emissions are negative. Besides, they exhibit the same behaviour in response of various warming threshold; that is TPBs and TRBs are about 20% smaller for 1.5°C than for 2°C. However, because of the assessed limitations of the simple climate model setup used in this chapter and in light of the recent literature we have medium confidence that the remaining carbon budgets presented in this section will be revised downward rather than upward in the future (Section 2.6.2).

2.2.2.2 *Remaining carbon budget and related uncertainties*

2.2.2.2.1 Methodological choices

Besides definitional choices (Section 2.2.2.1), large differences in remaining carbon budgets arise from methodological choices. In the literature, some studies (Friedlingstein et al., 2014a; Gasser et al.; IPCC, 2014; MacDougall et al., 2015; Peters et al., 2015; Rogelj et al., 2016b; Séférian et al., 2017) compute a total emission budget, that is a how much CO_2 could be emitted since preindustrial times, and then subtract historical cumulative emissions of $CO_2$from this total budget to obtain the remaining budget. The approach adopted within this report is to express carbon budgets relative to a specified year in the near past, such as 2013, 2014 or 2015 (Friedlingstein et al., 2014a; IPCC, 2014; Millar et al., 2017; Rogelj et al., 2016b; van Vuuren et al., 2016). Such approaches have the advantage of removing the effects of any possible accumulated biases in diagnosed emissions from Earth system models over the historical period (Richardson et al., 2016), but rely on the accuracy of estimated present levels of warming to provide accurate assessments of the remaining carbon budget for any given level of warming above pre-industrial levels.

This assessment employs historical net cumulative emissions reported by the Global Carbon Project (Le Quéré et al. 2017). They report 2200±240 $GtCO_2$ were emitted between 1870 and 2016 of which 1540±70 $GtCO_2$ is attributed to fossil fuel combustion and cement production, and 660±220 $GtCO_2$ is related to land-use and land-cover changes. The uncertainty in historical cumulative CO_2 emissions is of the same order of magnitude as the remaining budget compatible with meeting the 1.5°C target with a 66% likelihood; 10% of the uncertainty comes from our knowledge of past CO_2 emissions whereas 90% do from CO_2 emissions induced by past land-use and land-cover changes. Estimated CO2 emissions in 2017 should reduce remaining carbon budget compatible with 1.5°C or 2°C by 40±4 $GtCO_2$ (Le Quéré et al. 2017).

Remaining budgets can also be given for different thresholds of warming above a present-day average (Millar et al., 2017; Tokarska and Gillett), but any uncertainty in present-day warming is propagated into the uncertainty over the magnitude of future warming that would be compatible with a given warming threshold relative to the preindustrial period. Such a difference of 0.1°C in global temperature change translates into a difference of ~230 $GtCO_2$ on the remaining emission budgets, under the assumption of an average TCRE of ~1.6°C per 3660 $GtCO_2$. Here, projections of global temperature by the MAGICC model are expressed relative to the year 2015, offset by 0.95°C (the average temperatures of the decade 2006–2015 relative to 1850–1900, based on the three global datasets assessed in AR5, adjusted to account for the AR5 central estimate of the background warming trend over the period 2011–2015). Newer datasets to be assessed in AR6 (Cowtan and Way, 2014; Rohde et al., 2013) that give more weight to poorly-observed regions such as the Arctic would increase this offset by approximately 0.1°C (see Section 1.2.1), corresponding to a reduction in remaining carbon budgets of 200 $GtCO_2$. Richardson et al. (2016) find that redefining GMST as global surface air temperature rather than the conventional blend of air temperature over land and water temperatures over oceans could add a further 0.1°C to pre-2015 warming.

2.2.2.2.2 Physical uncertainties

There are several key uncertainties that determine the remaining carbon budget. A first uncertainty lies in the estimates of the Transient Climate Response to Emissions (TCRE).

CO_2 CO_2

CO_2 (Matthews et al., 2017; Rogelj et al., 2016b) AR5 WGI provides an assessed likely range of the TCRE of 0.8 to 2.5°C per 3660 $GtCO_2$ for 66% likelihood (Collins et al., 2013). Although recent research using different approaches provides further constraints on TCRE (Gillett et al., 2013; MacDougall et al., 2017; Tachiiri et al., 2015), our assessment is based on a TCRE as used in MAGICC of 1.6°C per 3660 $GtCO_2$which is closed to the AR5 best estimate (Collins et al., 2013). In regards of the recent literature assessed in Section 2.6, we assign a medium confidence on the TCRE best estimate as used in MAGICC that could be revised downward or upward in the future (see Section 2.6.2).

Another source of uncertainty, also related to the TCRE, stems from how non-CO_2forcers are handled in the TCRE computation process(Collins et al., 2013; Gillett et al., 2013). While many estimates of the TCRE are derived from idealized runs with atmospheric CO_2 concentrations rising at 1% per year (Gillett et al., 2013; Joshi, 2016; Tachiiri et al., 2015), several other estimates of TCRE rely on the fact that the linear relationship approximately holds when using the ratio of total warming to cumulative carbon emissions in a multi-forcer context, and hence assumes a proportionality between the total warming and the non-CO_2 warming (Friedlingstein et al., 2014a; IPCC, 2013b). this proportionality can break down in stringent emissions mitigation pathways, making the TCRE less directly relevant (see Sections 2.2.2.3 and 2.6.2).

2.2.2.2.3 Reversibility and Earth system feedbacks

In a situation where the cumulative CO_2 emissions exceed the TPB consistent with 1.5°C, net Carbon Dioxide Removal (CDR, see Section 2.4) is used in order to remove CO_2 from the atmosphere and bring back the carbon budget to an amount of CO_2 compatible with a given warming target, that is to say., TRB compatible with 1.5°C. In most cases, CDR reduces atmospheric CO_2 concentrations more quickly than would naturally be the case, and the response of the natural system is not necessarily the same per unit removed CO_2 as it is per unit emitted CO_2 during the emission regime. Such an asymmetrical behaviour, also called hysteresis, makes the emission budgets path-dependent in case of temperature overshoot (Herrington and Zickfeld, 2014; Krasting et al., 2014; Zickfeld et al., 2012; Zickfeld and MacDougall, 2016). Asymmetry of the TCRE implies deviation in carbon budgets for a given temperature threshold after the temperature overshoot. The TRB accounts for such a deviation, making it a metric suitable for overshoot scenarios (Figure 2.1). Using the 50th quantile (median) of the temperature outcomes from MAGICC, the likely range for TRBs is estimated to590–880 $GtCO_2$ for 1.5°C and to 570–1460 $GtCO_2$ for 2°C (see Table 2.4). The likely ranges of TRBs for both warming threshold overlap between each other and cannot be easily distinguished, which is not the case for TPBs likely range for the same level of likelihood. However, the TRB estimates and their differences from TPBs need to be viewed with caution as the MAGICC model used here only includes a simplified representation of the carbon cycle and climate and might not fully capture the asymmetrical behaviour of carbon cycle response to negative emissions (see Section 2.6.3). It also is important to stress that several Earth system feedbacks beyond the carbon cycle response impact the carbon budget compatible with 1.5°C and 2°C (See Section 2.6.2). Generally, they remain difficult to assess in regards of the current literature and their impacts would be limited although uncertain in the context of low warming threshold.

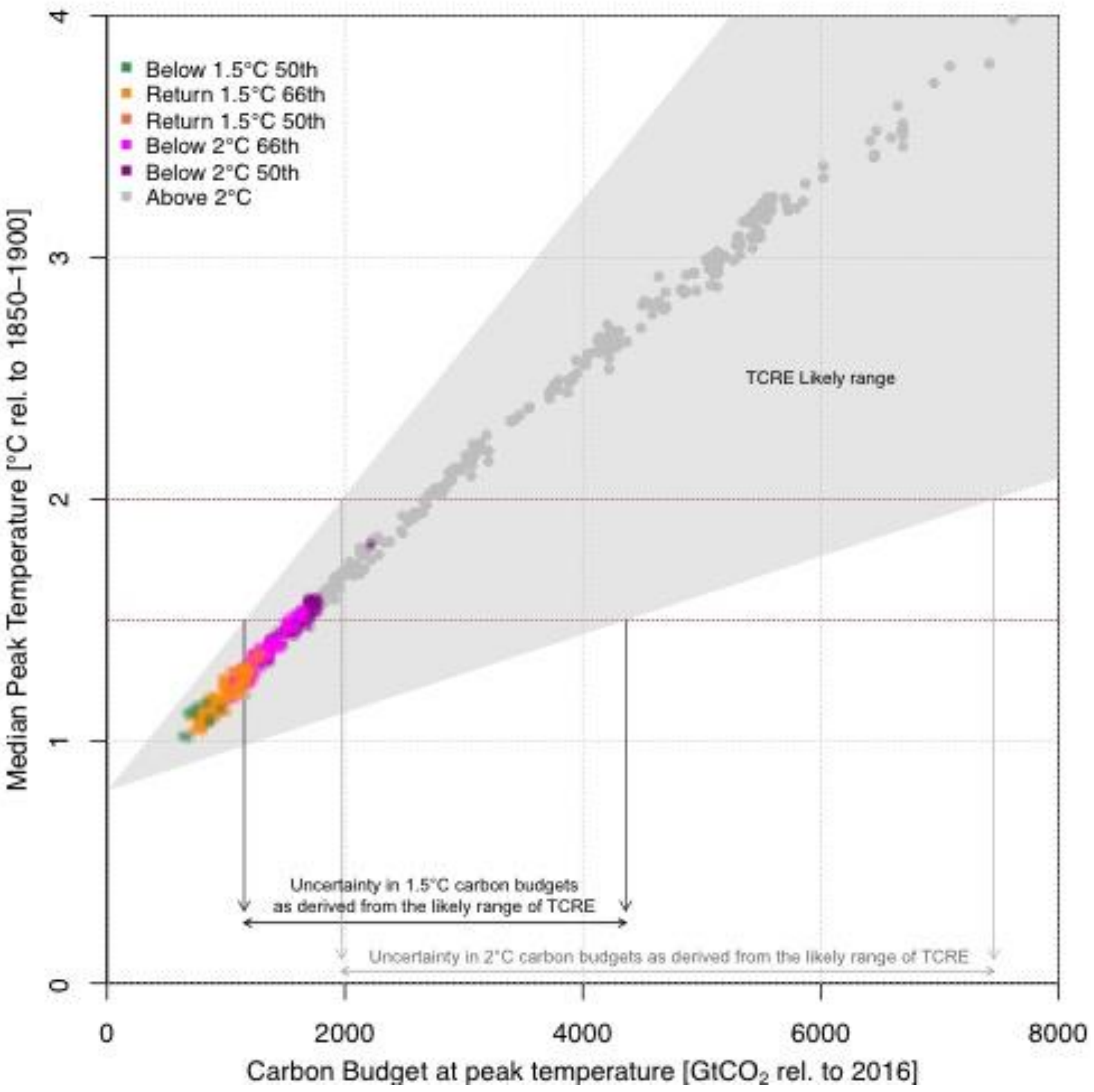


Figure 2.2: Peak temperature due to CO_2 (relative to 1850–1900) as a function of cumulative CO_2 emissions (relative to 2016). The grey shaded area represents the range of values derived from the assessed TCRE range as reported in Collins et al. (2013). Black and grey arrows are indicative of the likely range of carbon budgets as derived from the likely range of TCRE for 1.5°C and 2°C, respectively.

2.2.2.3 *Role of non-CO_2 GHGs and aerosols*

Non-CO_2 climate forcers include both greenhouse gases and aerosols that affect radiative forcings (Myhre et al., 2013; Stohl et al., 2015) and temperature outcomes(Harmsen et al., 2017; Rogelj et al., 2011, 2014b, 2015b; Shindell et al., 2012; Weyant et al., 2006). Most studies including non-CO_2 greenhouse gases and aerosols partition non-CO_2 forcers into two groups by their lifetime: methane, non-methane ozone precursors and aerosols are defined as short-lived climate forcers (SLCF) due to their lifetime of less than one to about 12 years in the atmosphere, while CO_2 and non-CO_2 long-lived climate forcers such as nitrous oxide, sulphur hexafluoride and other halogenated carbon gases contribute to forcing over decades and centuries. Non-CO_2 greenhouse gases and aerosols, or their precursors, are emitted by natural sources (e.g., wetlands, inland waters, forests) (Borges et al., 2015; Saunois et al., 2016; Tsigaridis et al., 2006) and human activities (e.g., industry, agriculture) (Bodirsky et al., 2012; Bond et al., 2013; Liousse et al., 2010; Rigby et al., 2010). Mitigation pathways assessed in this report rely on near-present estimates of non-CO_2 emissions as their starting point. For example, they use 2010 levels of emissions for methane (CH_4) and nitrous oxide (N_2O) ranging between 320–400 $MtCH_4\ y^{-1}$ and 7–11 $MtN_2O\ y^{-1}$, respectively. Compared to CO_2, emissions of non-CO_2 greenhouse gases and aerosols are still poorly constrained (Boucher et al., 2013; Ciais et al., 2013).

Impacts of non-CO_2 climate forcers on temperature outcomes are particularly important when evaluating stringent mitigation pathways (Harmsen et al., 2017; Rogelj et al., 2011, 2014b, 2015b; Shindell et al., 2012; Weyant et al., 2006). Because most of the non-CO_2climate forcers have radiative efficiencies much stronger than CO_2 (Myhre et al. 2013b) and many are short-lived, changes in their emissions could contribute substantially to the rate of global warming by mid-century (Chapter 1, Cross-Chapter Box 1.1). Several studies suggest that non-CO_2climate forcers could cause the global mean temperature to exceed 1.5°C by mid-century (Gambhir et al., 2017; Rogelj et al., 2014b; Stohl et al., 2015). In those studies, non-CO_2 warming is largely the result of the removal of scattering-aerosol precursor emissions, which acts to reduce their present-day aerosol cooling effect. Moreover, any increase in emissions of absorbing aerosols and greenhouse gases cause temperatures to rise. Even if non-CO_2 long-lived greenhouse gas emissions stay at the same level their concentrations and warming effect will increase. Stohl et al. (2015) estimated that a warming of 0.25°C in 2050 could be attributed to methane emissions alone in absence of mitigation. As shown in Figure 2.3a, a mean warming of about 0.5°C in 2050 can be attributed to non-CO_2 forcers, contributing to the temperature overshoots exhibited by most scenarios within the most stringent mitigation pathways of the current scenario database.

In a situation where non-CO_2 greenhouse gases and aerosols are co-emitted with CO_2 (e.g., with coal-fired power plants as detailed in Shindell and Faluvegi (2009) or within the transport sector as assessed in Fuglestvedt et al. (2010)) many CO_2-targeted mitigation measures in industry, transport and agriculture (see Section 2.3 and Section 2.4) also reduce non-CO_2 forcing magnitude (high confidence) (Rogelj et al., 2014b; Shindell et al., 2016). Among the non-CO_2 emissions reductions, there is high confidence that mitigation measures for non-CO_2 warming agents, including methane, nitrous oxide, and hydrofluorocarbon emission reductions, along with many black carbon measures, would help to limit warming to 1.5°C or 2°C by 2100 (Bowerman et al. 2011; Rogelj et al. 2014a, 2015c, 2016b;Ramanathan and Xu 2010; Shindell et al. 2012). However, reduction 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 (medium confidence), leading to warming (Myhre et al., 2013; Samset and Myhre, 2017). Emissions and radiative forcing for non-CO_2climate forcers are typically more uncertain and have greater geographical variation than CO_2 (Myhre et al. 2013; Aamaas et al. 2017). 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 impacts, especially those related to precipitation, depend significantly on forcing mechanism (Myhre et al., 2013; Samset et al., 2016; Shindell et al., 2015) (see Chapter 3, Section 3.6.2.2).

Because of the impacts of SLCF on temperatures outcomes (Etminan et al., 2016; Myhre et al., 2013; Stohl et al., 2015), most of the mitigation pathways compatible with 1.5°C or 2°C reduce SLCF such as CH_4 and black carbon as much as possible although not necessarily immediately. With a 50% likelihood to stay below 1.5°C or 2°C, most of the mitigation pathways lead to reductions in CH_4 of about 40% and of black carbon by about 60% in 2100 relative to 2030. Anthropogenic emissions of long-lived non-CO_2climate forcers such as N_2O, sulphur hexafluoride and other halogenated carbon gases are reduced less, by ~20% in 2100 relative to 2030 (see Section 2.3). Temperatures pass 2°C in nearly all scenarios in which non-CO_2 warming continues to grow, and there is a high risk that temperatures will pass 1.5°C even with the most stringent CO_2 mitigation considered in 1.5°C scenarios if non-CO_2 warming agents are not strongly reduced (medium confidence; see also Section 2.3.1.2.2).

Due to their impacts on temperature outcomes, future societal variations associated with non-CO_2 mitigation options will influence carbon budgets compatible with 1.5°C or 2°C and hence constrain the remaining amount of allowable CO_2 emissions to limit warming below these warming thresholds. The assessment of the available mitigation pathways indicates that the influence of non-CO_2 forcers on global mean temperature reduces both TRBs and TPBs by ~1540 $GtCO_2$ per degree of additional warming attributed to non-CO_2 climate forcers (the 1.5°C compatible pathways on Figure 2.3b). The assessed likely range of warming attributed to non-CO_2 climate forcers of 0.16–0.56°C leads to a range of median TRBs from 250 $GtCO_2$ up to 860 $GtCO_2$at the likely lowest or highest level of warming attributed to non-CO_2 climate forcers. It is thus very likely that societal variations associated with non-CO_2 mitigation options are the largest uncertainties for carbon budgets compatible with 1.5°C or 2°C (Figure 2.4). Scenarios with the least mitigation of non-CO_2 warming agents and/or strong reductions of cooling aerosol precursors (e.g., SO_2) give the strongest non-CO_2 warming. Scenarios with the strongest mitigation of non-CO_2 warming agents and/or little reductions of cooling aerosol precursors give the weakest non-CO_2 warming. In the 5% of scenarios with the strongest non-CO_2 warming, there is a likelihood of ~3% (medium confidence) that TPB is reduced to zero considering the assessed range of uncertainties (~25% likelihood for TRB). In contrast, this likelihood is close to 0% for TPB and 1% for TRB when the 5% of scenarios with the weakest non-CO_2 warming (medium confidence). Generally, the mitigation of non-CO_2 warming agents dominate over the reduced aerosol cooling. So (medium confidence).

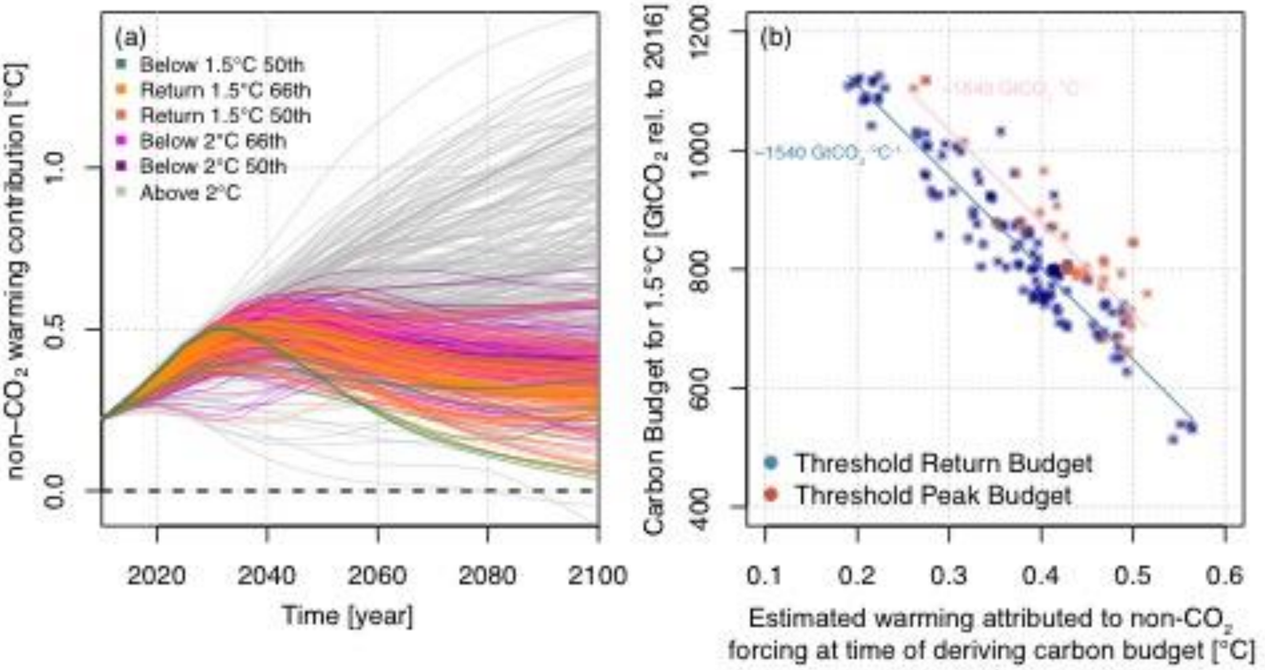


Figure 2.3: Role of non-CO_2 climate forcers in assessed pathways. (a) temporal evolution of the temperature contribution from non-CO_2 climate forcers and (b) variation in threshold return budgets (TRBs) and threshold peak budgets (TPBs) as a function of the temperature contribution from non-CO_2 forcing. In (b) numbers indicate the slope of TRBs and TPBs as function of temperature contribution from non-CO_2 forcing in $GtCO_2$ per °C of non-CO_2 warming. The non-CO_2 temperature contribution has been estimated with equation 8.SM.13 from Myhre et al. (2013).

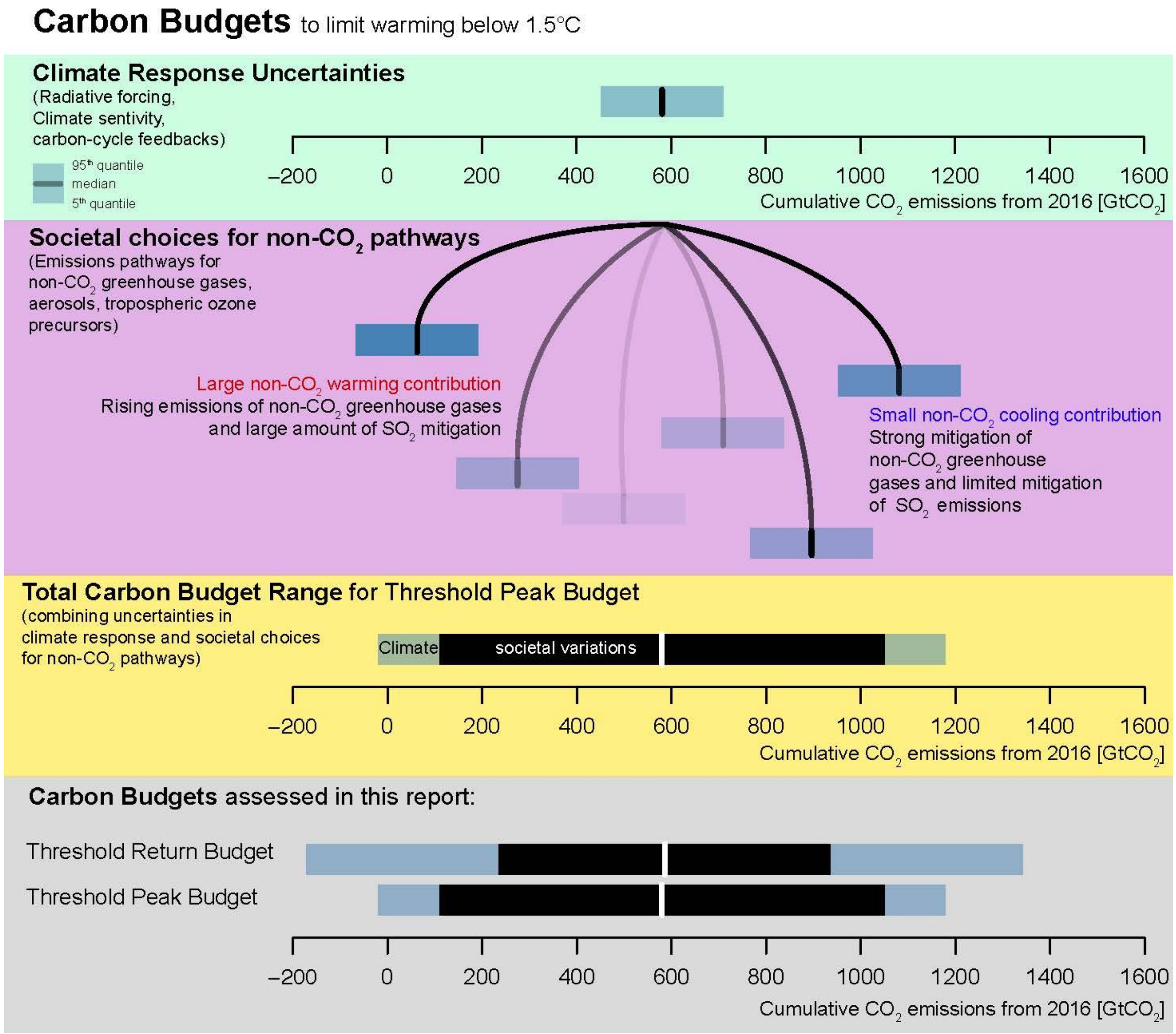


Figure 2.4: Summary of the various uncertainties affecting carbon budget size for holding warming below 1.5°C relative to preindustrial levels from the 1st January 2016 onwards. For Threshold Peak Budget best estimate of 580 $GtCO_2$ as given in Table 2.4, the climate response uncertainties associated to this budget are represented by the 5%-95% confidence interval inferred from outcomes due to variation of geophysical parameters in the simple climate model setup used for this assessment. Uncertainties in climate response includes those associated to radiative forcing, climate sensitivity, and carbon-cycle feedbacks. Societal choices impacting the carbon budget size are related to societal variations for non-CO_2 forcing which are illustrated by the full range of forcing futures found in the integrated pathways available in the SR1.5 Scenarios Database. A 'large non-CO_2 warming contribution' represents 0.85 W m-2 of non-CO_2 radiative forcing at the time of deriving the carbon budget, a 'small non- CO_2 cooling contribution' represents –0.02 W m-2 of non-CO_2 radiative forcing. The median non- CO_2 radiative forcing estimate across all available pathways is 0.45 W m-2 of non-CO_2 radiative forcing. The Total Carbon Budget Range provides an overview of the combined uncertainties in Threshold Peak Budget due to aforementioned factors. Median Threshold Peak Budgets and Threshold Return Budgets as given in Table 2.4 are indicated by the vertical bold white line in the bottom panel.

2.2.3 *Geophysical characteristics of mitigation pathways*

2.2.3.1 *Near-term to 2050*

Mitigation pathways assessed in this chapter contain fundamental structural differences that complicate their direct comparison. Those differences can be categorized by three key features as detailed in Section 2.1.3.

Even within the scenario typology (Table 2.1), there is a large degree of variance between emissions pathways. Still, mitigation pathways can be examined based on two key geophysical characteristics: the presence of a temperature overshoot and the timing of reaching net-zero CO_2 emissions. Those characteristics have been highlighted in several studies focusing on stringent mitigation pathways (Wigley et al. 2007; Huntingford and Lowe 2007; Zickfeld and Herrington 2015; Nohara et al. 2015; Schleussner et al. 2016; Rogelj et al. 2015d; Xu and Ramanathan 2017; Jacobson 2017; Clack et al. 2017; Holz et al.). In the ensemble of scenarios collected in the database for this report, only 10 out of 578 pathways hold warming below 1.5°C at a probability of at least 50% during the entire 21st century. Other 1.5°C consistent pathways all project to overshoot median temperature rise around mid-century before returning below that level in 2100. Also, net CO_2 emissions and radiative forcing are higher at the time of peak warming (at mid-century) than at the end of the century (Table 2.5). Both pathways holding warming below 1.5°C or returning below 1.5°C by 2100 reach carbon neutrality (or net-zero anthropogenic CO_2 emissions) before 2050 in most of those scenarios, and have the strongest rate of temperature decline after their peak (Figure 2.5). Both classes are also characterized by a strong reduction of the non-CO_2 warming contribution, which peaks around 2040 and then declines in virtually all available scenarios in the two 1.5°C classes (Figure 2.3a).

In contrast, mitigation pathways that limit warming below 2°C with 50% or 66% likelihood (see Table 2.1 for definitions) do not display similar features between 2016 and 2050. Although most of the <2°C pathways have overshoots and reach carbon neutrality at some point during the 21st century, most of those characteristics occur after 2050. The same goes for the types of mitigation pathways leading to higher warming threshold. The first group of pathways limiting warming below 1.5°C over the 21st century or by 2100 can thus be understood as early stringent mitigation action pathways, while the latter types of pathways include delayed mitigation actions pathways (see Section 2.3).

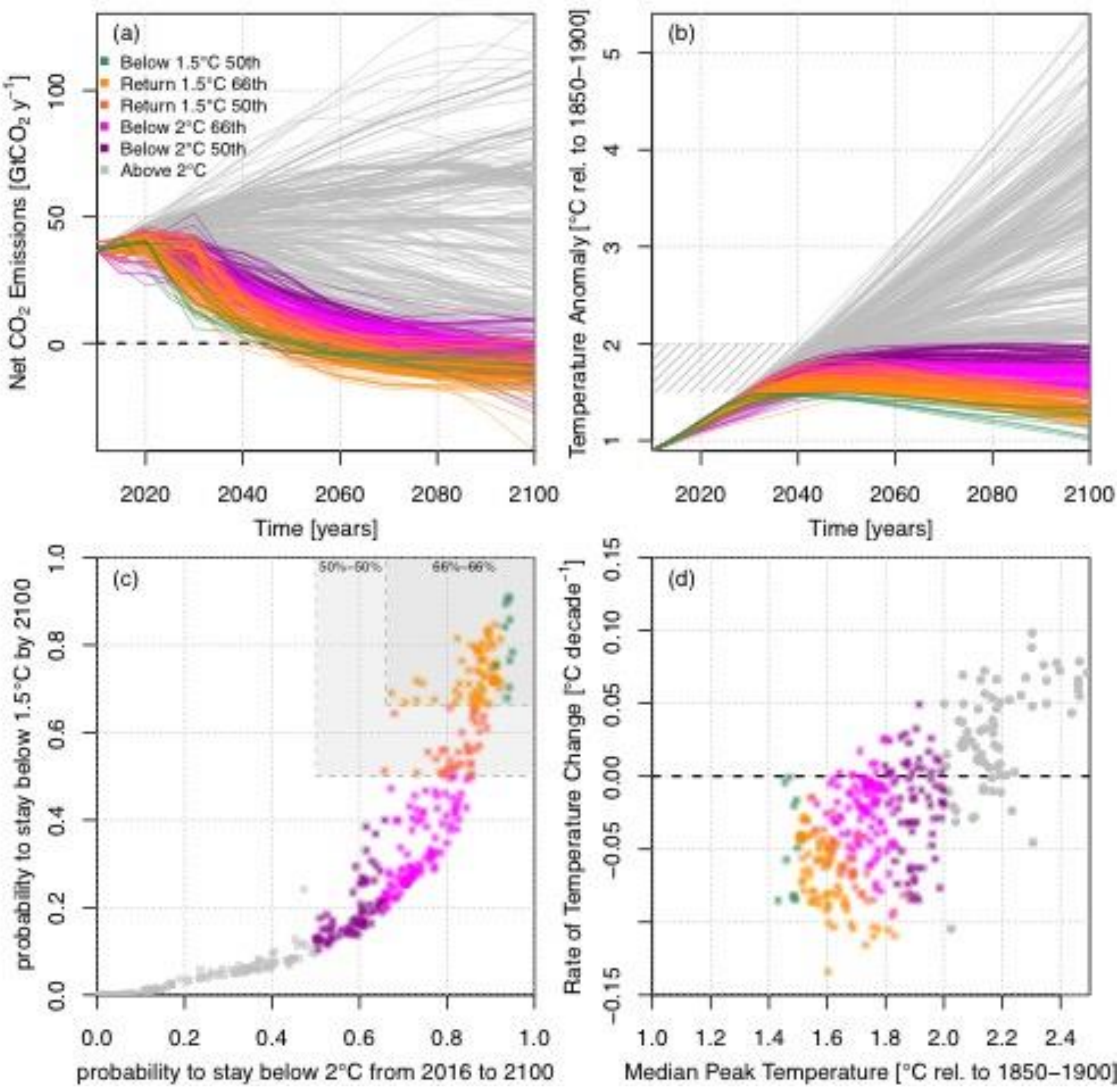


Figure 2.5: Pathways classification (typology) overview. (a) Net CO_2 emissions from 2000 to 2100, (b) 50th percentile global mean temperature increases relative to 1850–1900, (c) probability of holding warming below 2°C during the entire twenty-first century and below 1.5°C in 2100 (allowing for overshoot any time before 2100), and (d) the rate of median temperature change from 2081 to 2100 as a function of median peak temperature. In (c), grey shaded area indicated probabilities at 50–50% and 66–66% for the horizontal and vertical axis.

Mitigation pathways		Geophysical characteristics at peak temperature											Geophysical characteristics in 2100									Characteristics of mitigation pathways overshooting 1.5°C		
Category	Number of scenarios	Median warming	Year	CO$_2$ concentrations [ppm]	RF all [W m^{-2}]	RF CO$_2$[W m^{-2}]	RF non-CO$_2$[W m^{-2}]	Subm. Cumulative CO$_2$ emissions (2016 to peak)	Harm. Cumulative CO$_2$ emissions (2016 to peak)	Prob Exceed 1.5°C [%]	Prob Exceed 2.0°C [%]	Prob Exceed 2.5°C [%]	CO$_2$ concentrations [ppm]	RF all [W m^{-2}]	RF CO$_2$[W m^{-2}]	RF non-CO$_2$[W m^{-2}]	Subm. Cumulative CO$_2$ emissions (2016-2100)	Harm. Cumulative CO$_2$ emissions (2016 to 2100)	Prob Exceed 1.5°C [%]	2100 Prob Exceed 2.0°C [%]	Prob Exceed 2.5°C [%]	Overshoot Exceedance year	Overshoot Duration [years]|	Overshoot Severity [°Cyears]
Below 1.5°C 50%	10	1.48 (1.43 - 1.50)	2040 (2035 - 2050)	429 (418-441)	2.95 (2.69 - 3.02)	2.35 (2.19 - 2.50)	0.60 (0.35 - 0.64)	505 (407 - 742)	499 (438 - 735)	47 (41 - 50)	5 (3-8)	1 (0 - 1)	377 (37 - 399)	1.96 (1.56 - 2.40)	1.65 (1.58 - 1.94)	0.26 (-0.03 - 0.47)	208 (109 - 480)	177 (144 - 473)	19 (9 - 32)	3 (1 - 6)	1 (0 - 1)	NA	NA	NA
Return 1.5°C 66%	68	1.57 (1.51 - 1.83)	2050 (2040 - 2070)	434 (426-468)	3.00 (2.78 - 3.59)	2.41 (2.29 - 2.81)	0.59 (0.36 - 0.80)	673 (530 - 1058)	667 (525 - 1006)	61 (51-88)	11 (7 - 31)	1 (1 - 7)	384 (354-418)	2.06 (1.79 - 2.32)	1.74 (1.33 - 2.18)	0.35 (-0.01 - 0.69)	295 (-96 - 718)	281 (-85 - 755)	28 (15 - 34)	6 (2 - 9)	1 (0 - 2)	2034 (2030 - 2055)	30 (8 - 53)	2 (0 - 11)
Return 1.5°C 50%	40	1.65 (1.53 - 1.86)	2052 (2045 - 2065)	447 (426-466)	3.11 (2.82 - 3.58)	2.55 (2.30 - 2.79)	0.57 (0.31 - 0.87)	882 (516 - 1054)	893 (537 - 1063)	71 (54 - 89)	16 (9 - 34)	3 (1 - 8)	408 (369-427)	2.40 (2.18 - 2.55)	2.06 (1.55 - 2.29)	0.36 (0.07 - 0.78)	682 (-117 - 849)	672 (31 - 891)	45 (34 - 50)	12 (8 - 15)	3 (1 - 4)	2034 (2031 - 2049)	56 (20 - 67)	5 (0 - 14)
Below 2°C 66%	98	1.74 (1.56 - 1.84)	2065 (2045 - 2100)	454 (426-475)	3.14 (2.86 - 3.54)	2.63 (2.29 - 2.88)	0.51 (0.23 - 0.82)	1039 (543 - 1398)	1027 (649 - 1423)	78 (58 - 87)	27 (10 - 34)	7 (1 - 10)	433 (391-467)	2.83 (2.43 - 3.17)	2.37 (1.86 - 2.77)	0.45 (0.02 - 0.79)	954 (169 - 1423)	958 (351 - 1423)	70 (50 - 80)	24 (13 - 34)	8 (3 - 11)	2034 (2030 - 2049)	NA	NA
Below 2°C 50%	68	1.74 (1.56 - 1.84)	2065 (2045 - 2100)	454 (426-475)	3.14 (2.86 - 3.54)	2.63 (2.29 - 2.88)	0.51 (0.23 - 0.82)	1039 (543 - 1398)	1027 (649 - 1423)	78 (58 - 87)	27 (10 - 34)	7 (1 - 10)	433 (391-467)	2.83 (2.43 - 3.17)	2.37 (1.86 - 2.77)	0.45 (0.02 - 0.79)	954 (169 - 1423)	958 (351 - 1423)	70 (50 - 80)	24 (13 - 34)	8 (3 - 11)	2034 (2030 - 2049)	NA	NA
Above 2°C	290	1.90 (1.80 - 2.00)	2080 (2050 - 2100)	472 (437-512)	3.39 (3.06 - 3.64)	2.83 (2.43 - 3.28)	0.54 (0.11 - 0.92)	1286 (877 - 1957)	1351 (892 - 1995)	87 (78 - 93)	40 (31 - 50)	12 (7 - 18)	455 (401-512)	3.16 (2.59 - 3.42)	2.63 (1.98 - 3.28)	0.49 (0.11 - 0.93)	1158 (513 - 1957)	1262 (525 - 1995)	83 (60 - 90)	39 (17 - 49)	13 (6 - 18)	2032 (2030 - 2041)	NA	NA

Table 2.5: Geophysical characteristics of mitigation pathways derived at median peak temperature and at the end of the century (2100). Geophysical characteristics of overshoot for mitigation pathways exceeding 1.5°C is given in the last two columns. Overshoot severity is the sum of degree warming years exceeding 1.5°C over the 21st century. NA indicates that no mitigation pathways exhibits the given geophysical characteristics. Radiative forcing metrics are: total anthropogenic radiative forcing (RFall), CO$_2$ radiative forcing (RFCO$_2$), and non-CO$_2$ radiative forcing (RFnonCO$_2$). Cumulative CO2 emissions until peak warming or 2100 are given for submitted (Subm.) and harmonized (Harm.) IAM outputs.

2.2.3.2 *Post–2050*

After 2050, mitigation pathways lead to a wide range of geophysical characteristics (Table 2.5). The pathway classes as defined in Table 2.1 are also a relevant tool to assess the geophysical characteristics of mitigation pathways from 2050 to 2100.

With a 50% likelihood, 118 mitigation pathways out of 578 limit median temperature below 1.5°C and 167 to below 2°C by 2100. Our assessment of mitigation pathways under the range of physical climate uncertainties assessed in AR5 (such as TCRE, see Section 2.2.2.2) shows that the number of available mitigation pathways limiting warming below 1.5°C drop from ten to zero when moving toward a higher level of probabilities (i.e., 66% or 90% likelihood, see Table 2.5). With a likelihood between 50% and 66%, 40 mitigation pathways limiting warming below 1.5°C by the end of the century exceed 1.5°C around mid-century before returning below that level in 2100. We assign a low confidence to the temperature outcomes associated to those pathways since they are subject to Earth system feedbacks uncertainties that might affect carbon budgets (see Section 2.2.2.2), leading in turn to a higher level of warming by the end of the century. Pathways limiting warming below 1.5°C over the 21st century or by 2100 all reach net-zero CO_2 emissions in the period 2040–2065. Due to the inertia of the carbon cycle (Joos et al., 2013), most of these mitigation pathways display a peak in median temperature about 10 years before reaching carbon neutrality (Figure 2.6), due to an interplay of strongly reduced annual CO_2 emissions and declining short-lived forcers (see Section 2.3.1). Pathways limiting warming below 1.5°C lead to peak atmospheric CO_2 concentrations between ~420 and ~440 ppm; that is about 5 to 10% higher than the 2015 concentration (Le Quéré et al., 2017).

Substantial differences between 2°C and 1.5°C pathways arise from the timing at which mitigation pathways reach net-zero CO_2 emissions. All of the mitigation pathways holding warming below 2°C reach net-zero CO_2 emissions after 2060; some of which only reach net-zero CO_2 emissions by the end of the century (Figure 2.5 and Figure 2.6). As a consequence, pathways limiting warming below 2°C peak CO_2 concentrations at levels about 10 to 30 ppm CO_2 higher compared to 1.5°C pathways, and continue to see CO_2 concentrations by 2100 that are about 5–15% higher than today.

Within the group of 1.5°C pathways, the ratio of cumulative CO_2 emissions up to 2100 to the maximal cumulative carbon emissions (reached at the year of carbon neutrality), is non-linearly related to the year of net-zero CO_2 emissions (Figure 2.6). This provides an indication of both the level of negative CO_2 emissions deployed and the level of stringency of CO_2 emissions reduction measures in those mitigation pathways (see also Section 2.4). A part of these negative CO_2 emissions is used to compensate for the residual warming due to non-CO_2 GHG and aerosols by the end of the century (Figure 2.5) as suggested in the literature (Fuss et al., 2013, 2014a; Kriegler et al., 2013; Peters et al., 2017a; Rogelj et al., 2015a).

The rate of temperature change between 2081 and 2100 offers a complementary approach to map mitigation pathways after 2050. Indeed, all mitigation pathways limiting warming below 1.5°C display a decline in median temperature over the two last decades of the 21st century (Figure 2.5). This is not the case for mitigation pathways limiting warming to 2°C or higher levels. In 2°C pathways (<2°C and ~2°C) temperatures at the end of the century can be stabilized, be declining or still increasing.

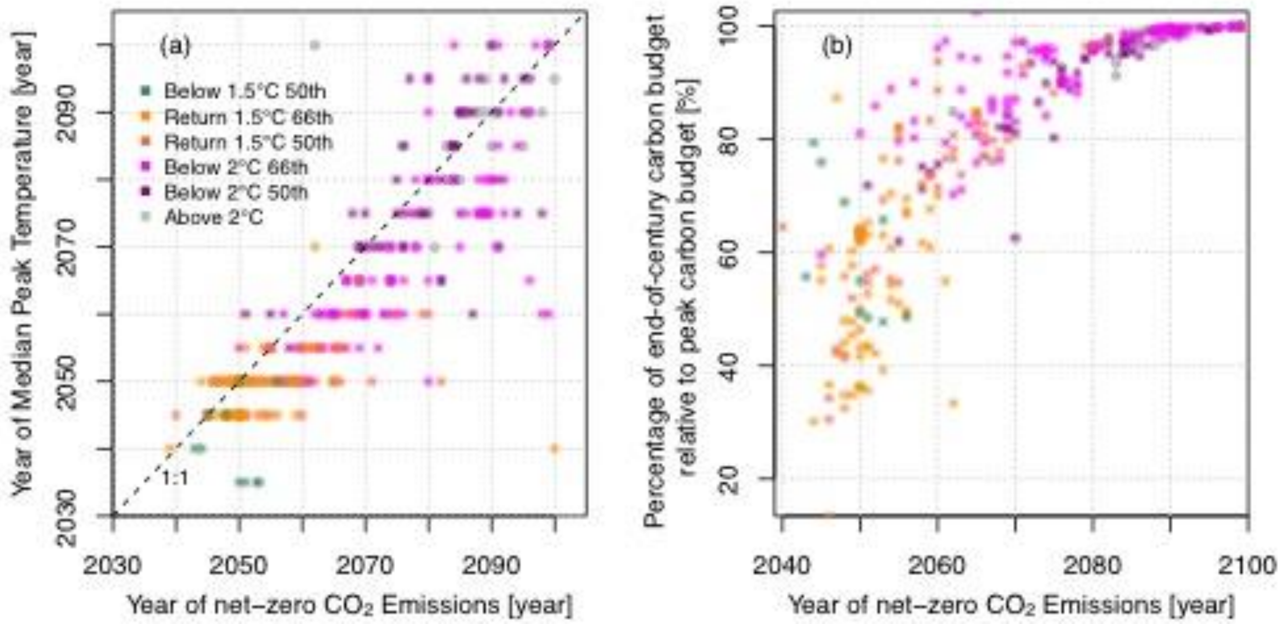


Figure 2.6: Characteristics of pathways reaching net-zero CO_2 emissions between 2016 and 2100. (a) Timing of median peak warming as function of the year of net-zero CO_2 emissions and (b) the ratio of end-of-century budget to budget until year of net-zero CO_2 emissions (i.e., the maximum carbon budget, derived at the year of net zero CO_2 emissions). In (a), the dashed line represents the first diagonal of the scatterplot.

2.3 Overview of 1.5°C mitigation pathways

Stabilizing global mean temperature increase at any level requires global CO_2 emissions to become net zero at some point in the future (Collins et al., 2013). At the same time, limiting the residual warming of shorter-lived non-CO_2 emissions, can be achieved by reducing their annual emissions as far as possible (Section 2.2). This will require large-scale transformations of the global energy-economy-land system, affecting the way in which energy is produced, agricultural systems are organised, and the extent to which energy and materials are consumed (Clarke et al., 2014). This section assesses how pathways compatible with limiting global mean temperature to 1.5°C relative to pre-industrial levels look like, including their underlying scenario characteristics.

Since the AR5, an extensive body of literature has appeared on pathways consistent with 1.5°C (see Section 2.1) (Bauer et al., 2017b; Bertram et al., 2017; Grubler et al., 2017; Harmsen et al., 2017; Holz et al., 2017; Krey et al., 2017; Kriegler et al., 2017d; Liu et al., 2017; Luderer et al., 2017c; Napp et al., 2017; Roelfsema et al., 2017; Rogelj et al., 2015a, 2017b; Strefler et al., 2017; Su et al., 2017; van Vuuren et al., 2017d). This section focuses on assessing insights from the literature on integrated pathways. This literature is characterized by pathways with global coverage, and a representation and interaction of all greenhouse gas (GHG) emitting sectors. Such integrated pathways allow the exploration of the whole-system transformation, as well as the interactions, synergies, and trade-offs between sectors. This contrasts with pathways from sectoral (IEA / IRENA, 2017; International Energy Agency (IEA), 2017) or national models (Kriegler et al., 2017e) (see Box 2.1 on National Pathways in Section 2.4) which provide detail in their domains of application but lack the integrated picture. This section hence provides the context in which the detailed sectorial transformations described in Section 2.4 of this chapter are taking place.

Scenarios are the exploration tool of preference in the pathway literature (Cross-Chapter Box 1.1). Such scenarios allow to answer specific questions, for example, “under which future socioeconomic conditions can climate change in 2100 be limited to low levels?” (Riahi et al., 2017) or “How does delay close the door for stringent mitigation scenarios?” (Luderer et al., 2013). This literature can be assessed in several ways, both of which are used 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). The ensemble of scenarios available to this assessment is an ensemble of opportunity. In other words, the scenario ensemble was neither designed nor developed by studies with a common set of questions in mind. This hence means that ranges can be useful to identify robust trends and changes across available scenarios and contributing modelling frameworks. They can also be useful to identify the variety of trends and changes that can be consistent with the goal of limiting warming to 1.5°C. However, to understand the reasons underlying the ranges, an assessment of the underlying scenarios and studies is required. To this end, this section highlights illustrative scenarios that clarify the variation in ranges. These highlighted scenarios can vary across the various subsections in this chapter, as specific aspects require specific scenarios for a deeper understanding.

This section starts with assessing what the pathways literature tells us on staying below or returning to 1.5°C and its underlying emissions evolutions. It then continues to assess the key factors affecting these emissions evolutions, and how these emissions evolutions can be achieved in a multitude of ways or societal configurations. Subsequently, it assesses the underlying whole-system transformations and its variations, the role and limitations of carbon dioxide removal (CDR) in 1.5°C pathways, and the role of near-term action in staying below or returning to 1.5°C.

2.3.1 *Pathways keeping warming below 1.5°C or temporarily overshooting it*

Stringent mitigation pathways are characterised by emissions reductions of all GHGs, and scenarios show reductions in CO_2, non-CO_2GHGs, and other climate forcers (Clarke et al., 2014). In this section, the salient temporal evolutions of the various climate altering emissions over the 21st century are assessed, based on the scenario classification presented in Section 2.1. Subsections further down are structured to assess factors that determine whether warming is kept below or temporarily overshoots a 1.5°C warming level (Section 2.3.1.1), and to address long- and short-lived climate forcers separately (Section 2.3.1.2).

2.3.1.1 *Factors determining overshoot*

A variety of pathways can limit warming to 1.5°C over the 21st century (Chapter 1, Section 1.2). These include pathways limiting warming to below 1.5°C with a given level of probability, and pathways temporarily exceeding a 1.5°C level of warming in order to return below it at a later point during the 21st century or beyond (also referred to as "overshoot" pathways) (see Table 2.1 in Section 2.1 for an overview).

As discussed in Section 2.2, to keep warming below 1.5°C with 50% likelihood, the cumulative amount of CO_2 emissions needs to remain below a 1.5°C threshold peak budget (TPB)of 580 (490–640) $GtCO_2$. Exceeding the TPB at some point in time results in overshooting the 1.5°C limit with a certain likelihood. Net negative CO_2 emissions would then be required to reduce total cumulative CO_2 emissions to levels consistent with a 1.5°C threshold return budget (TRB) of 590 (420–880) $GtCO_2$ (or 390 (200–730) $GtCO_2$) in order to return warming to levels below 1.5°C with 50–66% (or at least 66%) likelihood. The assessment of whether warming can be limited to 1.5°C without overshoot is thus closely connected to the question of whether CO_2 emissions over the 21st century can be kept below the 1.5°C TPB for a given likelihood. Beside on the likelihood, the TPB also depends on the warming from non-CO_2 forcers at the time of peak warming (Section 2.2). In addition, the CO_2 temperature response is determined by net global total CO_2 emissions from human activity including compensatory measures that remove carbon dioxide from the atmosphere. We therefore distinguish between the gross amount of CO_2 that humans emit into the atmosphere and the net amount which accounts for human carbon dioxide removal (CDR) activities year by year.

To assess the scope of the challenge to limit warming to 1.5°C without overshoot, we compare the estimated TPB range with the lower end of estimates of future CO_2 emissions. Recent global CO_2 emissions over the 2011–2015period were 180 ±10 $GtCO_2$ (fossil fuel and industrial processes) and 25 ± 15 $GtCO_2$ (land use change) (Le Quéré et al., 2017). Emissions in 2016 were 41 ± 4 $GtCO_2$, with a slight increase projected for 2017 (Jackson et al., 2017). If emissions stabilize at or slightly below this level in the next years, an additional 200 $GtCO_2$ will be emitted in the period 2016–2020. Estimates of committed fossil fuel emissions from existing fossil fuel infrastructure as of 2010 have been estimated at around 500 ± 200 $GtCO_2$ (with ca. 180 $GtCO_2$ already emitted by 2016) (Davis and Caldeira, 2010). The power sector contributes the largest part of these committed emissions. The sector's emission commitment is growing at a rate of about 4% mostly driven by installations of new coal-fired power plants (Davis and Socolow, 2014). 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 (Edenhofer et al., 2017; Yanguas-Parra et al.).The expected emissions until 2020 and the committed fossil fuel emissions already depreciate a significant part of the 1.5°C TPB. Estimated CO_2 emissions under the currently proposed NDCs are around 41 $GtCO_2yr^{-1}$ (36-43 $GtCO_2yr^{-1}$ range across model estimates) for 2030 (Roelfsema et al., 2017; Rogelj et al., 2016a). Starting from 2016, these NDC projections imply a total of about 600 $GtCO_2$ until 2030. Thus, following an NDC trajectory would exhaust the TPB of 1.5°C by 2030.

Estimates of the remaining CO_2 emissions from fossil fuel use until the end of the century vary across 1.5°C pathways. The remaining CO_2 emissions come partly from the energy supply sector which is projected to not contribute much more than the currently committed emissions due to the rapid decarbonisation of the power sector in 1.5°C pathways. The larger part of remaining CO_2 emissions come from direct fossil fuel use in the transport, buildings and industry sectors (Luderer et al., 2017c). The 1.5°C pathways from the literature that were reported in the scenario database project remaining emissions of 750–1480 $GtCO_2$ over the period 2016–2100 (5–95percentile range; fossil fuel and industrial process CO_2 emissions), with a very low energy demand scenario at the lower end (710 $GtCO_2$) (Grubler et al., 2017). Since the underlying scenario set covers a wide range of assumptions (Sections 2.1 and 2.3.2), this gives a robust indication of the lower limit of remaining fossil fuel and industry CO_2 emissions in the 21st century. Kriegler et al. (2017b) conducted a comprehensive sensitivity analysis that explores the four central options for reducing fossil fuel emissions, that is to say lowering energy demand, electrifying energy services, decarbonizing the power sector and decarbonizing non-electric fuel use in energy end use sectors, to their respective extremes. They found a lowest value of 610 $GtCO_2$ for the hypothetical case of aligning the strongest assumptions for all four mitigation options.

Land use turns from a source into a sink of atmospheric CO_2 in 1.5°C pathways. The remaining land use CO_2 emissions until the time they reach zero are projected to be 25–160 $GtCO_2$ (5–95 percentile range of 1.5°C scenarios in the database). This combines with the fossil fuel and industry CO_2 emissions to a total amount of gross emissions of 780–1640 $GtCO_2$ for the period 2016–2100 (5–95 percentile; Table 2.6). The lowest scenarios in the report's scenario database reach 740 $GtCO_2$, which is similar to what emerges for the period 2016–2050 from a scenario of transformative change that halves CO_2 emissions every decade from 2020 to 2050 (Rockström et al., 2017). Even the low end of the hypothetical sensitivity analysis of Kriegler et al., 2017a, about 100 $GtCO_2$ lower still when including the low end of land use CO_2 emissions, barely reaches the upper end of the TPB for the 1.5°C limit. We therefore make the assessment that gross CO_2 emissions in the 21st century will exceed the 1.5°C TPB based on multiple lines of evidence on the lower bound of gross CO_2 emissions in the 21st century and current knowledge about the TPB (medium confidence).

An overshoot of the 1.5°C TPB may still be avoided by simultaneous carbon dioxide removal (CDR) from the atmosphere (Ricke et al., 2017; Sanderson et al., 2016). CDR in its broad sense (including terrestrial CO_2 uptake, Section 4.3.8) is deployed by all 1.5°C pathways, but the scale of deployment varies widely (Section 2.3.4). CDR can have two very different functions in 1.5°C pathways. If deployed in the first half of the century, before carbon neutrality is 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 function it can be used to remain within the TPB 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 levels in line with a 1.5°C Threshold Return Budget (TRB, see Section 2.2). In the latter function, CDR enables temporary overshoot with a subsequent return to 1.5°C warming levels.

CDR fulfils both functions in 1.5°C pathways: it compensates residual CO_2 emissions and produces net negative emissions to return warming after a temporary overshoot. About 30–320 $GtCO_2$ cumulative CDR are deployed before the point of carbon neutrality, thus limiting peak cumulative emissions to 560–1050 $GtCO_2$ below the range of gross total CO_2 emissions (5–95 percentile based on 1.5°C scenarios in the SR1.5 database; see Table 2.6). The lower end of this range now falls into the estimated range of the 1.5°C TPB. The assessment in this chapter has identified ten non-overshoot scenarios that remain below 1.5°C throughout the 21st century. One of the lowest is the REMIND-MAgPIE 1.5°C Sustainability scenario (REM-Mag|1.5C-Sust henceforth) (Bertram et al., 2017) that peaks at 520 $GtCO_2$ and returns to 240 $GtCO_2$ by the end of the century. We will use it as an example of a deep non-overshoot pathway in the assessment in this section (Figure 2.7). The scenario still has a peak and decline shape reaching median warming levels of 1.1°C by the end of the century and using a substantial amount of mostly terrestrial CDR (790 $GtCO_2$). Given the proximity of the estimated 1.5°C TPB range and the lower end of remaining gross CO_2 emissions over the 21st century, a much more limited amount of CDR can suffice to remain within the 1.5°C TBP. On the low end, the MESSAGE-GLOBIOM very low energy demand (LED) pathway (MES-GLOB|LED, henceforth) (Grubler et al., 2017) relies on limited afforestation as its only CDR measure a (for a total of 190 $GtCO_2$), and yet only marginally overshoots the 1.5°C limit (<0.05°C overshoot). This is because its low energy demand development combined with rapid decarbonisation of energy use puts it at the low end of the remaining gross CO_2 emissions over this century (760 $GtCO_2$). In the assessment in this section, we will use this scenario as an example of the important class of 1.5°C pathways characterised by deep fossil fuel emissions reductions, very limited CDR deployment and only marginal net negative CO_2 emissions and overshoot (see Figure 2.7).

Cumulative emissions and CDR levels in 1.5°C pathways	5-95 percentile in 1.5°C Special Report scenario database
Gross CO_2 emissions 2016–2100	780–1640 $GtCO_2$
Peak net cumulative emissions in the 21st century	560–1050 $GtCO_2$
Net cumulative emissions 2016–2100	90–820 $GtCO_2$
Total CDR 2016–2100	380–1130 $GtCO_2$
CDR to compensate residual CO_2 emissions until the time of carbon neutrality	30–320 $GtCO_2$
CDR to compensate residual CO_2 emissions to maintain carbon neutrality from the time of carbon neutrality to 2100	40–460 $GtCO_2$
CDR to produce net negative emissions (= amount of net negative emissions) 2016–2100	90–750 $GtCO_2$
Function: Stabilizing temperatures (at 1.5°C, but also any other low level)	
Mitigation	***CDR use***
Deep reductions in CO_2 emissions. (Residual emissions from hard to decarbonise activities like aviation, shipping, and chemical and high temperature processes in industry can persist into 2nd half of century)	Compensate residual emissions in order to achieve and maintain carbon neutrality: 26–85% of CDR (interquartile range) is used for this purpose in 1.5°C pathways in the database.
Deep reductions of SLCF emissions to stable minimum levels	N/A (SLCF-induced warming reduces the carbon budget to stay under or return to a given temperature limit and therefore affects the need for CDR)
Function: Declining temperatures after an earlier higher peak	
N/A	Additional CO_2 removal beyond compensating for residual CO_2 emissions (= net negative emissions): 19–74% of CDR (interquartile range) is used for this purpose in 1.5°C pathways in the database.

Table 2.6: Cumulative amounts of CO_2 emissions and CDR and types of uses of CDR in 1.5°C pathways.

2.3.1.2 *Emissions evolution*

Short-lived climate forcers (SLCF) and long-lived climate forcers (LLCF) contribute in different ways to near-term, peak and long-term warming (Section 2.2). Because of their long lifetime, LLCFs accumulate in the atmosphere, and their cumulative emissions correlate with the warming they induce, while for SLCF the annual rate of emissions more closely matches their warming effect (Smith et al., 2012) (see also Cross-Chapter Box 1.2 on Metrics). This has led to the understanding that to limit peak global mean temperature rise, LLCFs and particularly CO_2 need to be kept to within a specific budget (Collins et al., 2013).

Despite identified and well-researched complexities related to the aggregation of various climate forcers (Myhre et al., 2013) GHGs are often aggregated and used as a benchmark measure for emissions reductions by a given year, for example, the aggregated Kyoto GHG basket expressed in CO_2 equivalent emissions using 100-year global warming potentials as a metric (Clarke et al., 2014; UNEP, 2016; UNFCCC Secretariat, 2016) (see also Cross-Chapter Box 1.2 on Metrics). Upon the explicit request of the UNFCCC (UNFCCC Secretariat, 2015), this section provides aggregated emissions levels as a guide, and consistent with their earlier use in the UNFCCC. A complete assessment of the applicability and values of GHG metrics falls outside the scope of this Special Report.

Appropriate benchmark values of aggregate 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 temporary overshoot is limited (Sections 2.2 and 2.3.2) (Rogelj et al., 2017b). But they also depend on the acceptable or desired portfolio of mitigation measures (Sections 2.3.3, 2.4, and 2.5.3) (Clarke et al., 2014; Krey et al., 2014a). The GHG emissions implications of near-term policy choices are often compared to benchmark values from cost-effective mitigation pathways to explore their consistency with long term climate goals (UNEP, 2017). If projected 2030 emissions levels are higher, this has strong implications for the post-2030 mitigation challenges after 2030, including the possibility that its implementation becomes increasingly out of reach (Section 2.3.5) (Clarke et al., 2014; Fawcett et al., 2015; Kriegler et al., 2017d; Luderer et al., 2013; Riahi et al., 2015; Rogelj et al., 2013). Benchmark emissions levels or estimates of emissions peak years are often misinterpreted as “requirements” in the sense that if they are not reached the goal becomes “infeasible” (see Cross-Chapter Box 1.3 in Chapter 1 for a discussion of infeasibility concepts). The identification of trade-offs between the pre-benchmark and post-benchmark period is the more adequate approach here. Those trade-offs which are particularly pronounced in the case of 1.5°C pathways are discussed in Section 2.3.5.

The range of aggregate emissions across available scenarios consistent with a specific climate outcome provides insights about the general order of magnitude of emissions levels. For instance, the interquartile range of aggregated GHG emissions in 2030 in ‘below 1.5C 50’ scenarios is markedly lower than levels in ‘below 2C 66’ and ‘below 2C 50’ scenarios (see Table 2.7 and Figure 2.8, and Section 2.1 for definitions of the scenario classes). This is due to the requirement in these scenarios to avoid overshoot which implies deeper reduction of CO_2 emissions, as well as non-CO_2 forcers in the coming decades so as stay within the CO_2 TPB for 1.5°C at the lowest possible level of non-CO_2 warming at the time of the peak (Section 2.2, Table 2.4). Year-2030 emissions levels in ‘return 1.5C 50’ scenarios overlap with the 2°C scenario categories. Various trade-offs and choices underlie the 2030 emissions ranges. For example, lower 2030 GHG emissions correlate with a lower dependence on the future availability and desirability of CDR (Strefler et al., 2017).

While net CO_2 emissions are markedly lower in 1.5°C scenarios than in 2°C scenarios, this is much less the case for methane (CH_4) and nitrous-oxide (N_2O) emissions (see Figures 2.7 and 2.8). AR5 identified two primary factors that influence the depth and timing of reductions in emissions of non-CO_2 Kyoto gases: (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 many low-cost mitigation options in some sectors for non-CO_2 gases in the near term compared to supply side measures for CO_2 mitigation (Clarke et al., 2014). A large share of this potential is hence already exploited in weaker mitigation scenarios in line with 2°C. At the same time, by mid-century and beyond, further reductions of non-CO_2 Kyoto gases, in particular CH_4 and N_2O, are hampered by the absence of mitigation options in the current generation of integrated models 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) (Section 2.4). This results in reductions of CO_2 taking up the largest share of emissions reductions when moving between a 1.5°C and a 2°C pathway(Luderer et al., 2017c; Rogelj et al., 2015a, 2017b).

2.3.1.2.1 Emissions of long-lived climate forcers

Emissions of LLCFs are dominated by CO_2, with smaller contributions of N_2O and some fluorinated gases (Blanco et al., 2014; Myhre et al., 2013). The overall reduction of net CO_2 emissions is achieved in scenarios through a combination of various anthropogenic contributions (see Figure 2.7) (Clarke et al., 2014): (a) CO_2produced by fossil fuel combustion and industrial processes (dark grey), (b) CO_2 emissions or removals from the Agriculture, Forestry and Other Land Use (AFOLU) sector (green), (c) CO_2capture and sequestration from fossil fuels or industrial activities before it is released to the atmosphere (i.e., fossil and industry CCS, light grey), (d) CO_2 removal by technological means, for example by capturing CO_2 (absorbed from the atmosphere during the growth of biomass) at the time it is processed in a centralised plant and storing it permanently (BECCS, light blue), amongst other conceivable options (see Chapter 4). Despite all reaching net CO_2 emissions levels in 2050 that are close to zero, scenarios apply these four contributions in different configurations. These configurations depend 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; Rogelj et al., 2017b; van Vuuren et al., 2017c), and come with very different implication for sustainable development (Section 2.5.3).

All 1.5°C scenario classes see global CO_2 emissions embark on a steady decline reaching (near) net zero by 2050 or shortly thereafter. Near-term differences between the various scenario classes are apparent, however. For instance, ‘below 1.5C 50’ and ‘return 1.5C 66’ scenarios show a clear shift towards lower CO_2 emissions in 2030 compared to other 1.5°C and 2°C scenario classes (Figure 2.7). These lower near-term emissions levels are a direct consequence of ‘below 1.5C 50’ pathways aiming at not exceeding the stringent TPB or ‘return 1.5C 66’ pathways to strongly limit the amount by which the budget is exceeded until peak warming so that a TRB with high probability can still be achieved (Sections 2.2 and 2.3.1.1). Median year-2030 global CO_2 emissions are of the order of 5–10 $GtCO_2yr^{-1}$ lower in ‘below 1.5C 50’ compared to ‘return 1.5C 66’ scenarios, which are in turn lower than ‘return 1.5C 50’ scenarios (Table 2.7). The ‘return 1.5C 50’ scenarios show similar emissions levels than the 2°C-consistent emissions pathways in 2030.

The development of CO_2emissions in the second half of the century in 1.5°C pathways is characterised by the need to stay or return within a very tight carbon budget (Section 2.2, Section 2.3.1.1).Figure 2.8 shows the net CO_2 and N_2O emissions from various sources in 2050 and 2100 in 1.5°C pathways in the literature.Virtually all 1.5°C pathways obtain net negative CO_2 emissions by the end of the century, but the extent to which net negative emissions are relied upon varies substantially (Figure 2.8) (Interquartile range: –4 to –12 $GtCO_2yr^{-1}$, –8 to –16 $GtCO_2yr^{-1}$, and –8 to –13 $GtCO_2yr^{-1}$ for ‘below 1.5C 50’, ‘return 1.5C 66’, and ‘return 1.5C 50’, respectively; see Table 2.6 for the cumulative amount of net negative emissions in 1.5°C pathways). This net withdrawal of CO_2 from the atmosphere compensates for the earlier build-up of CO_2 to return to higher likelihoods of staying below 1.5°C by the end of the century (see Section 2.3.1.1 for a discussion of various uses of CDR). Consequently, 1.5°C overshoot scenarios display larger values of net negative emissions by the end of the century than non-overshoot scenarios. End-of-century CO_2 emission levels of non-overshoot scenarios are very similar to levels displayed in 2°C pathways.

The underlying transformation of energy and land use that drives the evolution of CO_2 emissions in 1.5°C pathways is discussed in Section 2.3.3.

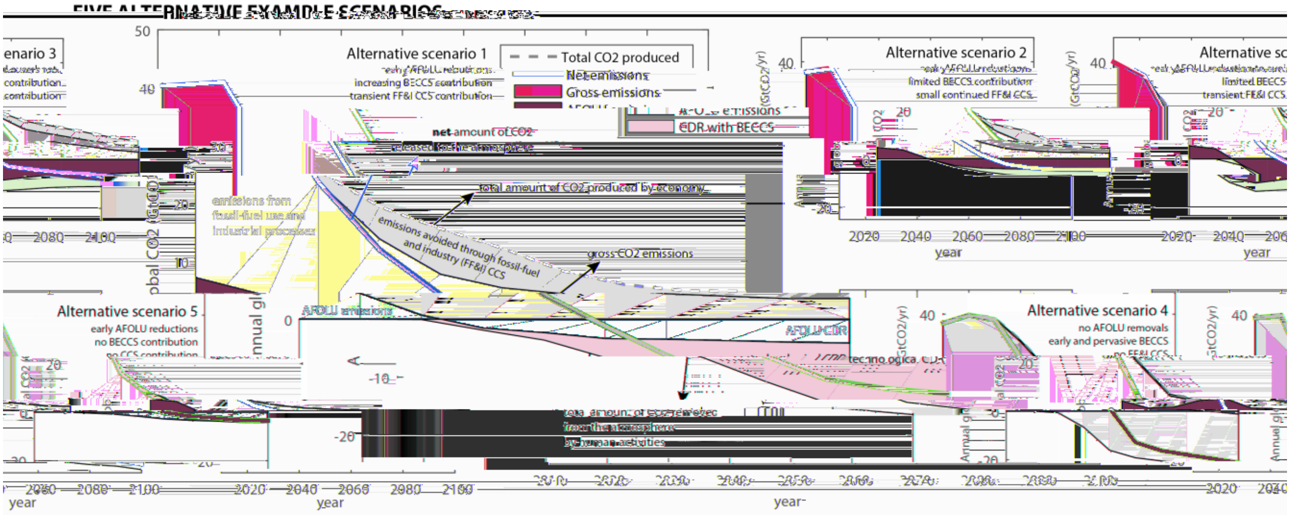
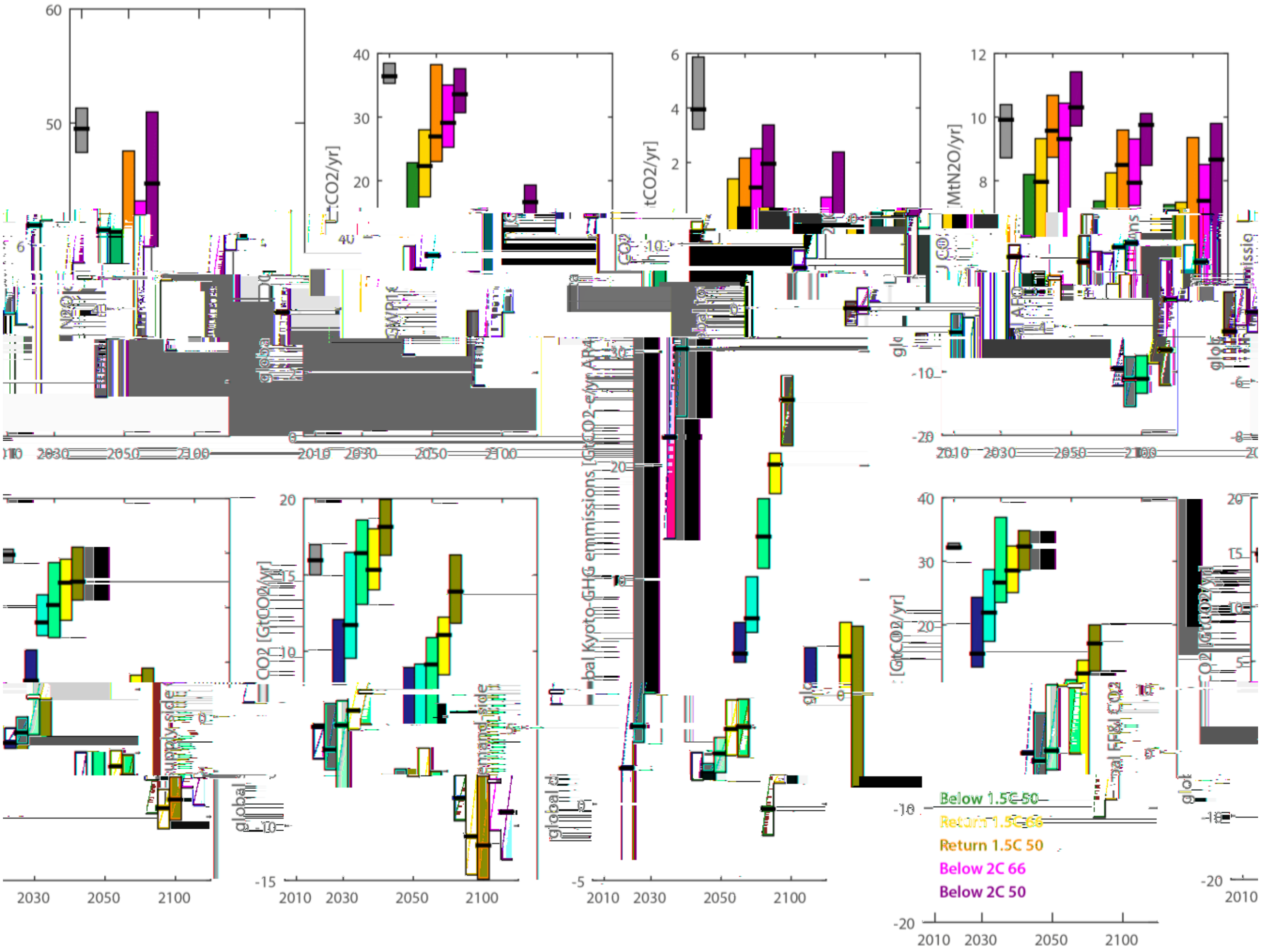


Figure 2.7: Evolution and break down of global CO_2 emissions until mid-century. The figure explains and illustrates the various CO_2 emissions contributions to total global CO_2 emissions. Five alternative example scenarios are highlighted, with characteristics described in each panel. Scenarios are MES-GLOB|SSP2-19 (Scenario 1) (Fricko et al., 2017), AIM|SSP1-19 (Scenario 2) (Fujimori, 2017), REM-Mag|1.5C-Sust (Scenario 3) (Bertram et al., 2017), REM-Mag|SSP5-19 (Scenario 4) (Kriegler et al., 2017c), MES-GLOB|LED (LowEnergyDemand, Scenario 5) (Grubler et al., 2017).



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2 **Figure 2.8:** Annual global emissions characteristics of five scenario classes used in this chapter for 2010, 2030, 2050,
3 2100 for Kyoto-GHG emissions (left-most panel), total CO_2 emissions, CO_2 emissions from the AFOLU
4 sector, and global N_2O emissions (top row), as well as CO_2 emissions from fossil-fuel use and industrial
5 processes. The latter is also split into emissions from the energy supply sector (electricity sector and
6 refineries), and direct emissions from fossil fuel use in energy demand sectors (industry, buildings,
7 transport) (bottom row panels). Boxes with different colours refer to different scenario classes (see left
8 panel). Ranges in the bottom panels show the interquartile range, horizontal black lines the median.

Global emissions	Scenario class	# scenarios	# modelling frameworks[1]	Annual emissions			Absolute annual change		Annual change relative to 2010[2]		Timing global zero
				2030	2050	2100	2010-2030	2030-2050	2010-2030	2030-2050	(interquartile range)
				GtCO2	GtCO2	GtCO2	GtCO2yr^{-1}	GtCO2yr^{-1}	%	%	yr
Total CO2 (net)	**Below 1.5C 50**	10	5	10.4/14.5/22.8	-2.8/-0.1/1	-12.3/-9.5/-4	-1.3/-1.2/-0.7	-1.3/-0.7/-0.5	-3.5/-3.2/-1.9	-3.6/-1.8/-1.4	2045/2053
	Return 1.5C 66	68	18	17.5/22.3/28	-1/-0.1/3.2	-15.5/-11.2/-7.6	-1/-0.7/-0.5	-1.5/-1.1/-0.9	-2.7/-2/-1.3	-4.1/-2.8/-2.3	2049/2056
	Return 1.5C 50	40	14	23/27/38.2	0.9/6.3/9.1	-13.4/-11.1/-7.5	-0.7/-0.5/0.1	-1.5/-1.3/-0.9	-1.9/-1.5/0.1	-4.2/-3.4/-2.2	2053/2067
	Below 2C 66	98	19	25.3/29.1/35	7.8/12/13.6	-8.7/-3.8/-0.9	-0.6/-0.4/-0.1	-1.2/-0.9/-0.7	-1.5/-1.1/-0.3	-3.3/-2.4/-1.9	2065/2090
	Below 2C 50	68	19	30.7/33.6/37.6	12.3/16.6/19.3	-12.2/-6.6/-1.4	-0.4/-0.1/0	-1.1/-0.8/-0.6	-0.9/-0.3/0.1	-2.9/-2.2/-1.7	2071/2095
CO$_2$ from Fossil-fuel use & Industry	**Below 1.5C 50**	10	5	13.4/15.5/24.3	0.8/1.6/4	-9.5/-3.9/0.2	-1/-0.9/-0.4	-1.1/-0.6/-0.6	-3/-2.6/-1.3	-3.2/-1.9/-1.8	2053/post-2100
	Return 1.5C 66	68	18	17.4/21.9/28.7	1.4/3.2/5.7	-11.9/-8.6/-5.7	-0.7/-0.5/-0.2	-1.2/-0.9/-0.7	-2.3/-1.6/-0.5	-3.8/-2.7/-2.2	2053/2063
	Return 1.5C 50	40	14	23.5/26.6/36.9	2.8/8.8/11.4	-10.5/-7.3/-3.7	-0.5/-0.3/0.2	-1.3/-1.2/-0.7	-1.4/-0.9/0.7	-4.2/-3.7/-2.3	2054/2080
	Below 2C 66	99	20	25.1/28.5/32.4	8.4/12.4/14.5	-5.5/-2.1/0.4	-0.3/-0.2/0	-1/-0.8/-0.6	-1.1/-0.6/0	-3.2/-2.5/-2	2071/post-2100
	Below 2C 50	68	19	28.6/32.3/34.8	12.7/17.1/20	-8.3/-3.6/-0.2	-0.2/0/0.1	-1/-0.7/-0.6	-0.5/-0.1/0.4	-3/-2.2/-1.7	2074/2105
AFOLU CO2	**Below 1.5C 50**	10	5	-3/-1.5/-1	-6.6/-1.6/-0.7	-4.9/-4.2/-2.7	-0.3/-0.2/-0.2	-0.3/0/0.1	-14.2/-7.1/-6.2	-6.6/-1.8/7.1	2022/2029
	Return 1.5C 66	68	18	-0.7/0.1/1.4	-4.4/-3/-1.3	-4/-2.5/-1.6	-0.3/-0.2/-0.1	-0.2/-0.2/0	-6/-4.9/-3.5	-5.4/-2.9/-1.3	2028/2037
	Return 1.5C 50	36	13	-0.4/0.3/2.2	-3.1/-2.2/-1.3	-4.2/-3.5/-2.1	-0.3/-0.2/-0.1	-0.2/-0.1/0	-5.6/-4.7/-3.4	-5.2/-1.8/-0.9	2029/2038
	Below 2C 66	91	18	0.2/1.1/2.5	-2.5/-1.1/0.7	-3.5/-2/-1	-0.2/-0.2/-0.1	-0.2/-0.1/0	-4.8/-4.1/-2.1	-3.4/-1.8/-0.8	2033/2059
	Below 2C 50	56	16	0.3/2/3.4	-2/-0.9/2.4	-3.9/-1.6/0.1	-0.2/-0.1/-0.1	-0.2/-0.1/0	-4.6/-3.1/-1.4	-3.8/-1.9/-0.6	2036/post-2100
Bioenergy combined with Carbon capture and storage (BECCS)	**Below 1.5C 50**	10	5	0/0/0.4	0/3.6/4.7	0/8.2/12.1	0/0/0	0/0.2/0.2	N/A	N/A	NA
	Return 1.5C 66	57	18	0/0.1/0.7	4.2/5.7/7.7	9.7/14.3/17.6	0/0/0	0.2/0.2/0.4	N/A	N/A	NA
	Return 1.5C 50	37	13	0/0.1/0.3	1.5/3.8/8.4	8.4/12.1/15.5	0/0/0	0.1/0.2/0.4	N/A	N/A	NA
	Below 2C 66	79	17	0/0/0.4	2.5/3.4/4.4	6.7/10/13.6	0/0/0	0.1/0.2/0.2	N/A	N/A	NA
	Below 2C 50	62	17	0/0/0.1	1.2/2.7/4.3	7.7/10.7/15	0/0/0	0.1/0.1/0.2	N/A	N/A	NA
Carbon capture and storage (CCS)	**Below 1.5C 50**	8	4	0.4/0.8/2.3	5.2/6.5/8.6	9.3/12.5/14	0/0/0.1	0.2/0.3/0.3	N/A	N/A	NA
	Return 1.5C 66	56	17	0.5/1.4/2.5	8.1/11.5/14.3	14.1/17.8/23.5	0/0.1/0.1	0.3/0.5/0.6	N/A	N/A	NA
	Return 1.5C 50	37	13	0.3/0.8/1.6	6.4/10.8/15.5	13.3/16.3/21.5	0/0/0.1	0.3/0.5/0.7	N/A	N/A	NA
	Below 2C 66	81	17	0.4/0.8/1.6	7.2/8.9/12.7	12.9/18.5/23.7	0/0/0.1	0.3/0.4/0.6	N/A	N/A	NA
	Below 2C 50	63	17	0.2/0.6/1.2	5.5/7.9/10.7	15.5/19.9/23.5	0/0/0.1	0.3/0.4/0.5	N/A	N/A	NA
Kyoto-GHG [in GtCO2e]	**Below 1.5C 50**	10	5	13.6/22.5/33.6	2.8/3.5/6.3	-10.8/-5.2/4.1	-1.6/-1.5/-0.9	-1.4/-0.7/-0.6	-3.5/-2.8/-1.7	-2.8/-1.5/-1.2	2056/post-2100
	Return 1.5C 66	60	16	24.3/30.2/39.2	5.4/6.6/10.3	-9.3/-5.9/-1.6	-1.3/-0.9/-0.7	-1.5/-1.1/-0.9	-2.6/-1.9/-1.3	-3/-2.1/-1.8	2060/2067
	Return 1.5C 50	29	11	31.2/37.1/47.6	11/13.8/17.1	-6.7/-5/0.8	-0.9/-0.7/-0.2	-1.5/-1.1/-0.9	-1.9/-1.4/-0.3	-3.1/-2/-1.8	2074/post-2100
	Below 2C 66	77	15	33.4/38.4/43.2	17.5/20.1/21.1	0.7/3.3/6.3	-0.7/-0.6/-0.3	-1.2/-0.9/-0.8	-1.6/-1.2/-0.6	-2.4/-1.8/-1.6	2110/post-2100
	Below 2C 50	51	16	41.3/44.7/51	21.7/25.8/27.9	-5.3/0.7/5.9	-0.5/-0.2/0	-1.3/-0.9/-0.7	-0.9/-0.5/0	-2.5/-1.8/-1.5	2087/post-2100

Table 2.7: Emissions levels in 2010, 2030, and 2050 comparing 1.5°C and 2°C scenario classes and annual rate of change between 2010 and 2030, and 2030 and 2050, respectively. Values show: 25th percentile, median, 75th percentile, across all available scenarios. GHG emissions are expressed in units of CO$_2$-equivalence computed with 100-year Global Warming Potentials reported in IPCC AR4. Emission reduction rates are often used to compare reductions in mitigation scenarios with abatement achieved in the past (Riahi et al., 2015; van Sluisveld et al., 2015; van Vuuren and Stehfest, 2013). Compound annual growth rates (the annual percentage change compared to the previous year) have been used in most cases, including in IPCC AR5 WG3 (Clarke et al., 2014). This functional form, however, is not applicable emissions evolutions in which emissions reach net zero levels or become negative, which is the case in several of the scenarios assessed here, for example, for net CO$_2$ emissions or AFOLU CO$_2$ emissions. Therefore, annual absolute emissions reductions and percentage emissions reductions relative to 2010 are reported instead. 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^{-1}, respectively (Le Quéré et al., 2017).

N_2O emissions are reduced to a much lesser extent than CO_2 emissions in the available scenarios (Figure 2.8). Scenarios show clear limits to the identified emissions reduction potential in current models (Gernaat et al., 2015). 'Below 1.5C 50' scenarios display markedly lower levels than other 1.5°C and 2°C scenario classes in 2030 potentially due to a greater reliance on sustainable food consumption (Figure 2.8). Given the small remaining carbon budget for 1.5°C, the additional reductions in these and other non-CO_2 forcers might be a key contributor to the possibility of keeping peak warming to below 1.5°C. However, all available 1.5°C pathways maintain substantial levels of N_2O emissions until the end of the century. As N_2O is an LLCF, these emissions accumulate in the atmosphere and also have to be compensated for by net negative CO_2 emissions. The substantial level of residual N_2O emissions in the second half of the century in these stringent mitigation pathways, highlights the difficulty of eliminating N_2O emission from agriculture (Bodirsky et al., 2014), and in particular the reliance of many pathways on significant amounts of bioenergy after mid-century (Section 2.4.3) coupled to a substantial use of nitrogen fertilizer (Popp et al., 2017). As a result, N_2O emissions can be a major contributor to end of century LLCF emissions, and measures to effectively mitigate them will be of continued relevance for 1.5°C societies in the second half of the century. 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 2.4.3 provides a further assessment of the agricultural non-CO_2 emissions reduction potential.

2.3.1.2.2 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 scenarios as is the case for 2°Cscenarios (Figure 2.9). SLCF emissions ranges of 1.5°C and 2°C scenario classes strongly overlap, indicating that the main incremental mitigation contribution between 1.5°C and 2°C scenarios comes from CO_2 (Luderer et al., 2017c; Rogelj et al., 2017b). Despite reductions of warming SLCFs contributing to limiting peak warming and being of particular importance to limiting warming to 1.5°C, there is low confidence that the differences between SLCF ranges of 'below 1.5C 50' and 'return 1.5C 66' scenarios are robustly different, due to the low number of scenarios in the lowest scenario class.

Significant emissions of CH_4 remain by 2050, despite their high warming effects (Etminan et al., 2016; Myhre et al., 2013), indicating that only limited mitigation options are identified in mitigation scenarios (Gernaat et al., 2015). The AFOLU sector contributes an important share of the residual CH_4 emissions until mid-century, with its share increasing from 47% (median; interquartile range: 45–50%) in 2010 to 53–58% in 2030, and 63–70% in 2050 in 1.5°C pathways (range of median estimates for 'below 1.5C 50', 'return 1.5C 66', and 'return 1.5C 50' scenario classes). Many of the proposed measures to target methane (Shindell et al., 2012; Stohl et al., 2015) are included in 1.5°C scenarios (Figure 2.9), though some, such as intermittent irrigation of rice paddies, not always (see Table 2.8). More speculative or experimental measures to further reduce AFOLU CH_4 emissions fall outside the scope of this Special Report.

Emissions of fluorinated gases in 'below 1.5C 50' and 'return 1.5C 66' pathways are reduced by roughly 65–80% relative to 2010 levels (interquartile range across scenarios) in 2050, with 'below 1.5C 50' scenarios showing reductions of that magnitude already by 2030. This is in strong contrast with unabated HFC evolutions, which are projected to increase in absence of mitigating policies (Velders et al., 2015). Recently, however, the Kigali Amendment 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 scenarios. In all three 1.5°C classes for which scenarios are available, the median projection of HFCs is estimated to be about 80% below 2010 levels in 2050 (Figure 2.9). Such reductions by 2050 are below published estimates of what a full implementation of the Montreal Protocol's Kigali Amendment would achieve (Höglund-Isaksson et al., 2017).

Aerosols include particle types that cause warming and cooling, whereas ozone generated from precursor emissions causes warming (Myhre et al., 2013). Reductions in aerosols can in addition affect regional climate change (Anenberg et al., 2012; Shindell et al., 2012; Stohl et al., 2015). The overall reduction in emissions of these SLCFs can have effects of either sign on temperature depending on the balance between cooling and warming agents, prompting suggestions to target the warming agents only (referred to as short-lived climate pollutants or SLCPs; e.g., Shindell et al., 2012). Black Carbon (BC) emission reach similar levels across 1.5°C and 2°C scenarios available in the literature, with median emissions reductions across scenarios of about 25–5% and 55–60% in 2030 and 2050, respectively, relative to 2010 (Figure 2.9). Recent studies that specifically focus on SLCF measures have identified further reduction potentials for the near term, with global reductions of about 80% being suggested (Klimont et al., 2017; Stohl et al., 2015). Because the dominant sources of certain aerosol mixtures are emitted during the combustion of fossil fuels (Bond et al., 2013), the rapid phase-out of unabated fossil-fuels would also result in removal of these short-lived climate forcers. 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 and affect regional and global climate change (Sand et al., 2015; Stohl et al., 2015). Simultaneously, cooling air pollutant species are being reduced by the transformations required to limit CO_2 emissions. For example, median sulphate emissions in the three 1.5°C classes for which scenarios are available (‘below 1.5C 50’, ‘return 1.5C 66’, and ‘return 1.5C 50’) are about 75–80% lower than their 2010 levels. These reductions in cooling pollutants will result in unmasking some of the current warming.

Action on SLCFs (and in particular on the warming sub-set of SLCPs) has also been suggested to facilitate achievement of the sustainable development goals (Shindell et al., 2017a). Reductions in both surface aerosols and ozone provide health co-benefits as air pollution is reduced (Anenberg et al., 2012; Jacobson, 2002, 2010; Shindell et al., 2012; Stohl et al., 2015). Public health benefits of stringent mitigation pathways in line with 1.5°C can be sizeable and potentially larger than the initial mitigation costs (West et al., 2013). However, some sources of SLCFs with important impacts for public health, like for example traditional biomass burning, are only mildly affected by climate policy in the integrated scenarios available in the literature and are more strongly impacted by baseline assumptions instead (Rao et al., 2016, 2017).

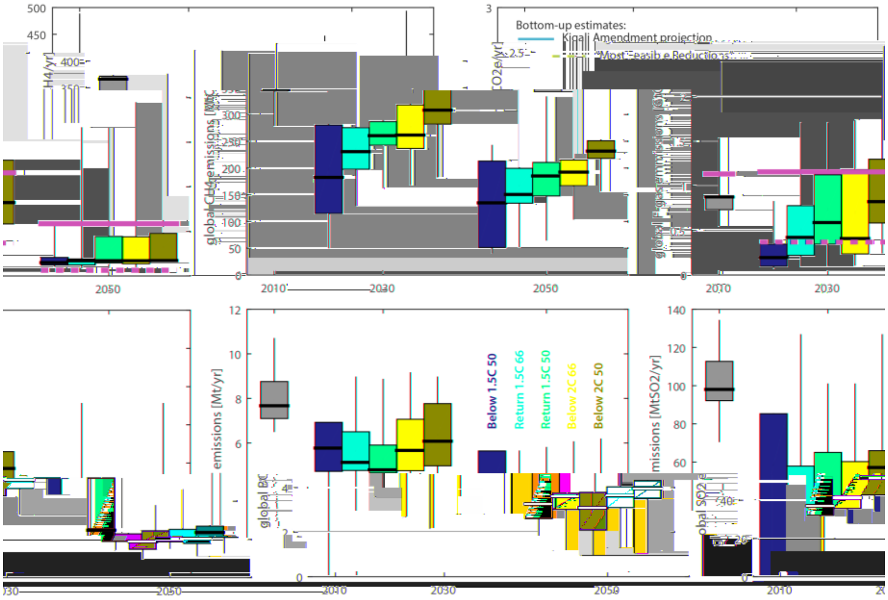
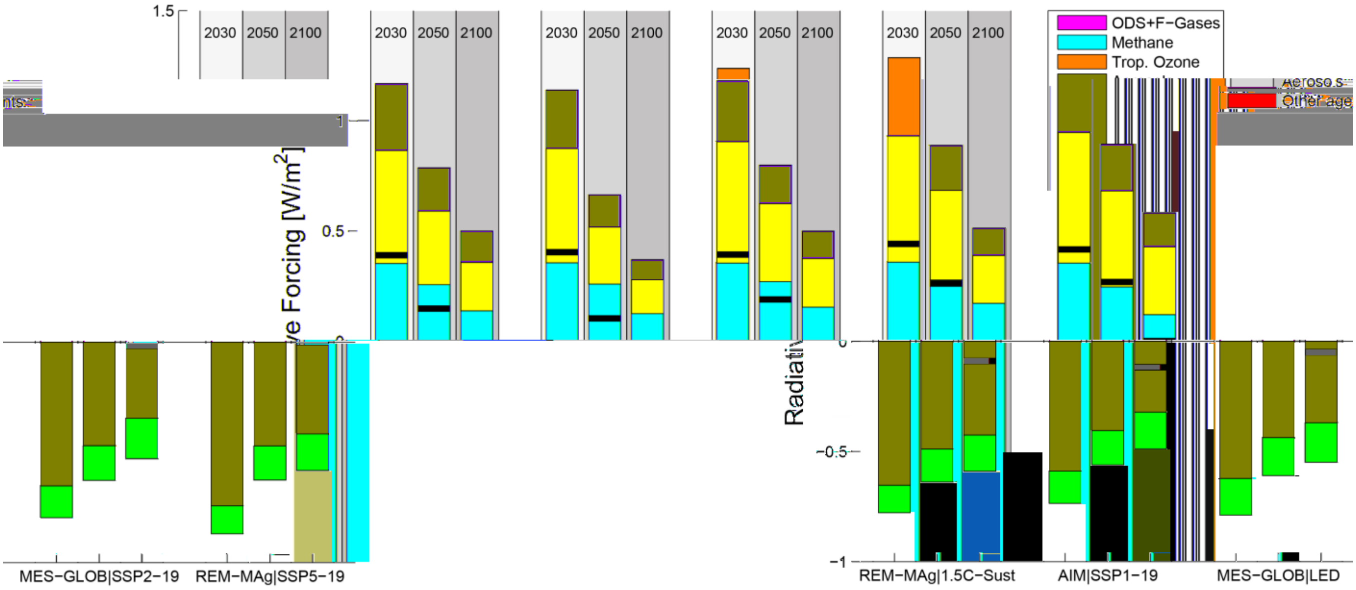


Figure 2.9: Global characteristics of a selection of global short-lived non-CO_2emissions until mid-century for five scenario classes used in this chapter in terms of annual emissions levels in 2010, 2030, and 2050. Data is shown for methane (CH4), fluorinated gases (F-gas), black carbon (BC), and sulphur dioxide (SO_2) emissions. Boxes with different colours refer to different scenario classes (defined in the bottom left panel). Ranges in the bottom panels show the interquartile range, horizontal black lines the median, while vertical thin lines 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. Horizontal blue lines in the top right HFC F-gas panel indicate estimates of F-gas emissions under implementation of the Kigali Amendment (solid) or under implementation of the “most feasible reductions” identified by (Höglund-Isaksson et al., 2017).

Figure 2.10 investigates the development of radiative forcing from SLCFs, fluorinated gases (F-gases) and ozone depleting substances (ODS) and a set of other forcing agents in 1.5°C pathways. There is broad agreement across scenarios that positive forcing from methane, tropospheric ozone, F-gases and ODS is more strongly reduced than net negative forcing from aerosol effects. As a result, the net forcing contribution from these substances vanishes by the end of the century. This is similar to developments in 2°C pathways (Riahi et al., 2017; Rose et al., 2014b) which show only a slightly higher median forcing contributions (by ca. 0.05 W m^{-2}) from these forcing agents. Nevertheless, there can be substantial additional gains from targeted deeper reductions of SLCF emissions with positive forcing contribution. Scenario that put particular emphasis on energy efficiency and limiting energy demand (e.g., REM-Mag|1.5C-Sust (Bertram et al., 2017), AIM|SSP1-19 (Fujimori, 2017; Rogelj et al., 2017b), MES-GLOB|LED (Grubler et al., 2017) in Figure 2.11) project relatively deeper reductions in methane and ozone forcing leading to a net cooling of up to –0.2 W m^{-2} by 2100, which allows a larger carbon budget to remain within the 1.5°C temperature limit (Section 2.2). ODS and F-gas forcing is controlled by the Montreal protocol and its Kigali Amendment on phasing out hydrofluorocarbons (see also Figure 2.10), the largest and fastest growing group of F-gases (Velders et al., 2015). The 1.5°C pathways project around 0.1 W m^{-2} residual forcing from hydrofluorocarbons in 2100. Based on the evidence available, achieving this forcing level as projected for 1.5°C scenarios is currently expected to require reductions beyond those mandated by the Kigali Amendment (Figure 2.9) (Höglund-Isaksson et al., 2017).



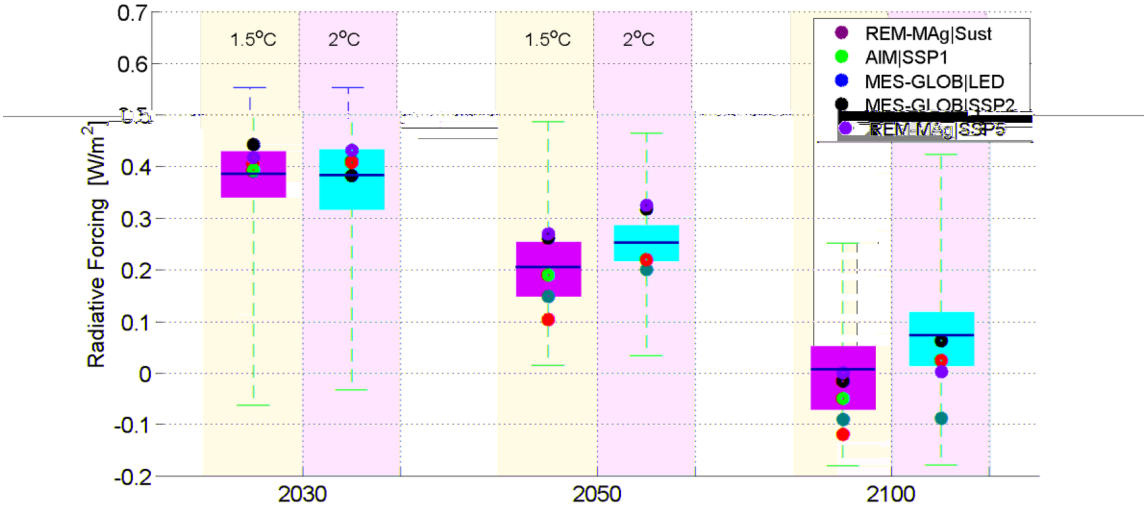


Figure 2.10: Radiative forcing from fluorinated (F) gases and ozone depleting substances (ODS), short-lived climate forcers including methane, tropospheric ozone, and aerosols (net total of sulphate, nitrate,, organic

carbon, black carbon, and indirect aerosol forcing), and other forcing agents (comprising mineral dust, stratospheric ozone and water vapour, land albedo changes). The upper panel shows the forcing by group of substances for selected 1.5°C pathways, and the lower panel the range of estimates for net forcing from all of these substances for 1.5°C and 2°C scenario classes (lower panel). The black horizontal bars in the upper panel indicate net total forcing from these substances for each point in time and scenario. Scenarios from (Bertram et al., 2017; Fricko et al., 2017; Fujimori, 2017; Grubler et al., 2017; Kriegler et al., 2017c; Rogelj et al., 2017b; van Vuuren et al., 2017b), see Section 2.3.2.1.

2.3.2 *Key elements and variations of 1.5°C pathways*

Earlier assessments have highlighted two important, related concepts in the framing and understanding of mitigation pathways (Clarke et al., 2014). First, there is no single pathway to achieve a specific climate objective. In the context of 1.5°C, a variety of pathways exist that achieves the required emissions reductions and phase-out of global CO_2 emissions until about mid-century (Figure 2.7). These variations in 1.5°C pathways depend on the underlying societal choices and preferences, which affect the drivers of projected future baseline emissions, for example, population growth, economic development and the evolution of regional and societal inequalities, as well as overall future energy and food demand. 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, for example by means of an international carbon price and market, or focussed on individual regions. A key finding is that 1.5°C pathways could be identified under a considerable range of assumptions in model studies despite the tightness of the 1.5°C emissions budget (Bauer et al., 2017b; Luderer et al., 2017c; Roelfsema et al., 2017; Rogelj et al., 2017b).

The second concept related to the framing of mitigation pathways (Clarke et al., 2014)is that owing to this diversity in solutions, pathways come with distinct features which vary in their synergies and trade-offs with other societal objectives, such as poverty eradication, food security, or clean air (Section 2.5.3). Ultimately, the portfolio of societal choices and mitigation options will to a large degree determine the facility with which synergies with other societal objectives can be achieved. The variety in 1.5°C pathways suggests that policy decisions and societal choices are essential in shaping pathways and their achievement of multiple societal objectives (Bertram et al., 2017; Krey et al., 2017; Kriegler et al., 2017d; van Vuuren et al., 2017d).

Integrated 1.5°C pathways covering all sectors and regions over the 21st century have been created with a wide variety of integrated assessment models (see Section 2.6 and Table A.II.14 in Krey et al. (2014b) for an overview on IAMs) in a number of studies, including model comparison and individual model studies (Bauer et al., 2017b; Bertram et al., 2017; Grubler et al., 2017; Harmsen et al., 2017; Krey et al., 2017; Kriegler et al., 2017d; Liu et al., 2017; Luderer et al., 2017c; Napp et al., 2017; Roelfsema et al., 2017; Rogelj et al., 2015a, 2017b; Strefler et al., 2017; Su et al., 2017; van Vuuren et al., 2017d). These pathways vary in their assumed socio-economic drivers, the demand for energy and land, their available mitigation measures, and in which climate policy target they pursue. These aspects have significant implications for the characteristics of 1.5°C pathways and how they differ. Here we provide background on these aspects to inform the pathway assessment in the following (sub-)sections.

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

The diversity of pathways available to achieve the required stringent emission reductions calls for a structured approach that allows a differentiation of scenarios along dimensions related to socioeconomic and technological assumptions, for example, economic growth and population development, the evolution of energy and food demand, choices related to preferences in technologies for the energy sector, and choices related to agricultural productivity and land use. There is deep uncertainty about the ways humankind will use energy and land in the 21st century which 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) (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 (see Cross-Chapter Box 1.1 on scenarios and pathways). The narratives include a world moving towards sustainability (SSP1: low population, high economic growth per capita, high technological progress rate, environmentally oriented technological and behavioural change, low energy and food demand per capita), a world maintaining focus on fossil fuel driven growth in the absence of climate policies (SSP5: low population, very high economic growth per capita, high technological progress rate, ample fossil fuel resources, resource intensive lifestyles, high energy and food demand), a world with rising inequality within and between countries (SSP4), a world that increasingly falls back into regional blocks (SSP3: high population, low economic growth and technological progress, focus on food and energy security), and a middle of the road development between those distinctly different world futures. The SSP framework is increasingly adopted by integrated assessment modelling to systematically explore the impact of socio-economic assumptions on mitigation pathways (Riahi et al., 2017), and has also been applied to the study of 1.5°C pathways (Rogelj et al., 2017b).

Population and economic growth projections can vary strongly across integrated scenarios (Crespo Cuaresma, 2017; Dellink et al., 2017; KC and Lutz, 2017; Leimbach et al., 2017). For example, based on alternative future fertility, mortality, migration and educational assumptions, population projections vary between 8.5 and 10.0 billion people by 2050, and 6.9 to 12.6 billion people by 2100 across the SSPs. These ranges to a large extent depend on 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 (KC and Lutz, 2017; Lutz and KC, 2011; Snopkowski et al., 2016). Consistent with populations development, GDP per capita also varies strongly in future scenarios, with 2050 GDP in SSP baselines varying between 18 and more than 40 thousand USD per capita (2005USD), in part driven by assumptions on development convergence between and within regions (Crespo Cuaresma, 2017; Dellink et al., 2017; Leimbach et al., 2017). For comparison, the lower end of this bracket would roughly correspond to the GDP per capita in 2005 of Slovenia or Bahrain, while the high-end would correspond to the UK, US, or Finland (IMF, 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). The literature has shown that economic growth mostly drives energy-related greenhouse gas emissions, while population growth mostly affects land use emissions (Kriegler et al., 2016). SSP-based studies have identified very high challenges to mitigation (and hence very few to no scenarios compatible with 1.5°C) for worlds in which global population growth proceeds along the high-end of current projections (around 10 and 12.6 billion people in 2050 and 2100, respectively) combined with low educational achievements, low per capita income growth (global mean around 10.7 and 11.5 thousand USD per capita in 2050 and 2100, respectively), high inequality and a focus on regional security, respectively (Riahi et al., 2017; Rogelj et al., 2017b).

As part of the assessment, we will use illustrative examples of typical 1.5°C pathway configurations to explain differences in pathway characteristics (e.g., as already done in Figure 2.7). These examples comprise three scenarios based on the SSPs that all aim at limiting anthropogenic radiative forcing in 2100 to 1.9 W m^{-2}(Rogelj et al., 2017b): a sustainability oriented scenario (AIM|SSP1-19 (Fujimori, 2017), a fossil-fuel intensive and high energy demand scenario (REM-Mag|SSP5-19; Kriegler et al., 2017c), and a middle-of-the-road scenario (MES-GLOB|SSP2-19 (Fricko et al., 2017)). Furthermore, we include two additional scenarios with particular focus on sustainability issues, including low energy demand, and limiting peak warming to 1.5°C or below under different assumptions (REM-Mag|1.5C-Sust, Bertram et al., 2017); MES-GLOB|LED i.e., Low Energy Demand, Grubler et al., 2017).

2.3.2.2 *Mitigation options in 1.5°C pathways*

Transformation pathways assessed in this section have been developed by global integrated assessment models that represent key societal systems and their interactions, like the energy system, the land system, 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. IPCC AR5 provided an overview of how differences in model structure can influence the outcome of transformation pathways (see Section 6.2 in Clarke et al., 2014 as well as Table A.II.14 in Krey et al., 2014b). These insights also apply here. Furthermore, in the context of ambitious 1.5°C transformation pathways, the portfolio of mitigation options available to the model also becomes increasingly important. Integrated assessment models include a wide variety of mitigation options, as well as measures that achieve

CDR from the atmosphere (Krey et al., 2014a, 2014b) (see also Chapter 4 for a bottom-up discussion of these mitigation technology options). While integrated assessment models cover most of the supply-side mitigation options on the process level, many demand-side options are treated as part of the underlying assumptions, which can be varied (Table 2.8) (van Sluisveld et al., 2016). There has been increasing attention on improving the modelling of behavioural change and other factors influencing future demand for energy and food in recent years (McCollum et al., 2016), including in the context of 1.5°C pathways (Grubler et al., 2017; van Vuuren et al., 2017c). The literature on the many diverse CDR options (Chapter 4) only recently started to develop strongly (Minx et al., 2017), and these options and its related insights are therefore at times only partially included in integrated assessment model analyses. Several studies have either directly or indirectly explored the dependence of 1.5°C pathways on specific (sets of) mitigation technologies (Grubler et al., 2017; Holz et al., 2017; Kriegler et al., 2017d; Napp et al., 2017; Rogelj et al., 2017b; Strefler et al., 2017; van Vuuren et al., 2017c).There are a number of more speculative, disruptive technologies that are not yet included in most of integrated pathway modelling and that have the potential to alter the shape of mitigation pathways beyond the ranges in the literature. Those are included in Table 2.8 and briefly highlighted in Section 2.3.3.4 (see Chapter 4 for a more comprehensive discussion of mitigation technologies).

MITIGATION MEASURES REPRESENTATION IN INTEGRATED PATHWAY LITERATURE			
A: Explicit and endogenous representation **B: Endogenous response included in scenarios** (not modelled as individual option but as part of a group of measures) **C: Exogenous representation** (measure assumed as input to a model, and illustrated by alternative scenarios) **D: Not represented**	Level of inclusion in integrated pathway literature	Studies presenting/ assessing measures (example references)	Integrated studies explicitly exploring specific measures
Demand side measures			
Energy efficiency improvements in energy end uses (appliances in buildings, engines in transport, industrial processes, …)	B/C/D	Fischedick et al., 2014; Lucon et al., 2014; Sims et al., 2014)	Grubler et al., 2017; Luderer et al., 2017c; Riahi et al., 2012
Electrification of transport demand (electric vehicles, electric rail …)	A/B/C	Sims et al., 2014	Edelenbosch et al., 2017b, 2017c; McCollum et al., 2014
Electrification of energy demand for buildings (heat pumps, electric stoves, …)	A/B/C	Daioglou et al., 2012; Lucon et al., 2014	
Electrification of industrial energy demand (electric arc furnace, heat pumps, electric boilers, conveyor belts, …)	B/C	Fischedick et al., 2014	Edelenbosch et al., 2017a
CCS in industrial process applications (cement, pulp and paper, iron steel, oil and gas refining, chemicals)	A/D	Fischedick et al., 2014	Luderer et al., 2017c; van Ruijven et al., 2016
Higher share of useful energy in final energy (e.g., insulation of buildings, lighter weight vehicles, coupled heat and power, …)	C	Fischedick et al., 2014; Lucon et al., 2014; Sims et al., 2014	
Reduced energy and mobility service demand (via behavioural change, reduced material and floor space demand, infrastructure and buildings configuration, new mobility business models, modal shift in individual transportation, eco-driving, car/bike-sharing schemes, …). Mostly represent price and income elasticity of energy (service) demand	B/C	Cuenot et al., 2012; Lucon et al., 2014; Sims et al., 2014	Grubler et al., 2017; van Sluisveld et al., 2016; van Vuuren et al., 2015
Reduced material demand via higher resource efficiency, structural change, behavioural change and material substitution (e.g., steel and cement)	C	Lucon et al., 2014; Pauliuk et al., 2017	Grubler et al., 2017
Urban form and influence of avoided transport and building energy demand	C/D	Creutzig et al., 2015a; Güneralp et al., 2017; Lucon et al., 2014; Seto et al., 2014	
Switch from traditional biomass and solid fuel use in the residential sector to modern fuels, or enhanced combustion practices, avoiding wood fuel	C	Daioglou et al., 2012; Griscom et al., 2017	van Vuuren et al., 2015
Dietary changes, reducing meat consumption	A/C	Bajželj et al., 2014; Hedenus et al., 2014; Popp et al., 2010; Smith and Bustamante, 2014; Stehfest et al., 2009	Popp et al., 2010; Stehfest et al., 2009; van Sluisveld et al., 2016
Reduction of food waste	A/C	Bajželj et al., 2014; Kummu et al., 2012; Smith and Bustamante, 2014	Bajželj et al., 2014; Bodirsky et al., 2014; van Vuuren et al., 2015
Supply side measures			
Decarbonisation of electricity:			
Solar PV/Solar CSP	A	Bruckner et al., 2014)	Creutzig et al., 2017; Luderer et al., 2014, 2017b; Massetti and

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			Ricci, 2013; Pietzcker et al., 2014b, 2017a; Zhang et al., 2010
Wind (on-shore and off-shore)	A	Bruckner et al., 2014)	Gernaat et al., 2014; Luderer et al., 2014, 2017b; Pietzcker et al., 2017a
Hydropower	A	Bruckner et al., 2014)	Gernaat et al., 2017; Luderer et al., 2014
Bio-electricity, including biomass co-firing	A	Bruckner et al., 2014; Hetland et al., 2016)	Klein et al., 2014; Rose et al., 2014a
Nuclear energy	A	Bruckner et al., 2014)	Bauer et al., 2012; Kim et al., 2014
CCS at coal and gas-fired power plants	A	Bruckner et al., 2014	Koelbl et al., 2014
Ocean energy (tidal and current energy, …)	D	Bruckner et al., 2014	
High-temperature geothermal heat	A/D	Goldstein et al., 2011	Krey and Clarke, 2011
Decarbonisation of non-electric fuels:			
Hydrogen	A/D		Krey et al., 2014a; van Ruijven et al., 2007
Biofuels	A		Bauer et al., 2017a; Klein et al., 2014; Rose et al., 2014a
Power-to-gas, methanisation, synthetic fuels	D		
Artificial photosynthesis to hydrogen and other chemical bonds	D		
Solar and geothermal heating	A/D		Luderer et al., 2014
Nuclear process heat	D		
Other processes:			
Fuel switching and replacing fossil fuels by electricity in end-use sectors (partially a demand-side measure)	A	Bruckner et al., 2014	
Material substitution of fossil CO_2 with bio-CO_2 in industrial application (e.g. the beverage industry)	D		
Substitution of halocarbons for refrigerants and insulation	A		
Reduced gas flaring and leakage in extractive industries	A/B	Bruckner et al., 2014	
Electrical transmission efficiency improvements	C	Bruckner et al., 2014	
Technological energy production innovations that improve sustainability and efficiency (e.g. advanced nuclear reactor designs)	B/D		
AFOLU measures			
Reduced deforestation / forest protection / avoided forest conversion	A	Griscom et al., 2017; Houghton et al., 2015; Jackson et al., 2008; Kindermann et al., 2008; Smith and Bustamante, 2014	Calvin et al., 2014; Popp et al., 2014a; van Vuuren et al., 2015

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Forest management	A/C/D	Jandl et al., 2007; Smith and Bustamante, 2014	Fricko et al., 2017; van Vuuren et al., 2015
Reduced land degradation, and forest restoration	D	Chazdon, 2008; Houghton et al., 2015; Lal, 2004; Smith and Bustamante, 2014	
Methane reductions in ruminants, rice paddies and so on	A/B	Kirschke et al., 2013; Popp et al., 2010; Shindell et al., 2012; Smith and Bustamante, 2014	Frank et al., 2017b; Popp et al., 2017
Livestock and grazing management, protein feed, …	A/C/D	Griscom et al., 2017; Havlík et al., 2014; Herrero et al., 2016; Smith and Bustamante, 2014	Havlík et al., 2014; Weindl et al., 2017
Increasing agricultural productivity	A/C	Havlik et al., 2013; Smith and Bustamante, 2014; Valin et al., 2013	Popp et al., 2011; Valin et al., 2013; van Vuuren et al., 2015
Nitrogen pollution reductions by fertilizer reduction, increasing nitrogen fertilizer efficiency, substitution of nitrogen with mineral fertilizer	C	Bodirsky et al., 2012, 2014; Smith and Bustamante, 2014	Bodirsky et al., 2014; Frank et al., 2017b; Popp et al., 2010; van Vuuren et al., 2015
Changing agricultural practices enhancing soil carbon	B/D	Smith and Bustamante, 2014	Frank et al., 2015
Agroforestry	D	Griscom et al., 2017; Verchot et al., 2007	
Fire management and pest control	D	Aragão and Shimabukuro, 2010; Canadell and Raupach, 2008; Griscom et al., 2017; Hurteau and North, 2010	
Conservation agriculture	D	Griscom et al., 2017; Lal et al., 2007	
Influence on land albedo of land use change	A/D	Caiazzo et al., 2014; Pongratz et al., 2010	Jones et al., 2015a; Kreidenweis et al., 2016; Thornton et al., 2017
Carbon-dioxide (greenhouse gas) removal			
Biomass use for energy production with carbon capture and storage (BECCS) (through combustion, gasification, or fermentation)	A	Creutzig et al., 2015b; Fuss et al.; Minx et al.; Smith et al., 2015	Calvin et al., 2014; Kriegler et al., 2013; Muratori et al., 2016; Rose et al., 2014a

MITIGATION MEASURES REPRESENTATION IN INTEGRATED PATHWAY LITERATURE			
A: Explicit and endogenous representation **B: Endogenous response included in scenarios** (not modelled as individual option but as part of a group of measures) **C: Exogenous representation** (measure assumed as input to a model, and illustrated by alternative scenarios) **D: Not represented**	Level of inclusion in integrated pathway literature	Studies presenting/ assessing measures (example references)	Integrated studies explicitly exploring specific measures
Direct air capture (DACS) of CO_2 using chemical solvents and solid absorbents, with subsequent storage	A/D	Fuss et al.; Minx et al.; Smith et al., 2015	Chen and Tavoni, 2013
Mineralization of atmospheric CO_2 through enhanced weathering of rocks	A/D	Fuss et al.; Hartmann et al., 2013; Minx et al.; Smith et al., 2015	Strefler et al.
Afforestation / Reforestation	A/D	Fuss et al.; Griscom et al., 2017; Minx et al.; Nilsson and Schopfhauser, 1995; Smith and Bustamante, 2014	Calvin et al., 2014; Humpenöder et al., 2014; Kreidenweis et al., 2016; van Vuuren et al., 2017b
Restoration of wetlands (coastal and peat-land restoration, blue carbon …)	D	Griscom et al., 2017; Lohila et al., 2004	
Biochar	C	Fuss et al.; Lal, 2004; Minx et al.; Smith, 2016; Smith and Bustamante, 2014; Woolf et al., 2010	
Soil carbon enhancement, including wood burial	B/D	Smith, 2016; Smith and Bustamante, 2014; Zeng, 2008	Frank et al., 2017a
Carbon Capture and Usage – CCU; bioplastics, carbon fiber	A/D	Mac Dowell et al., 2017	
Ocean iron fertilization	D	Fuss et al.; Minx et al.; Williamson et al., 2012	
Ocean alkalinisation	D	Fuss et al.; Minx et al.; Renforth and Henderson, 2017; Smith et al., 2017b	
Removing CH4, N2O and halocarbons via photocatalysis from the atmosphere	D	Boucher and Folberth, 2010	

Table 2.8: Taxonomy of mitigation options for 1.5°C transformation pathways. This table provides a general overview of mitigation measures represented in the integrated pathway literature assessed in this chapter. Measures are classified according to the level to which they are included in scenarios (see first rows for explanation). Measures with several characters in the last column are treated differently by different models.

2.3.2.3 *Policy assumptions in 1.5°C pathways*

Besides assumptions related to socio-economic drivers and mitigation technology, scenarios are also subject to assumptions about the mitigation policies that can be put in place. Mitigation policies can either be applied immediately in scenarios, or follow staged or delayed approaches. Policies can span many sectors (e.g., economy wide carbon pricing), or policies can be applicable to specific sectors only (like the energy sector) with other sectors (e.g., the agricultural or the land-use sector) treated differently (Wise et al., 2009). These variations can have an important impact on the ability of models to generate scenarios compatible with stringent climate targets like 1.5°C. In the scenario ensemble available to this assessment, several variations of near-term mitigation policy implementation can be found: immediate global cooperation from 2020 onward towards a global climate objective, including all sectors (Kriegler et al., 2017d; Luderer et al., 2017c; Roelfsema et al., 2017; Rogelj et al., 2017b), a phase in of globally coordinated mitigation policy from 2020 to 2040 (Rogelj et al., 2017b; Strefler et al., 2017), and a delay of global mitigation policy, following NDCs until 2030 (Kriegler et al., 2017d; Luderer et al., 2017c; Roelfsema et al., 2017; Vrontisi et al., 2017a). The impact of near-term policy choices on 1.5°C pathways will be discussed in Section 2.3.5. The literature has also explored 1.5°C pathways building on a portfolio of policy approaches until 2030, including the combination of regulatory policies and carbon pricing (Kriegler et al., 2017d) and a variety of ancillary policies to safeguard other sustainable development goals (Bertram et al., 2017; van Vuuren et al., 2017c). A further discussion of policy implications of 1.5°C pathways is provided in Section 2.5, while a general discussion of policies for a 1.5°C world and options to strengthen action are subject of Chapter 4.

2.3.3 *Whole-system transformation*

The wide range of future socioeconomic drivers, choices of mitigation measures and policy assumptions (e.g., as captured by the SSPs; O’Neill et al., 2017; Riahi et al., 2017) leads to a diversity of potential pathways in line with 1.5°C, each of which strongly reduces global GHG emissions in the coming decades. Subsequent sections discuss general changes in energy supply and demand, the AFOLU sector, their interactions, and different configurations of carbon neutral systems in 1.5°C mitigation pathways, focussing on general trends and characteristics. Deep dives into the sectoral evolution and achievement of these high-level characteristics are provided in Section 2.4.

2.3.3.1 *Energy systems transformation*

The way humankind produces and uses energy is closely connected to present and future land use, markets, and societal institutions in a 1.5°C world as it is a key determinant how carbon neutrality can be achieved and maintained. Clear visions of transitions and possible end points of the 1.5°C energy transformation are important to set expectations and inform key choices on re-configuring global energy systems today. At the same time, it is deeply uncertain which key technologies, preferences and institutions will shape the energy system 50 to 80 years out – in contrast to the next one to two decades, where boundary conditions are more certain. It is therefore necessary to explore different visions of the global energy system of the future with a scenario approach (Riahi et al., 2012). Here we will discuss the range of visions presented by model-based 1.5°C pathways in the literature.

Four contributing factors or macro decarbonisation indicators can help to understand the structure of the energy (including transportation and buildings) and industry transformations: limits to the increase of energy demand, reductions in the carbon intensity of electricity, an increasing share of final energy being provided by electricity, and reductions in the carbon intensity of the residual fuel mix, each of which are affected by scenario assumptions. Figure 2.11 shows these general trends in the 1.5°C and 2°C scenario classes.

In general, 1.5°C and 2°C pathways are similar in their evolution of macro indicators for decarbonisation, both having to comply with a stringent carbon budget. Pathways in both the 1.5°C and 2°C classes show a general fast transition until mid-century and a slower, more sustained evolution thereafter. The largest differences between 1.5°C and 2°C pathways are seen in the first half of the century, where 1.5°C pathways show lower energy demand, a faster electrification of energy end use, and a faster decarbonisation of the carbon intensity of electricity and of the residual fuel mix (that is, the fuel mix which does not contribute to the production of electricity in the energy system). There are very few scenarios in the class keeping warming to below 1.5°C. However, they appear to distinguish themselves by noted reductions in final energy demand, carbon intensity of electricity generation and residual fuel mix, and electricity shares already by 2030. Despite this limited evidence, there is high agreement and confidence about the direction of these differences but low to medium confidence about the precise magnitude of differences between 'below 1.5C 50' and other pathway classes.

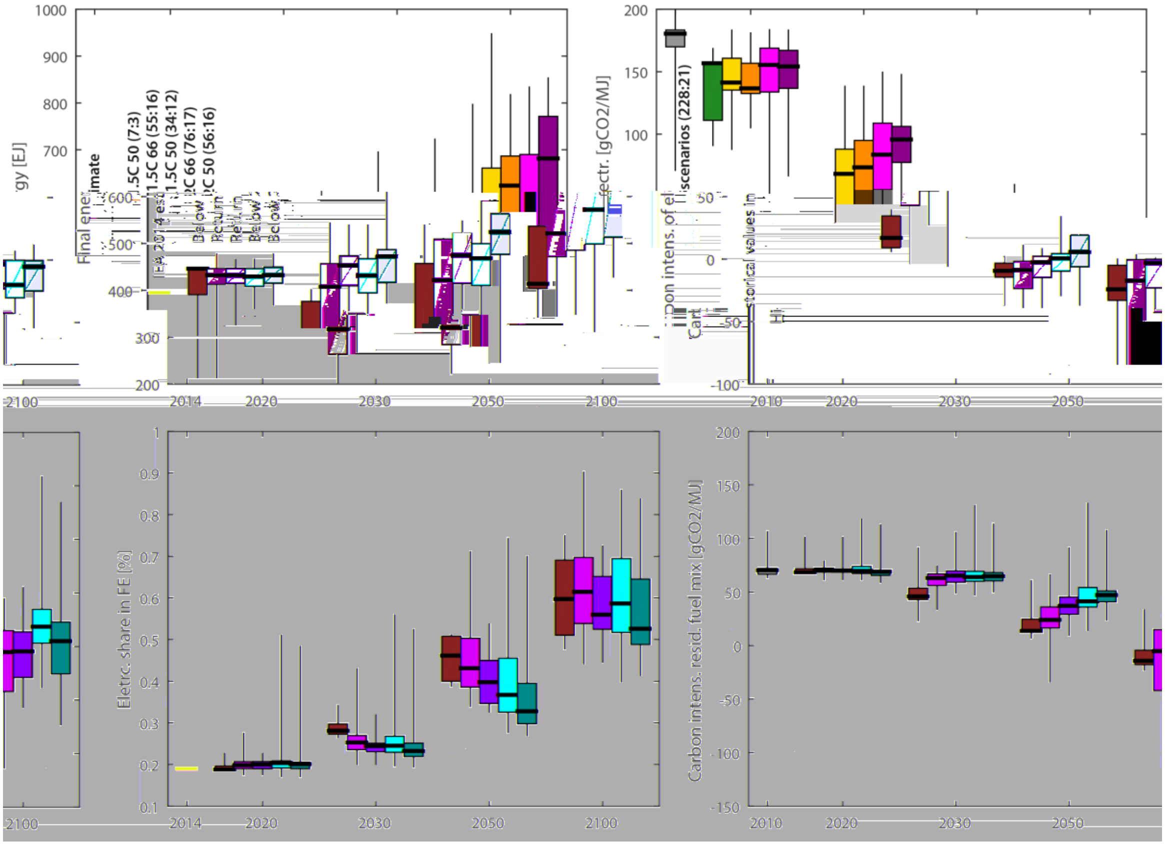


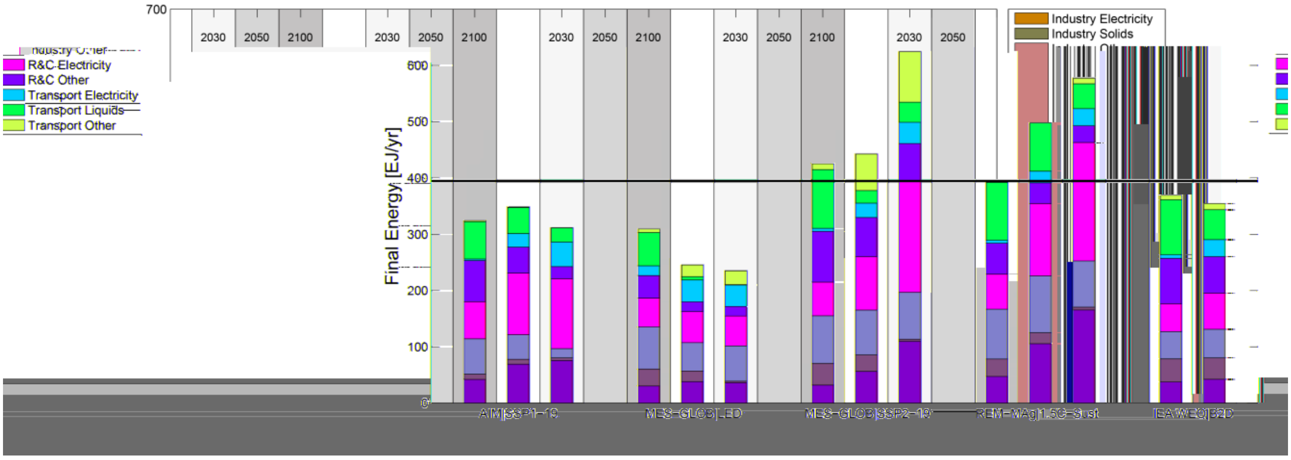
Figure 2.11: Decomposition of transformation pathways in energy demand (top left: EJ of final energy), carbon intensity of electricity (top right: Electricity CO_2over Electricity in Final Energy), the electricity share in final energy (bottom left), and the carbon intensity of the residual (non-electricity) fuel mix (bottom right). Boxplots show median, interquartile range and full range. The legend for the scenario classes is provided in the top left panel. Values behind the class labels report the number of available scenarios and the number of contributing modelling framework. Classes are defined in Section 2.1.Historical values in the left panels are from IEA (IEA, 2016b).

2.3.3.1.1 Energy demand

Energy demand reductions are a key characteristic of 1.5°C pathways. Limiting energy demand results in an overall smaller energy system and therewith facilitates the transition to a low-carbon society (Clarke et al., 2014; Grubler et al., 2017; Napp et al., 2017; Riahi et al., 2012; van Vuuren et al., 2017d). Energy demand reductions are particularly important because end-use efficiency improvements are able to leverage upstream energy reductions. These up-stream energy reductions can be several times to an order of magnitude larger than the initial end-use demand reduction. This is immediately clear when comparing useful energy output for a particular service category like lighting to the associated primary energy input (see data in De Stercke, 2014). The more demand can be limited, the more flexible supply-side mitigation measures can be combined to decarbonise the overall system (Riahi et al., 2012). This feature is particularly visible in scenarios that limit peak warming to as low as possible levels (for example, the ‘below 1.5°C 50’ class but also other scenarios that limit warming to levels no more than 0.1°C higher than 1.5°C) (Grubler et al., 2017; Napp et al., 2017; Vrontisi et al., 2017b). Overall, absolute final energy demand levels in ‘return 1.5°C 66’ scenarios are 410 EJ yr^{-1} (350-460 EJ yr^{-1}),420 EJ yr^{-1} (350-510 EJ yr^{-1}) and 510 EJ yr^{-1} (470-630 EJ yr^{-1})in 2030, 2050 and 2100, respectively, compared to 395 EJ yr^{-1} in 2014 (IEA, 2016b)(median and interquartile range, see Figure 2.11). In ‘below 1.5°C 50’ scenarios, lower final energy demand projections are assumed throughout the 21st century, showing a significant difference to overshoot 1.5°C scenarios already in 2030. At the low end is a dedicated low energy demand pathway (MESSAGE-GLBM|LED; Figure 2.12) (Grubler et al., 2017) which reduces energy demand by about 40% compared to today by mid-century and keeps it at level until the end of the century. The ranges within a specific scenario class are due to a variety of factors as introduced in Section 2.3.2, as well as differences between modelling frameworks. The important energy demand reductions that facilitate many of the 1.5°C pathways raise issues of potential rebound (Saunders, 2015), which, while promoting development, would make the achievement of low energy demand futures more difficult than anticipated (Section 2.6).

Final energy demand is driven by demand in energy services for mobility, residential and commercial activities, and manufacturing which in turn is heavily dependent on assumptions about socio-economic futures as represented by the SSPs (Bauer et al., 2017a). The structure of this demand drives the composition of final energy use in terms of energy carriers (electricity, liquids, gases, solids, hydrogen etc.). The introduction of climate policy further influences the composition of final energy demand for providing these services, both by lowering it due to the carbon penalty on fossil fuels and by re-structuring it towards energy carriers that can be provided in a carbon neutral way more easily than others (i.e., electricity and hydrogen vs. liquids, gases and solids).

Figure 2.12 shows the structure of global final energy demand in 2030, 2050 and 2100 as projected in 1.5°C pathways. Electrification continues throughout the second half of the century (up to 50–70% (interquartile range) of final energy by 2100) leading to a 3.5 to 6-fold increase (interquartile range; median 4.5) in electricity demand by the end of the century relative to today (Grubler et al., 2017; Luderer et al., 2017c; Rogelj et al., 2017b). Since the electricity sector is completely decarbonised by mid-century in 1.5°C pathways, electrification is the primary means to decarbonise energy end use. Electrification is strongest in the residential and commercial sector, but many pathways also project the electrification rate of industry to reach 50% or higher levels by the end of the century. Transport electrification rates are projected to be lower due to different assumed limits to electrifying aviation, shipping and road freight transport even in the long run (Carrara and Longden, 2017; Pietzcker et al., 2014a), but some of the low energy demand scenario project the majority of transport to be electrified by the end of the century. Even though some pathways include an increased use of hydrogen in the transport sector, most continue to rely on liquid fuels and in some cases gases to cover non-electric fuel demand for transportation.



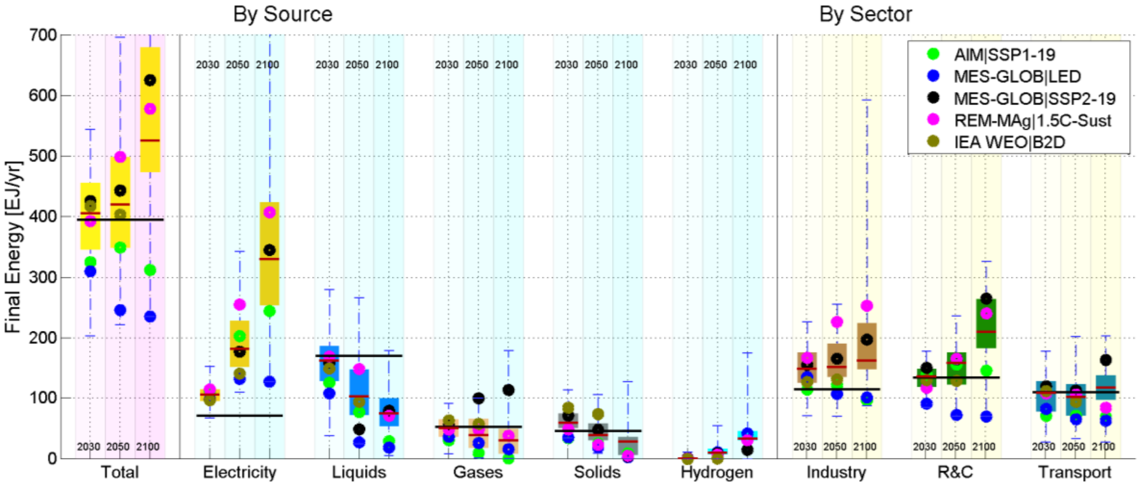


Figure 2.12: Final energy consumption for four selected 1.5°C pathways and the IEA's B2D scenario (IEA / IRENA, 2017) (upper panel) and their relative location in the range of 1.5°C scenarios in 2030, 2050 and 2100. Scenarios from (Bertram et al., 2017; Fricko et al., 2017; Fujimori, 2017; Grubler et al., 2017; Rogelj et al., 2017b), see Section 2.3.2.1. Black lines indicate values of final energy consumption in 2014 (IEA, 2016b). 'R&C' stands for the residential and commercial sector and comprises energy use in buildings. The category 'Industry Other' includes all non-electric fuel use except of solids in the industry sector (liquids, gases, hydrogen), 'R&C Other' includes all non-electric fuel use in buildings (liquids, gases, hydrogen, central heat), and 'Transport Other' includes all non-liquid, non-electric fuel use in the transport sector (hydrogen and gases).

Combined with its use in industry, the continued demand for liquid fuels for transport keeps liquids the second largest contributor to final energy demand by the end of the century, albeit at half today's level and at a level four times lower than end of century electricity demand (median estimates in Figure 2.12). 1.5°C pathways project that around 60–100 EJ of final energy (interquartile range, median 75 EJ) are still supplied by liquids and gases in 2100, which in the second half of the century is the defining challenge to achieve and maintain carbon neutrality. Most integrated assessment models currently foresee bioenergy as the sole means to decarbonise these fuels, which would lead to bioenergy demand of a few hundred EJ per year to completely eliminate emissions from their combustion. In most cases, 1.5°C pathways project only a partial substitution of oil and natural gas for the provision of liquids and gases by biomass and deploy CDR measures to neutralise the residual CO_2 emissions. In addition, as discussed in Section 2.3.4, bioenergy can also be a major provider of CDR via BECCS, which explains the robustness of its value in deep mitigation pathways independently of whether BECCS is available or not (Klein et al., 2014). However, a low energy demand scenario with large shares of electricity and hydrogen use in the transport and industry sectors projects residual liquids use reduced to 20 EJ by the end of the century, resulting in only limited demand for bioenergy (Grubler et al., 2017).

2.3.3.1.2 Energy Supply

Energy supply in 1.5°C pathways is tailored to meet the projected demand of final energy carriers at very low emissions levels. The two main mitigation options on the energy supply side are the decarbonisation of electricity generation and the decarbonisation of liquids, gases and solids provided to industry, residential and commercial activities, and the transport sector. They differ significantly in terms of decarbonisation potential and speed. While fossil fuel use for electricity generation is phased out around mid-century in 1.5°C pathways, their use for providing liquids and gases to the transport and industry sector can persist until the end of the century (Luderer et al., 2017c). Residual oil and gas use without CCS is reduced to 30–100 EJ yr^{-1} (interquartile range, median 60 EJ yr^{-1}) by the end of the century (Figure 2.13), reflecting decarbonisation bottlenecks in the transport (shipping, aviation, freight transport) and heavy industry. In contrast, coal without CCS is rapidly phased out by mid-century. CCS combined with fossil fuel use with remains limited in many 1.5°C pathways (Rogelj et al., 2017b) as the very high decarbonisation requirements penalize CCS technologies with less than 99% capture rates. Most of the fossil fuel use with CCS occurs at point sources in the industry sector (Luderer et al., 2017c). A few 1.5°C pathways with very low energy demand do not include CCS at all (Grubler et al., 2017). Earlier studies showed 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 and the ability to remove carbon dioxide from the atmosphere in combination with bioenergy. This remains a valid finding for 1.5°C and 2°C pathways, which do not radically reduce energy demand and offer carbon neutral alternatives to liquids and gases that do not rely on bioenergy (see Section 2.3.3.4)

By mid-century, the majority of primary energy supply in 1.5°C pathways comes from alternative sources to fossil fuels. Electricity is predominantly provided by solar and wind power. As electricity is the dominant final energy carrier in the second half of the century, non-biomass renewables (including hydro, solar and wind power) make up the largest portion of primary energy supply by 2100 ranging between 200 and 480 EJ yr^{-1} (interquartile range, median 280 EJ yr^{-1}) (Luderer et al., 2014; Pietzcker et al.). At the end of the century, 60–90% of electricity generation (interquartile range; median 70%) is projected to come from non-biomass renewables. Nuclear power plays a much smaller role in the electricity sector with large disagreement between models and scenarios (Kim et al., 2014; Rogelj et al., 2017b). 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 scenarios (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 still project 200 EJ yr^{-1} of nuclear power in 2100. Bioenergy is a major supplier of primary energy for reasons discussed above (200–270 EJ yr^{-1} interquartile range, median 230 EJ yr^{-1}, in 2100) (Bauer et al., 2017b). In the majority of scenarios, the largest part of bioenergy is used in combination with CCS if it is available. As the energy transition is accelerated by several decades in 1.5°C pathways compared to 2°C pathways, residual fossil-fuel use without CCS is lower in 2050, while combined hydro, solar, wind power deployment is higher than in 2°C pathways. A detailed discussion of energy sector developments, and in particular electricity sector developments, in deep decarbonisation scenarios drawing also on energy-sector modelling is provided in Section 2.4.

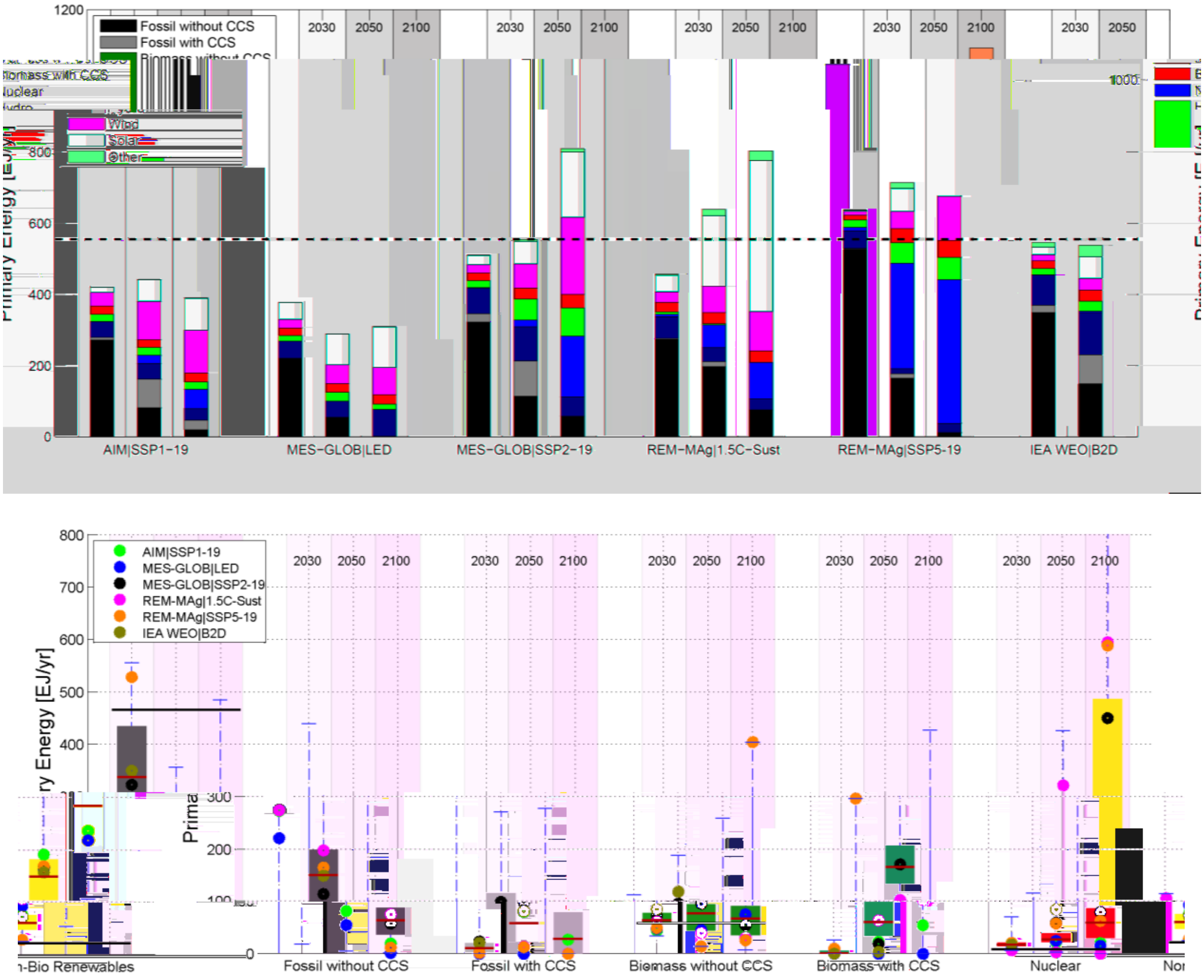


Figure 2.13: Primary energy supply for five selected 1.5°C pathways (top panel) plus the IEA's recently published B2D scenario (IEA / IRENA, 2017) and their relative location in the ranges for 1.5°C and 2°Cscenario classes (lower panel). The category 'Other' includes primary energy sources not covered by the other categories, for example. geothermal energy. Scenarios from Bertram et al. (2017), Fricko et al. (2017); Fujimori (2017), Grubler et al. (2017), Kriegler et al. (2017c), Rogelj et al. (2017b), van Vuuren et al. (2017b, see Section 2.3.2.1.. Scenarios from Bertram et al. (2017), Fricko et al. (2017), Fujimori (2017), Grubler et al. (2017), Kriegler et al. (2017c), Rogelj et al.)2017b), see Section 2.3.2.1 (lower panel). Black horizontal lines indicate values of primary energy supply in 2014 (IEA, 2016b).

2.3.3.2 *Land transformation*

An important further aspect of global transformation pathways is the role of the agricultural and land system (Clarke et al., 2014; Popp et al., 2017; Smith and Bustamante, 2014) described together under the umbrella of the AFOLU (Agriculture, Forestry, and Other Land Use) sector. This system is responsible both for food and feed production and for the production of biomass for energy or other uses (Smith and Bustamante, 2014). The demand for these agricultural products is thus a key driver for the mitigation challenges in this sector, together with technological change in the agricultural sector (Havlík et al., 2014; Weindl et al., 2015), changes in dietary patterns (Smith et al., 2013), trade, and interactions with other sectors (Popp et al., 2017). Assessment of available scenarios shows a large range of potential land use futures in 1.5°C pathways including pathways in which global forest cover is approximately kept constant and pathways in which it is increased by 20% or more due to afforestation and reforestation measures by the end of the century (Figure 2.14). Furthermore, the agricultural system is the major contributor of CH_4 and N_2O emissions that are very hard to eliminate with current technologies assumed in integrated models (Figure 2.14) (Gernaat et al., 2015). These increase in their relative importance in very stringent mitigation pathways, for example, through their impact on the remaining carbon budget (Section 2.2). Limiting demand for GHG-intensive foods is thus key and can be achieved through shifts to healthier and more sustainable diets (Springmann et al., 2016; Tilman and Clark, 2014) and lifestyles that limit food waste (Popp et al., 2017) (see also Chapter 4, and Section 2.4.4). Depending on societal choices and preferences, a 1.5°C pathway could be achieved while increasing forest cover over the 21st century and strongly reducing GHG emissions from agriculture (a reduction of 40% and more relative to 2010 by 2050) or, under alternative societal choices, while keeping forest cover approximately constant and higher, yet still decreasing agricultural GHG emissions until 2100. For example, (i) high agricultural yields and application intensified animal husbandry, (ii) implementation of best-available technologies for reducing non-CO_2emissions and full adoption of cultured meat in 2050, (iii) 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 (van Vuuren et al., 2017c). Section 2.4.4 provides a further discussion of mitigation pathways for the AFOLU sector. In addition to afforestation and reforestation, the AFOLU sector provides further potential for active terrestrial carbon storage, for example via land restoration, improved land management (Griscom et al., 2017) and biochar applications (Smith, 2016), which so far have not been adequately represented in the mitigation scenario literature. The deployment terrestrial carbon dioxide removal can impact the deployment of other CDR technologies, like BECCS (Section 2.3.4).

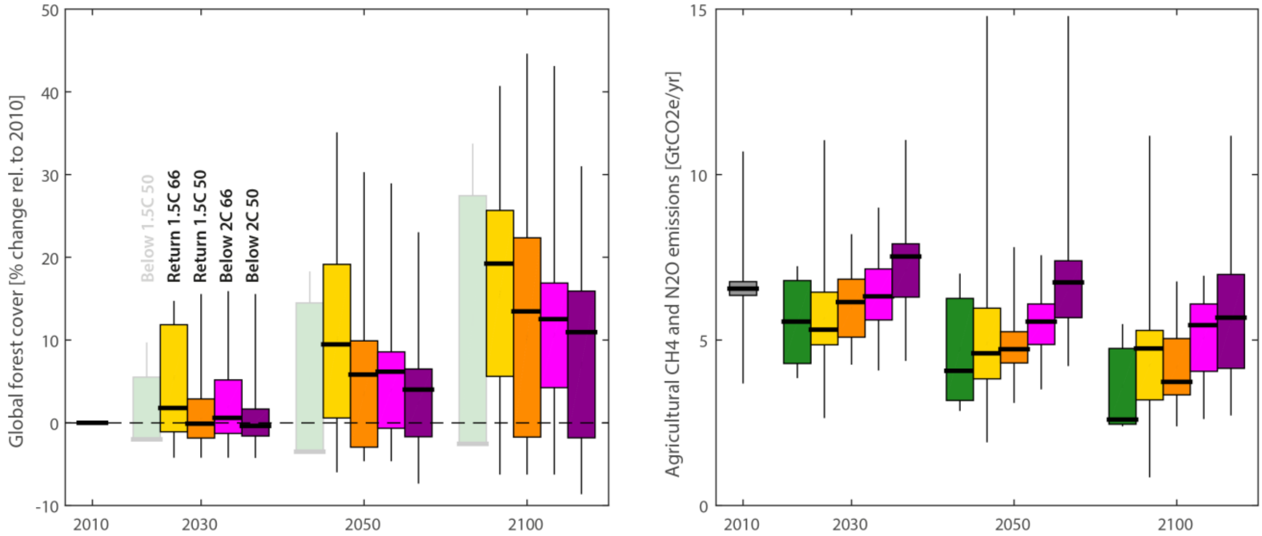


Figure 2.14: Illustration of land-use related transitions in transformation pathways. Change in global forest cover relative to 2010 (left panel) and global agricultural GHG emissions of CH_4 and N_2O (right panel, aggregated with the AR4 GWP-100 metric). Boxplots show median, interquartile range and full range. The legend for the scenario classes is provided in the top left panel. Classes are defined in Section 2.1. Forest data for "Below 1.5C 50" scenarios is shaded because it might be subject to strong model sampling bias, which requires more vetting once the scenario set is finalized. For comparison, in 1990 the world had 4128 million hectares (Mha) of forest; by 2015 this area had decreased to 3999 Mha (Keenan et al., 2015).

2.3.3.3 *Different portfolios of measures*

As discussed above, 1.5°C transition pathways are characterised by large-scale transformations of the energy, industry, and land sector (Bauer et al., 2017a; Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2017b). Already earlier in the AR5, it was highlighted that the choice of mitigation measures can play an important role for the attainment and cost of achieving stringent mitigation targets (Clarke et al., 2014). Be it for the energy, transport, buildings, industrial, or AFOLU sector, the assessment in this section also shows that multiple options and choices are available in each of these sectors to pursue the stringent emissions reductions required for a 1.5°C pathway. Because the overall emissions total under a pathway is limited by a geophysical carbon budget (Section 2.2), choices in one sector affect the efforts that are required from others (Clarke et al., 2014). The impact of either reduced or improved availability of key technologies on costs and achievability of stringent mitigation pathways has been explored with dedicated multi-model studies for questions related to 2°C (Krey et al., 2014a; Kriegler et al., 2014b; Riahi et al., 2015). Similar technology focussed multi-model studies are not yet available for questions related to 1.5°C, except of a study on the role of bioenergy in mitigation pathways, including 1.5°C pathways (Bauer et al., 2017b).Some single-model studies are available that explore this question either tangentially (Luderer et al., 2013; Rogelj et al., 2013) or more directly (Napp et al., 2017; van Vuuren et al., 2017c).

However, from the scenarios available to this assessment, a set of possible 1.5°C consistent mitigation portfolios can be identified, which differ between them in underlying socioeconomic and policy assumptions as well as models by which they are generated (see Sections 2.3.2, 2.4 and 2.5). Figure 2.15 shows five scenarios, which mitigation CO_2 in very different ways so as to stay within a carbon budget in line with staying below 1.5°C warming with 50% probability (S1: REMIND-MAgPIE|1.5C-Sust), only marginally overshooting (S2: AIM|SSP1–19, S3: MESSAGE-GLBM|LED), or returning to 1.5°C with at least 66% probability in 2100 (S4: MESSAGE-GLBM|SSP2-1.9, S5: REMIND-MAgPIE|SSP5-1.9) (Section 2.2, Section 2.3.1). The selection of 1.5°C scenarios agree on a full decarbonisation of the energy supply system by mid-century. This is a feature shared across 1.5°C pathways as well as with 2°C pathways. The additional emissions reductions in 1.5°C pathways compared to 2°C pathways come predominantly from energy end use sectors (transport, buildings, industry) .However, the selected scenarios show different options to apportion emissions across sectors, for example, by focussing on reducing the overall amount of CO_2 produced in the transport, buildings and industry sectors, and using limited contributions of CDR by the AFOLU sector (afforestation and reforestation, e.g., see scenarios S2, and S3 in Figure 2.15), 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 (e.g., see scenarios S4 and S5 in Figure 2.15). Major drivers of these differences are assumptions about demand and the stringency of near term climate policy (see the difference between early action in the scenarios S1–S3 and more moderate action until 2030 in the scenarios S4 and S5). Furthermore, the carbon budgets in each of these pathways depend also on the non-CO_2 mitigation measures assumed and achieved in each of these scenarios, particularly for agricultural emissions (Section 2.2). Finally, each of these portfolios has very different implications for the achievement of sustainable development objectives, as further discussed in Section 2.5.3.

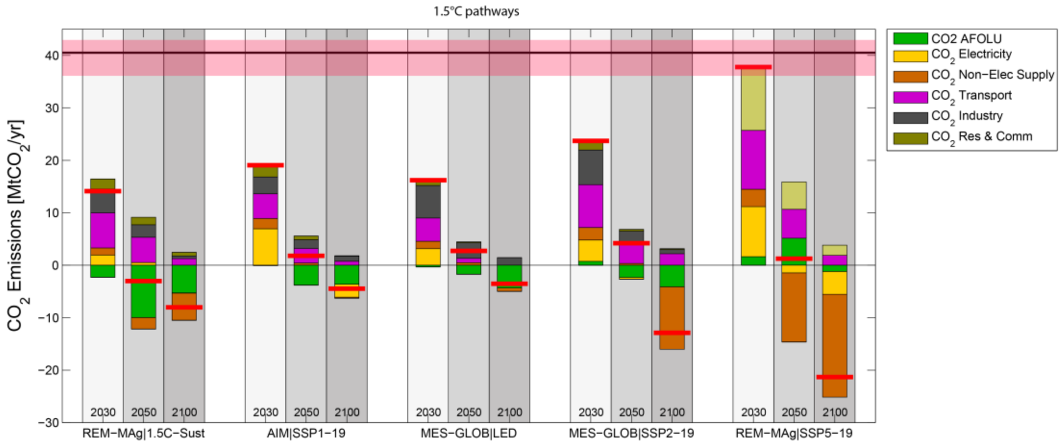


Figure 2.15: Emissions of CO_2 for selected 1.5°C pathways (Bertram et al., 2017; Fricko et al., 2017; Fujimori, 2017; Grubler et al., 2017; Kriegler et al., 2017c; Rogelj et al., 2017b) separated into direct emissions from six sectors. 'Res & Comm' stands for residential and commercial sector, i.e. direct CO_2 emissions from buildings. The lighter grey for REM-Mag|SSP5-19 indicates combined emissions from buildings and industry as the scenario did not report the split of these emissions onto the two sectors. The bold horizontal red lines indicate the net emissions. The horizontal black line indicates the best estimate of 2016 global CO_2 emissions (Le Quéré et al., 2017). The horizontal light red band indicates an estimated range of CO_2 emissions in 2030 under the NDCs (Roelfsema et al., 2017).

2.3.3.4 *Visions of carbon neutral energy systems*

There are a number of alternative visions of carbon neutral energy systems. Such visions are important as goal posts for the transition to a carbon-free future. The configuration of carbon-neutral energy systems projected in integrated mitigation pathway can vary widely, but they all share a substantial reliance on bioenergy. There are other visions with less reliance on bioenergy that are currently not yet comprehensively covered by global mitigation pathway modelling. One such vision is to further reduce energy demand for mobility and manufacturing to levels that make residual liquid fuels and gases use negligible as presented in a first-of-its kind low energy demand scenario (Grubler et al., 2017) which is part of this assessment. Associated measures and radical demand reduction scenarios are further assessed in Chapter 4 of this report.

Other visions rely on a complete substitution of liquids and gases use by electricity (Jacobson et al., 2017), hydrogen (Marbán and Valdés-Solís, 2007)or some other carbon-free energy carrier. Yet other visions propose the production of carbon-neutral hydrocarbons, e.g., via combination of hydrogen generated from renewable electricity and carbon dioxide captured from the atmosphere (Zeman and Keith, 2008). Alternatively, algae are considered as a bioenergy source with much more limited implications for land use and agricultural systems (Walsh et al., 2016). As an alternative to CDR measures with uncertainties about CO_2 storage, CDR measures with permanent storage (mineralisation and enhanced weathering) are investigated (Hartmann et al., 2013; Mazzotti et al., 2005). Progress in the understanding of the potential, economics and viability of these alternative ways to achieve and maintain carbon neutral energy systems can affect the characteristics of 1.5°C mitigation pathways assessed here.

2.3.4 ***Carbon dioxide removal in 1.5°C pathways***

Since all 1.5°C pathways in the literature deploy CDR technologies, it is important to carefully assess their use in these pathways. Three key questions emerge: What types of CDR measures are deployed at which scale in 1.5°C pathways? How strongly does reliance on CDR vary between 1.5°C pathways and how does this depend on other pathway characteristics? And how does this relate to questions about availability, policy implementation, and sustainable development implications that have been raised about CDR technologies? The first two questions are assessed in this section with the goal to provide an overview on CDR deployment and its contingencies in the available 1.5°C pathway literature. This information is taken up by Chapter 4 (Section 4.3.8.) to assess the third question in the context of the literature on techno-economic, societal and environmental aspects of CDR technologies. Individual CDR technologies will only be briefly introduced and discussed here to the extent this is needed for assessing the purpose, type, scale and timing of their use in 1.5°C pathways. For a detailed discussion of CDR technologies, the reader is referred to Chapter 4.

2.3.4.1 *CDR technologies and deployment levels in 1.5°C pathways*

A number of approaches to actively remove carbon dioxide from the atmosphere are increasingly discussed in the literature (Minx et al.). Approaches under consideration include the enhancement of terrestrial carbon storage in plants and soils such as afforestation and reforestation (Canadell and Raupach, 2008), soil carbon and biochar sequestration (Smith, 2016), improved land management and restoration of natural land (Griscom et al., 2017). Other approaches under consideration 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) (Gough and Upham, 2011; Keith and Rhodes, 2002; Obersteiner et al., 2001) and direct air capture with storage (DACS) using chemical solvents and sorbents (Keith et al., 2006; Socolow et al., 2011; Zeman and Lackner, 2004). Further approaches investigate the mineralisation of atmospheric carbon dioxide (Matter et al., 2016; Mazzotti et al., 2005) including enhanced weathering of rocks (Hartmann et al., 2013; Schuiling and Krijgsman, 2006; Strefler et al.). A fourth group of approaches under discussion is concerned with the sequestration of carbon dioxide in the oceans, for example. by means of ocean alkalinisation (Ilyina et al., 2013; Kheshgi, 1995; Rau, 2011). The costs, carbon removal potential and environmental side effects of several of these CDR measures have been investigated and compared, but large uncertainties remain (Fuss et al.; Psarras et al., 2017; Smith et al., 2015; The Royal Society, 2009) (see Chapter 4). 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).

Only some of these approaches have so far been considered in integrated assessment and other pathway models. 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 well below 2°C and 1.5°C pathways including additional CDR measures such as DACS have become available (Chen and Tavoni, 2013; Marcucci et al., 2017; Strefler et al., 2017). 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. Integrated assessment modelling has not sufficiently covered natural land restoration and land management options to remove carbon dioxide from the atmosphere, although these measures have low technological requirements and come with the potential for environmental co-benefits. The carbon dioxide removal potential of associated individual measures is limited (below or around 1 GtCO2yr^{-1}; excluding reforestation and avoided deforestation which are covered by IAMs), but when taken together have been estimated to be on the order of several $GtCO_2yr^{-1}$ (Griscom et al., 2017). Despite the evolving capabilities of IAMs in accounting for a wider range of CDR measures, this assessment will have to rely on the more consolidated research concerning the role of BECCS and afforestation / reforestation in 1.5°C pathways. Due to data availability constraints, the magnitude of net carbon uptake by the AFOLU sector (after it converted from a source to a sink of CO_2 emissions) is used as proxy for afforestation / reforestation and more broadly terrestrial CDR.

The amount, type of use and type deployment of CDR assumed in 1.5°C pathways varies widely (Figure 2.16). Overall CDR deployment over the period 2016–2100, including terrestrial (such as afforestation / reforestation) and geological CDR measures (such as BECCS and DACS), is substantial in most of the pathways in the literature (740 (620–890) $GtCO_2$ median and interquartile range). At the low end, pathways exist that limit CDR to 200 $GtCO_2$ coming entirely from terrestrial CDR measures with no or small use of fossil fuel CCS and BECCS. These are pathways with very low energy demand limiting the need for net negative emissions to neutralize fossil fuel emissions in excess of the 1.5°C TPB (Grubler et al., 2017) (Figure 2.11) and/or rapid shifts to sustainable food consumption and land use freeing up sufficient land areas for terrestrial CDR applications (van Vuuren et al., 2017d).

The use of CDR in deep mitigation pathways falls into two categories: compensating for residual emission at a given year to move more rapidly towards the point of carbon neutrality or to maintain carbon neutrality after it has been reached; and CDR deployment beyond the point of carbon neutrality to produce net negative emissions which draw down the cumulative amount of anthropogenic CO_2 in the atmosphere and thus can allow to establish a temporary overshoot of the 1.5°C TPB to increase the likelihood of returning below 1.5°C warming levels by the end of the century (Section 2.3.1). Both uses have equal importance in 1.5°C pathways (Figure 2.16, Table 2.6). This is a distinguishing feature from 2°C pathways. 1.5°C pathways rely on average more on net negative emissions (due to the smaller carbon budget compared to 2°C, Section 2.2), but even they reach the point of carbon neutrality several decades earlier than 2°C pathways, they do not deploy more, and in many cases even less, compensating CDR up to this point. This indicates that the more rapid drawdown of CO_2 emissions in 1.5°C pathways compared to 2°C pathways is achieved by additional deployment of mitigation measures rather than CDR measures, reflecting limitations on the upscaling of these measures before mid-century in the integrated pathways. Comparing median levels, end-of-century net cumulative CO2 emissions are roughly 600 $GtCO_2$ smaller in 1.5°C than in 2°C pathways, with approximately two thirds coming from further reductions of gross CO2 emissions and the other third from increased CDR deployment. As a result, total CDR deployment in 1.5°C pathways is only ca. 30% larger (by 180 $GtCO_2$ based on the medians) than in probably 2°C pathways (Figure 2.16).

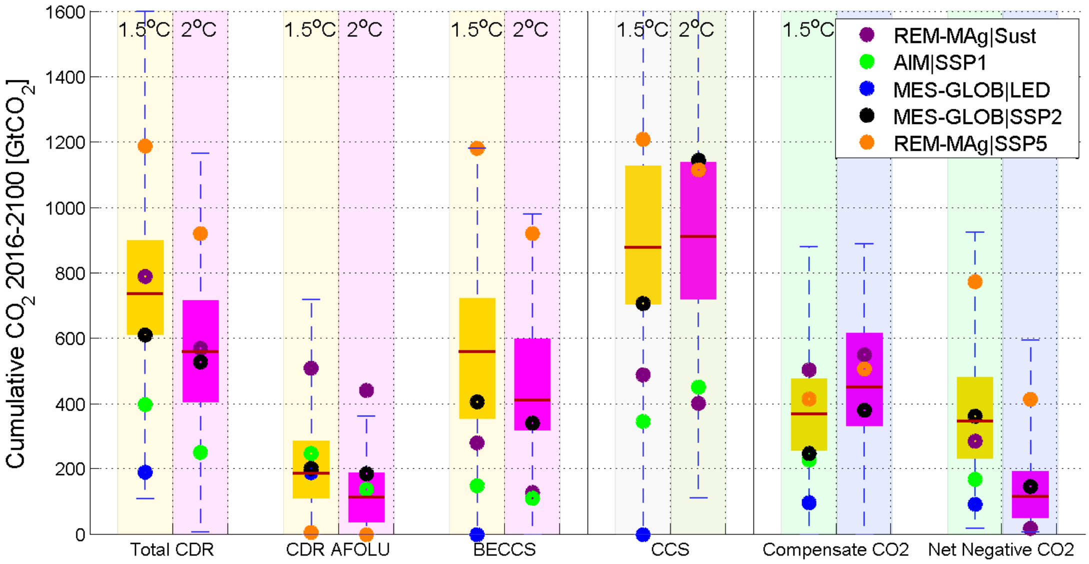


Figure 2.16: Cumulative CDR and CCS deployment in 1.5°C and below 2°C pathways in the literature as reported in the database collected for this assessment (Section 2.1). Total CDR comprises all forms of CDR, including CDR AFOLU, BECCS and in a few pathways other CDR measures like DACS. It does not include CCS combined with fossil fuels (which is not a CDR technology as it does not actively remove CO2 in the atmosphere). CDR AFOLU describes the cumulative amount of net negative CO2 emissions in the AFOLU sector. CCS comprises all forms of CCS, including from fossil fuel installations. ‘Compensate CO2’ depicts the cumulative amount of CDR that is used to neutralize residual CO2 emissions in a given year. ‘Net negative CO2’ describes the additional amount of CDR that is used to produce net negative emissions and reduce the cumulative amount of anthropogenic CO2 emissions in the atmosphere from peak levels. The two quantities taken together yield the total amount of CDR depicted in the leftmost boxplots. Selected 1.5°C pathways (Bertram et al., 2017; Fricko et al., 2017; Fujimori, 2017; Grubler et al., 2017; Kriegler et al., 2017c; Rogelj et al., 2017b) used as illustrative examples in this section are highlighted.

These insights are relevant for the debate about the feasibility of ramping up CDR deployment at rates projected in the pathways (Nemet et al., 2017). They are also relevant for the discussion whether expectations about future availability of CDR would lead to an actual reduction of near term mitigation efforts (Anderson and Peters, 2016; Geden, 2015).The 1.5°C pathway literature does not provide support for a wait and see approach. In essence, the 1.5°C budget is so tight, that rapid and stringent mitigation as well as rapid upscaling of CDR deployment occur simultaneously in 1.5°C pathways. Furthermore, the comparison of 1.5°C and 2°C pathways shows that the temperature goal from 2°C to 1.5°C results primarily in a further strengthening of emissions reduction efforts and only a limited increase in CDR deployment. However, the literature has pointed out that the availability of CDR affects the shape of cost-effective mitigation pathways towards climate goals (Krey et al., 2014a; Strefler et al., 2017), and that emissions gap estimates (UNEP, 2017) are dependent on them. Thus the use of this benchmarks in climate policy makes implicit assumptions about CDR availability which should be made more explicit (Fuss et al., 2014b; van Vuuren et al., 2017a).

Concerning the use of individual CDR measures in 1.5°C pathways, the largest contribution comes from BECCS (560 (350–750) $GtCO_2$), but AFOLU CDR also plays a major role (190 (100–290) $GtCO_2$ median and interquartile range). This assessment needs to be seen as preliminary given the current state of knowledge. As additional CDR measures are built into integrated assessment models, the prevalence of BECCS is expected to be reduced. Particularly the addition of further terrestrial CDR measures such as soil carbon management and biochar (Smith, 2016) and land restoration and management (Griscom et al., 2017) can have an impact here. Terrestrial CDR measures and BECCS are partial substitutes due to their shared demand for land. When deployed simultaneously, overall CDR increases, while the deployment of each individual measure is reduced (Humpenöder et al., 2014).There is also correlation between the choice of afforestation vs. BECCS and the extent to which CDR is used for compensating residual CO_2 emissions at a given point in time versus excess emissions in the past. This is due to the timing of the two measures in the mitigation pathways. Although the AFOLU sector is a net sink by 2100 in almost all 1.5°C pathways, the amount of end-of-century CO_2 uptake by this sector is much smaller compared to BECCS deployment in the energy sector (Figure 2.15). This reflects the fact that CO_2 uptake from afforestation ceases once forests are grown. In 1.5°C pathways afforestation is mostly deployed before and around carbon neutrality, while BECCS is projected to be used predominantly in the 2nd half of the century.

The large variation of scale and type of CDR deployment between 1.5°C pathways stems from differences in underlying assumptions about socio-economic drivers (Riahi et al., 2017), energy (Grubler et al., 2017).and food demand (van Vuuren et al., 2017d), availability of CCS (Grubler et al., 2017; Krey et al., 2014a) and afforestation (Popp et al., 2014b, 2017), and near term policy choices (Kriegler et al., 2017d; Strefler et al., 2017). The impact of these assumptions on CDR deployment can be highlighted by comparing CDR use in selected 1.5°C pathways that differ considerably in these dimensions (Figure 2.17). Some scenarios dedicate half or more of the CDR to the compensation of residual CO_2 emissions (REM-Mag|Sust, AIM|SSP1-19, MES-GLOB|LED; Bertram et al., 2017; Fujimori, 2017; Grubler et al., 2017; Rogelj et al., 2017b), while other scenarios use half or more of the CDR to compensate for excess emissions in the past (MES-GLOB|SSP2-19, REM-Mag|SSP5-19; Fricko et al., 2017; Kriegler et al., 2017c; Rogelj et al., 2017b). One scenarios specifically excludes the use of CCS and BECCS (Grubler et al., 2017) and another one does not account for afforestation (REMI-Mag|SSP5-19) (Kriegler et al., 2017c). In both cases 1.5°C pathways can be identified.

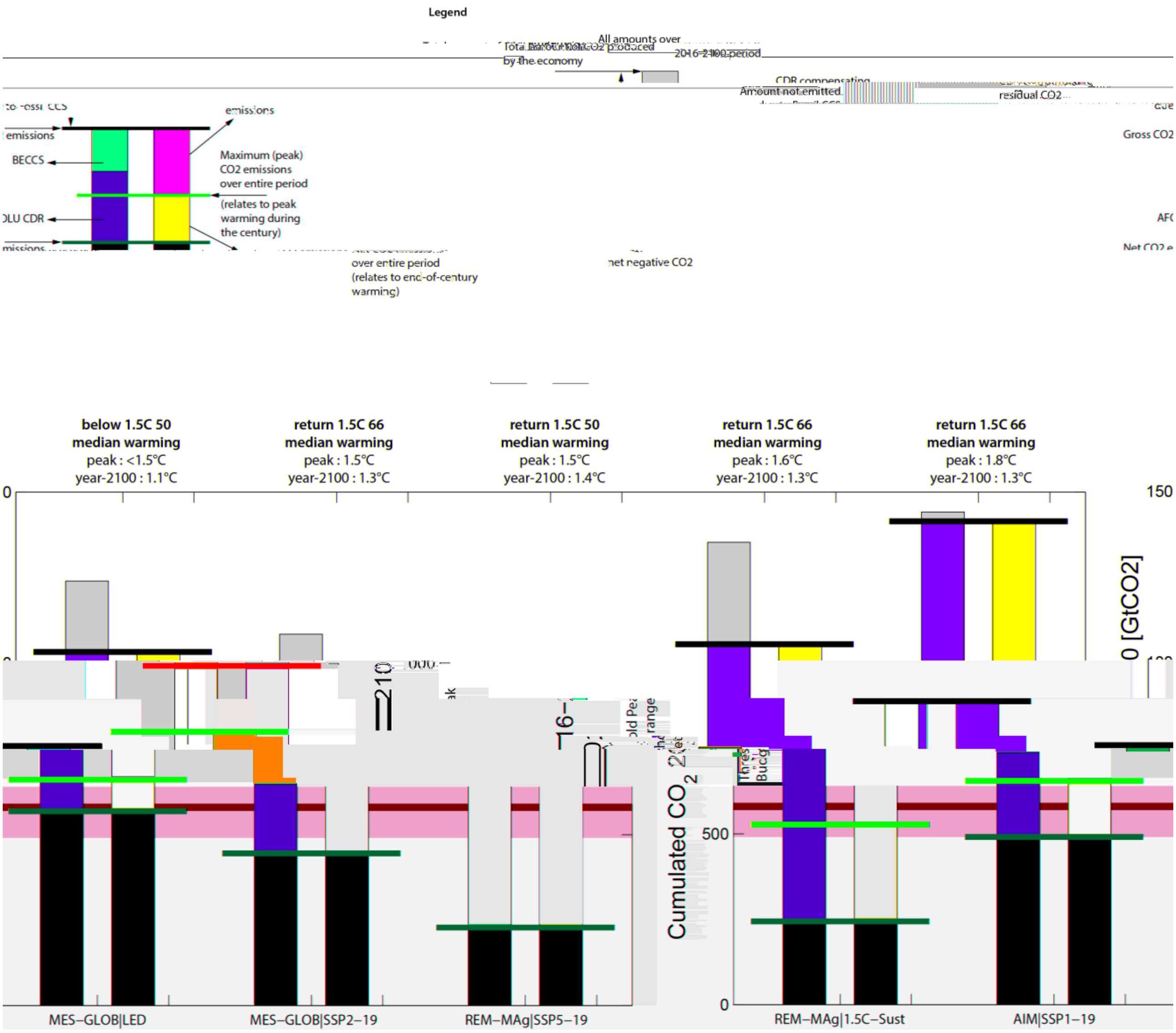


Figure 2.17: Cumulative CO_2 emissions accounting for selected 1.5°C pathways (Bertram et al., 2017; Fricko et al., 2017; Fujimori, 2017; Grubler et al., 2017; Kriegler et al., 2017c; Rogelj et al., 2017b). See top panel for explanation of the barplots. Total CDR is the difference between gross (black horizontal bar) and net (brown horizontal bar) cumulative CO2 emissions over the period 2016–2100.Total CCS is the sum of the BECCS (orange) and fossil fuel CCS (grey) contributions. Cumulative net negative emissions are the difference between peak (red horizontal bar) and net (brown) cumulative CO2 emissions. The blue shaded area depicts the estimated likely range of the 1.5°C Threshold Peak Budget (TPB) (median shown as blue line).

2.3.4.2 *Sustainability implications of CDR deployment in 1.5°C pathways*

Strong concerns about the high level of CDR deployment in deep mitigation pathways have been raised on sustainable development grounds (Williamson and Bodle, 2016). There is substantial uncertainty about the adverse effects of large-scale CDR deployment on the environment and societal sustainable development goals (Fuss et al., 2016; Shepherd, 2012). A detailed assessment of the literature on potentials, implementation constraints, and sustainable development implications of CDR measures is provided in Chapter 4 (Section 4.3.8) of this report. Here, we describe some of the key potential environmental side effects to provide initial context for our discussion of land use, geological storage and bioenergy deployment implications of CDR use as projected in 1.5°C pathways. This will be followed up by Chapter 4, which contrasts these results with other strands of literature on limitations of CDR. To this end, it is important to note that integrated modelling aims to explore a range of developments compatible with 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), 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 1.5°C pathways in the literature and assessed in this report were developed within a larger sustainable development context (Bertram et al., 2017; Grubler et al., 2017; van Vuuren et al., 2017c).

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 measures – like afforestation and BECCS that directly compete with other land uses – could have significant impacts on agricultural and food systems (Creutzig et al., 2012; Kreidenweis et al., 2016; Popp et al., 2017; Smith et al., 2015) as well as ecosystems (Boysen et al., 2016; Heck et al., 2016). BECCS using dedicated bioenergy crops could substantially increase agricultural water demand (Bonsch et al., 2014) and nitrogen fertilizer use. DACS and BECCS rely on CCS and would require safe storage space in geological formations. Some approaches like DACS can have high energy and water demand. 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).

An important consideration for CDR which basically shifts carbon from the atmosphere to the geological, oceanic or terrestrial carbon pools is the permanence of carbon stored in these different pools (Jones et al., 2016; Matthews and Caldeira, 2008) (see Chapter 4 for a more detailed discussion). Terrestrial carbon storage is subject to particular concerns about permanence as terrestrial carbon can be returned to the atmosphere on decadal timescales by a variety of mechanisms such as soil degradation and forest fires. There are similar concerns about outgassing of CO_2 from ocean storage. Understanding of the assessment and management of the potential risk of CO_2release from geological storage of CO_2 has improved since IPCC (2005) with experience and the development of practices in geological storage projects (Pawar et al., 2015). Geological storage practice includes a set of steps to assess (e.g., including site selection and characterization, risk identification, vulnerability assessment, and exposure assessment), manage (e.g., risk evaluation, risk treatment, and monitoring and evaluation), and communicate risk with stakeholders in storage projects (Pawar et al., 2015). Successful risk management would prevent sustentative leakage from geological storage, and associated storage practices would improve with further storage experience. The literature on the potential environmental impacts from the leakage of CO_2 – and approaches minimize these impacts should a leak occur – has also grown and is reviewed by (Jones et al., 2015b).

Figure 2.18 shows the land requirements for BECCS and afforestation in the selected 1.5°C pathways, including three that were developed following a sustainable development paradigm (REM-Mag|1.5C-Sust, Bertram et al., 2017; AIM|SSP1-19, Rogelj et al., 2017b; MES-GLOB|LED, Grubler et al., 2017). In pathways that allow for large-scale afforestation in addition to BECCS, land demand for afforestation is larger than for BECCS. This is because the amount of carbon to be stored in soils and trees on a unit of land is limited, while BECCS is assumed to allow continuous sequestration of CO_2 from biomass year by year (Smith et al., 2015). The combined land demand for the two CDR measures can be very substantial by the end of the century, up to the magnitude of the current global cropland area. In the modelled pathways, this is achieved in particular by a conversion of pasture land, and to more limited extent cropland for food production, as well as expansion into natural land. However, implementing such large scale changes in land use would pose significant governance challenges (Buck, 2016; Unruh, 2011) (see Chapter 4). These dynamics are heavily influenced by assumptions about future population levels, food crops and livestock demand (Popp et al., 2017).

An important finding from the pathway literature is that demand for bioenergy is robust independently of the availability of BECCS as CDR option (Bauer et al., 2017b). If BECCS is available, most of the bioenergy use in mitigation pathways is combined with CCS (Rose et al., 2014a). However, if BECCS is not available, large amounts of bioenergy are still used to substitute fossil-fuel based liquids, gases and solids (Bauer et al., 2017b; Klein et al., 2014). In contrast, CCS deployment can be significantly increased if BECCS and, DACS are added as CDR measures compared to scenarios that only allow for CCS at fossil fuel installations. (Marcucci et al., 2017; Rogelj et al., 2017b).

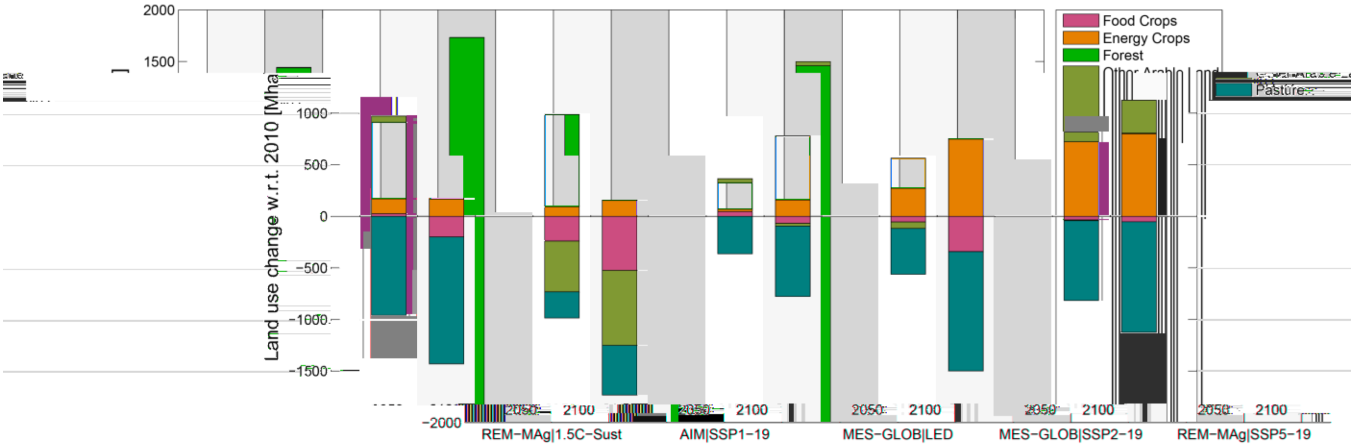


Figure 2.18: Land use changes in 2050 and 2100 in selected 1.5°C pathways (Bertram et al., 2017; Fricko et al., 2017; Fujimori, 2017; Grubler et al., 2017; Kriegler et al., 2017c; Rogelj et al., 2017b).

The quantity of CO_2 stored in geological formations over this century in 1.5°C pathways ranges from 880 (780–1130) $GtCO_2$, which is similar to what is found in 2°C pathways (including CCS at fossil fuel and bioenergy installations; median and interquartile ranges from scenario database to this report) (Figure 2.16). However, the 1.5°C pathways developed under a sustainable development paradigm show lower CCS deployment, the very low energy demand scenario even completely excludes it (Grubler et al., 2017). The IPCC (2005) found that available evidence suggests that, worldwide, it is likely that there is a technical potential of at least about 2000 $GtCO_2$ of storage capacity in geological formations, which is larger than the global demand for storage across all of the 1.5°C pathways in the database collected for this chapter. 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) there have been detailed regional surveys of storage capacity (e.g., Vangkilde-Pedersen et al., 2009; Wei et al., 2013; Bentham et al., 2014; Riis and Halland, 2014; Ogawa et al., 2011; DOE et al., 2012; Warwick et al., 2014) and improvement and standardisation of methodologies (e.g., Bachu et al. 2007a,b). Dooley (2013) synthesised published literature at that time on both the global geological storage resource as well as the potential demand for geologic storage of mitigation pathways, and found that the cumulative demand for CO_2 storage was small compared to their practical capacity (as defined by Bachu et al. 2007a) of 3900 $GtCO_2$ storage capacity 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 8000 to 55000 $GtCO_2$ (accounting for differences in detailed regional and local estimates), again 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.

[Note on the SOD: The discussion of the relationship between bioenergy and BECCS will be further updated in the TOR]

2.3.5 *Implications of near term action in 1.5°C pathways*

Less ambitious CO_2 emissions reductions in the near term implies steeper and deeper reductions afterwards. 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 (Collins et al., 2013). Besides this clear geophysical trade-off over time, delaying GHG emissions in the near-term (i.e., over the coming years and decade) also leads to 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. IPCC AR5 hence 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). Delaying emissions reductions and mitigation actions over the coming decade can lead to the continued deployment of unabated fossil-fuel technologies. Studies show that to still meet stringent climate targets despite near-term delays in emissions reductions, models need to prematurely retire carbon-intensive infrastructure, in particular coal without CCS (Bertram et al., 2015a; Johnson et al., 2015). These insights are further supported by estimates of committed emissions due to fossil fuel-based infrastructure (Davis and Socolow, 2014; Seto et al., 2016). Studies in the literature generally have focussed on delayed action until 2030 in the context of meeting a 2°C goal (Bertram et al., 2015a; Johnson et al., 2015; Riahi et al., 2015). 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 pathways. Scenarios created by the ADVANCE project (Luderer et al., 2016b) allow comparison of the implied emission reduction rates between scenarios that meet a 1.5°C objective starting in 2020 (global mean temperature rise in 2100 is limited with >60% probability) and "well below 2°C" scenarios starting from NDC levels in 2030 (global mean temperature rise limited to below 2°C with >66% probability during the 21st century). They show that the implied transitional emissions reduction rates are very similar in the first two decades. Both scenario categories project global CO_2 emissions from fossil fuels and industry to decline at an annual rate of about 1.4 $GtCO_2 yr^{-1}$ after 2020 and 2030, respectively, indicating comparable transitional challenges.

All available 1.5°C pathways see global mitigation action before 2030 leading to global GHG emissions declining by 2030 (Section 2.3.3). This allows for a comparison with estimated emissions in 2030 implied by the Nationally Determined Contributions (NDCs) submitted by Parties to the Paris Agreement. Altogether, these NDCs are assessed to result in global GHG emissions on the order of 49–58 $GtCO_2$-eq yr^{-1} in 2030 (Rogelj et al., 2016a; UNFCCC Secretariat, 2016). More recent NDC studies have not fundamentally changed this range (Fawcett et al., 2015; Fujimori et al., 2016; Hof et al., 2017; Iyer et al., 2015b; Rogelj et al., 2016a, 2017a; Rose et al., 2017; Sanderson et al., 2016; Vandyck et al., 2016). In contrast, 1.5°C scenarios available to this assessment show an interquartile range of 25 to 41 $GtCO_2$-eq yr^{-1} in 2030. Modelling studies that explicitly attempted to design scenarios in line with 1.5°C starting from 2030 GHG levels in line with the NDCs report that the large majority of models failed to produce such a scenario (Luderer et al., 2016b) or only under assumptions of global cooperation and sustainable lifestyles which would require great efforts to materialise in the real world (Rogelj et al., 2017a).This indicates 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).

2.4 Disentangling the whole-system transformation

2.4.1 *Key characteristics of transitions in 1.5°C pathways from today until mid-century*

Transition from today to middle-century presents the central role in the whole transition in 1.5°C pathways. Fundamental transitions can be observed from IAM and other sector scenarios (Section 2.3, and Section 2.4) underpinning the stringent declines in CO_2 and other emissions by the middle of the century (Section 2.3.1), and which basically make the transition, in a time period of about three decades. There is a wide variety of pathways consistent with achieving the stringent net CO_2 emissions phase-out to stay within a 1.5°C carbon budget (Section 2.2, Section 2.3), therewith limiting global mean temperature increase to 1.5°C relative to preindustrial levels. However, despite their diversity, these pathways also share some key characteristics. Table 2.9 provides a list of characteristics based on the assessment in this chapter.

1.5°C pathway characteristic	**Supporting information**	**Reference**
Rapid and profound near-term decarbonisation of energy supply	Strong upscaling of renewables and sustainable biomass, a rapid phase-out of unabated (no CCS) fossil fuels combined with rapid deployment of CCS lead to a zero-emission energy supply system by mid-century.	Section 2.4.2
Greater mitigation efforts on the demand side	All end-use sectors show significant demand reductions beyond the reductions projected for 2°C pathways, already by 2030. Demand reductions from integrated models for 2030 and 2050 lie well 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 is covering significant larger shares of the total demand by mid-century.	Section 2.4.3.2 Section 2.4.3.3
Comprehensive emission reductions are implemented in the coming decade	Net annual CO_2 emissions are reduced to 18–28 $GtCO_2\ yr^{-1}$ by 2030 and to –1 to 3 $GtCO_2\ yr^{-1}$ in 2050, reaching carbon neutrality by mid-century or shortly thereafter in scenarios limiting warming to 1.5°C in 2100 with greater than 66% probability. GHG emissions in these scenarios are reduced to 25–39 and 5–10 $GtCO_2$–eq yr^{-1} in 2030 and 2050, respectively. Aiming to limit warming to 1.5°C without overshoot requires deeper reductions by 2030, and similar reductions by 2050. If allowing overshoot and having a lower 50–66% probability of returning warming to below 1.5°C in 2100, CO_2 emissions in 2030 can be about 5–10 $GtCO_2\ yr^{-1}$ higher, and between 0–9 $GtCO_2\ yr^{-1}$ in 2050. When attempting to reach 1.5°C scenarios, either with or without overshoot, from higher 2030 emissions studies indicate many failed attempts.	Section 2.3.1.2
Additional reductions, on top of reductions from both CO_2 and non-CO_2 required for 2°C, are mainly from CO_2	All climate forcers, including CO_2, non-CO_2 GHGs and aerosols, are strongly reduced by 2030 and until 2050 in 1.5°C scenarios. The greatest difference to 2°C scenarios, 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 0.8-2.9 trillion 2010USD yr^{-1}globally to 2050. Investments in fossil fuels decline, with investments in unabated coal halted by 2030 in most 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 and measure portfolio. 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 terrestrial CDR measures (mostly afforestation) of 1-4 $GtCO_2yr^{-1}$ and deployment of BECCS at a scale of 2.5–7.5 $GtCO_2yr^{-1}$ (interquartile ranges), depending on the level of energy demand reductions and mitigation in other sectors. Some 1.5°C scenarios are available that do not use BECCS. Deployment of terrestrial CDR and BECCS tend to substitute each other, i.e. pathways with higher levels of terrestrial CDR tend to have lower deployment of BECCS.	Section 2.3.3 Section 2.3.4.1

Table 2.9: Overview of key characteristics of 1.5°C pathways.

2.4.2 *Energy supply*

Energy transitions play a key role in low CO_2 emission pathways (Bruckner et al., 2014; Clarke et al., 2014). In mitigation pathways consistent with the 1.5°C target, a rapid transition towards a zero or negative CO_2 emission energy system is crucial (Rogelj et al., 2015a). Compared with to limiting warming to 2°C, both the pace and magnitude of the energy transition are more rapid when limiting warming to 1.5°C. Two characteristics are typical in 1.5°C pathways: 1) rapid growth in the share of energy derived from low carbon sources including renewables, nuclear, and fossil fuel with CCS, 2) BECCS which can provide carbon dioxide removal (CDR). For both characteristics, the pace of change and associated investment are potential hurdles.

2.4.2.1 *Evolution of primary energy contributions over time*

Based on the mitigation pathways consistent with the 1.5°C target from the scenario database from IAMs, CO_2 emissions from energy supply would need to decline to zero sometime between 2030 and 2060, with continued large decreases thereafter. Among the IAMs, the WITCH model reaches negative emissions soonest, by 2030, while the AIM model is latest at 2050 to 2060.

Renewable energy, including biomass, hydro, solar, wind, and geothermal, develops rapidly in all 1.5°C scenarios (Table 2.10). By 2050, renewable energy provides more than half of total primary energy in these scenarios from IAMs (Figure 2.13), with the largest portion from bioenergy. Wind and solar together, however, provide nearly as much energy, and have a much faster projected annual growth rate over 2020–2050. Nuclear power exhibits a moderate increase in the future for the average of these scenarios. In some mitigation pathways, however, both the absolute capacity and share of power from nuclear generators declines.

In addition to IAM-generated pathways, there are also sector-based analyses on energy demand and supply options. Even though these were not 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 100% renewable energy by 2050 (Clack et al., 2017; Creutzig et al., 2017; Jacobson, 2017), which describe what is entailed for large potential for solar and wind. There are also studies show the role of nuclear energy in mitigation of GHGs in the whole energy system could be large (Berger et al., 2017; Hong et al., 2015; International Energy Agency (IEA), 2017; Xiao and Jiang, 2017). BECCS could also contribute, but faces challenges related to its land use and impact on food supply (Burns and Nicholson, 2017). As in the AR5 for 2°C emission pathways, the results of IAMs were consistent with sectoral analyses.

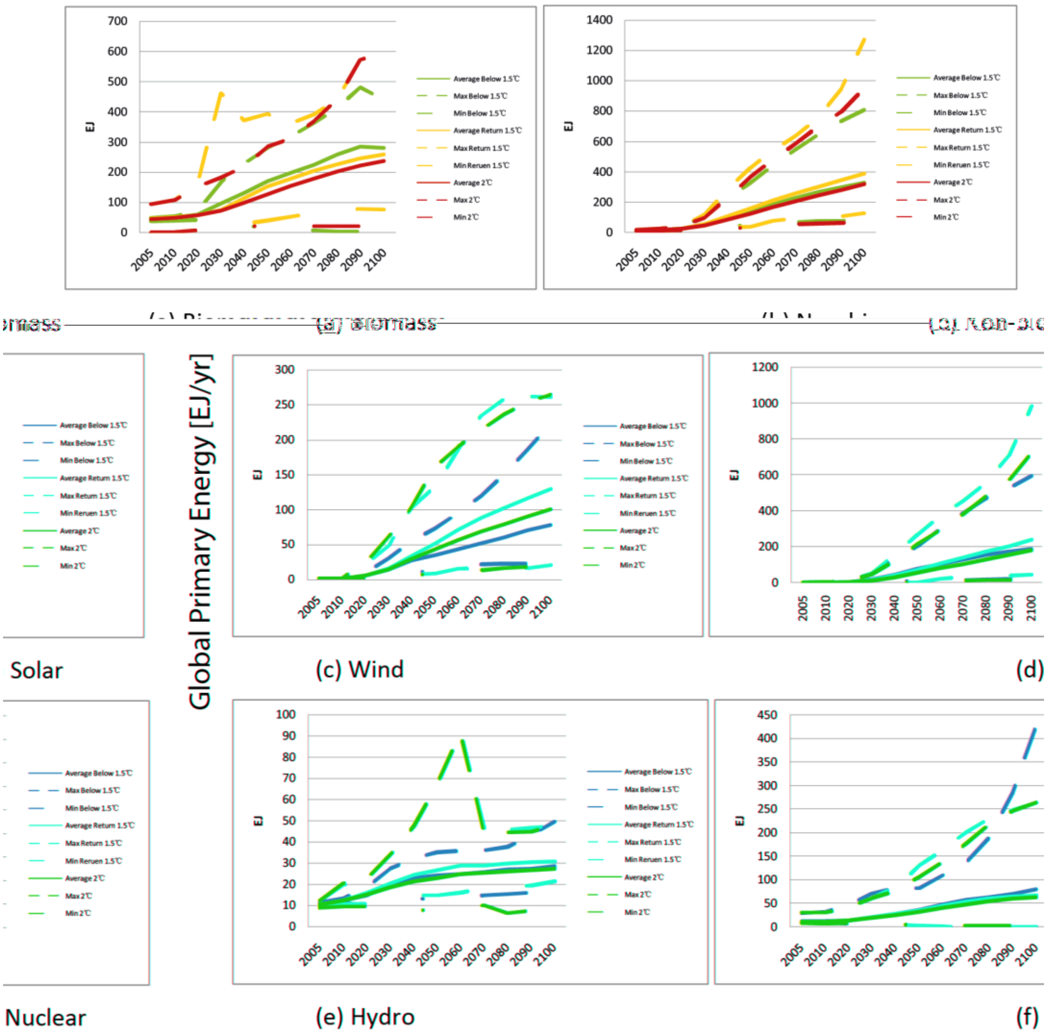
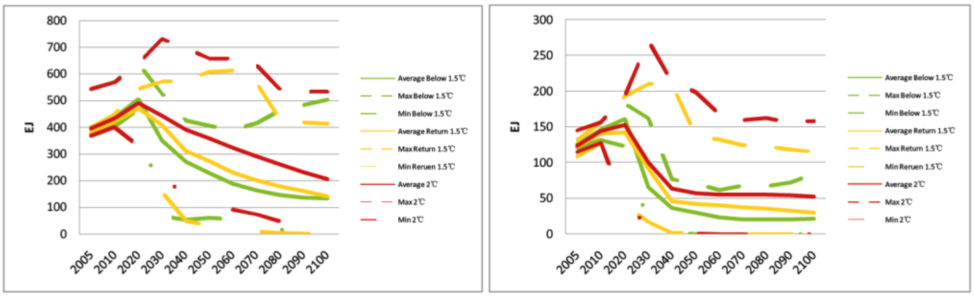
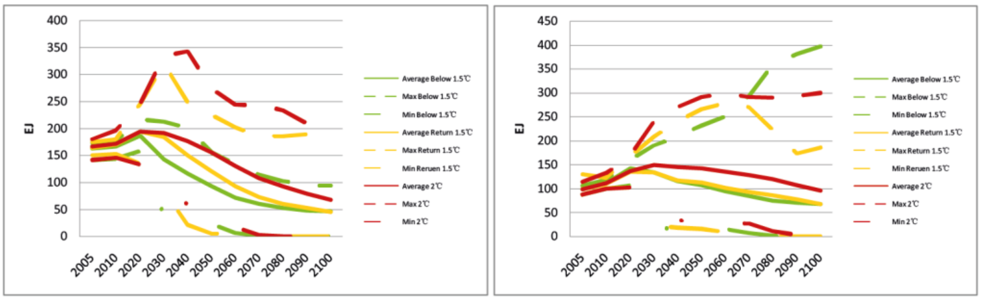


Figure 2.19: Low carbon primary energy evolutions in 1.5°C and 2°C scenarios.

Overall use of fossil fuels to provide energy decreases rapidly after 2020 in nearly all 1.5°C scenarios, although there are variations between specific fossil fuel types. In particular, coal demand reduction is much faster than that for fossil fuel as whole. Combined with the growth of non-fossil energy, coal's share of energy decreases from slightly more than one-quarter of global supply in 2020 to just under 7% in 2050 (average across scenarios). Before 2050, the natural gas trend is more complex, with demand through 2050 highly diverse across scenarios. Some show rapid decreases after 2020, whereas in others demand continues increasing through 2050 (see Figure 2.14). Scenarios with higher demand for natural gas adopt CCS for natural gas use. Like coal, oil demand decreases in these scenarios and its share of global primary energy drops by more than half. The transition also implies social impacts such as rapid shifts in employment – which occurred, for example, in the reduction of coal use from 2014 to 2016 – and such impacts raise challenges for the energy transition which go beyond the cost analyses in IAM and sectoral analyses (Shi, 2017).



(a) Fossil fuel (b) Coal



(c) Oil (d) Natural Gas

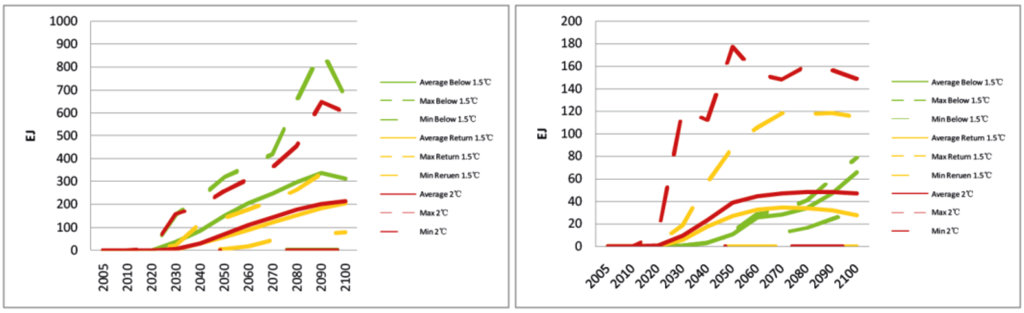
Figure 2.20: Fossil fuel energy demand transition in 1.5°C scenarios and 2°C scenarios.

	2020 Share (%)	2050 Share (%)	2020 Demand (EJ)	2050 Demand (EJ)	Annual growth (%)
Renewables	13.6 (9.9 to 16.2)	56.2 (30.9 to 86.3)	79 (63 to 95)	311 (230 to 491)	4.7
Wind+Solar	1.6 (1 to 3.5)	24.4 (7.9 to 44.4)	9 (5 to 17)	127 (67 to 197)	9.5
Biomass	9.5 (6.8 to 12.8)	26.8 (15.2 to 45.8)	55(42 to 68)	156 (67 to 310)	3.5
Nuclear	2.3 (1.5 to 3.4)	6.6 (0.7 to 13.8)	13 (9 to 18)	42 (4 to 117)	3.9
Fossil Fuels	84.2	40.3	489 (435 to 585)	223 (44 to 587)	–2.6
Coal	26.2	6.9	152 (130 to 193)	38 (2 to 131)	–4.5
Oil	33.7	15.2	196 (166 to 237)	84 (36 to 197)	–2.8
Gas	24.8	16.5%	141(115 to 195)	101(11 to 258)	–1.1%

Table 2.10: Overview of energy supply system transformation characteristic. Data from (Riahi et al., 2017; Rogelj et al., 2017b). (Note: these ranges will be updated as more studies and scenarios are submitted and become available).Values indicate means, bracketed values the minimum maximum range.

2.4.2.2 *Deployment of Carbon Capture and Storage*

CCS is deployed in all mitigation pathways consistent with 1.5°C shown in Figure 2.20 and grows to have a large role between 2020 and 2050. In mitigation pathways that do not phase out the use of coal for energy (Figure 2.20b), much of the CO_2 emissions to the atmosphere from coal are avoided with CCS (see Figure 2.21a). Some mitigation pathways, however, do phase out coal by 2050 (for example, the 1.5°C REMIND-MAgPIE pathways) and in these pathways CCS is deployed for only a small fraction of the limited coal use between 2020 and 2050 (see Figure 2.20b). In mitigation pathways with substantial remaining use of natural gas for energy (Figure 2.20d), much of the CO_2 emissions to the atmosphere from natural gas are avoided with CCS by 2050 (see Figure 2.21b). Mitigation pathways consistent with 1.5°C with higher coal or natural gas demand, exhibit higher penetration of CCS for those fuels, while those pathways with lower demand, achieve 1.5°C with more limited application of CCS to coal or natural gas, respectively.



(a) Biomass (b) Coal

(c) Natural gas

Figure 2.21: CCS deployment in 1.5°C scenarios and 2°C scenarios.

There is uncertainty in the future deployment of CCS given the limited pace of current deployment. The current lack of incentives for large-scale implementation of CCS is associated with the current slow pace of CCS deployment. In the pathways considered in this section, there is rapid deployment soon after 2020. It also is noted, that the relevant technologies and methods would evolve, and to varying degrees, respond to the challenges and risks of CCS (Bruckner et al., 2014; Clarke et al., 2014; Riahi et al., 2017). Given the importance of CCS in mitigation pathways and its current slow pace of improvement, there is a need to further develop the technology in short term to make enable large scale deployment of CCS as an option. Chapter 4 discusses how to accelerate progress on CCS.

2.4.2.3 *Pace of change*

Power generation sector is most important sector in the transition, and need to make change in a rapid rate. Figure 2.22 presents the newly installed capacity per year. All low carbon power generation need to go much beyond than today's development pace. From the figure, there is not big increase for newly installed capacity per year for wind, solar and biomass, from 2020 to 2030, but nuclear power need to departure in near future. After 2030, all newly installed capacity for low carbon power need to go much beyond than today's pace.

In all mitigation pathways shown in Figure 2.22, BECCS needed to achieve the deep cuts of CO$_2$ emissions consistent with 1.5°C carbon budget, however, some scenarios implement significantly more BECCS than others. By 2050 BECCS is projected to take up 59% (17% to 95%) of total biomass demand (see Figure 2.22c). Demand for BECCS is on average 102 EJ yr^{-1} (19 EJ yr^{-1} to 296 EJ yr^{-1}) by 2050 for the mitigation pathways shown in Figure 2.22c, on average nearly as much as wind and solar combined and nearly half as much as total fossil fuel energy (and more than worldwide use of oil). Higher use of BECCS in 1.5°C mitigation pathways is correlated with higher fossil fuel demand, which requires CO$_2$ emissions reductions from BECCS to compensate for the fossil fuel-related emissions that are not captured by CCS. Conversely, lower use of BECCS in 1.5°C mitigation pathways is correlated with lower fossil fuel demand. Such trade-offs are illustrated in Figure 2.14, showing scenarios with similar carbon budgets with one case relying heavily on BECCS and the phase-out of fossil fuel demand (see Figure 2.22a), and the other case relying on rapidly increasing the penetration of low carbon power generation such as renewables, nuclear and fossil fuels with CCS (see Figure 2.22b) .

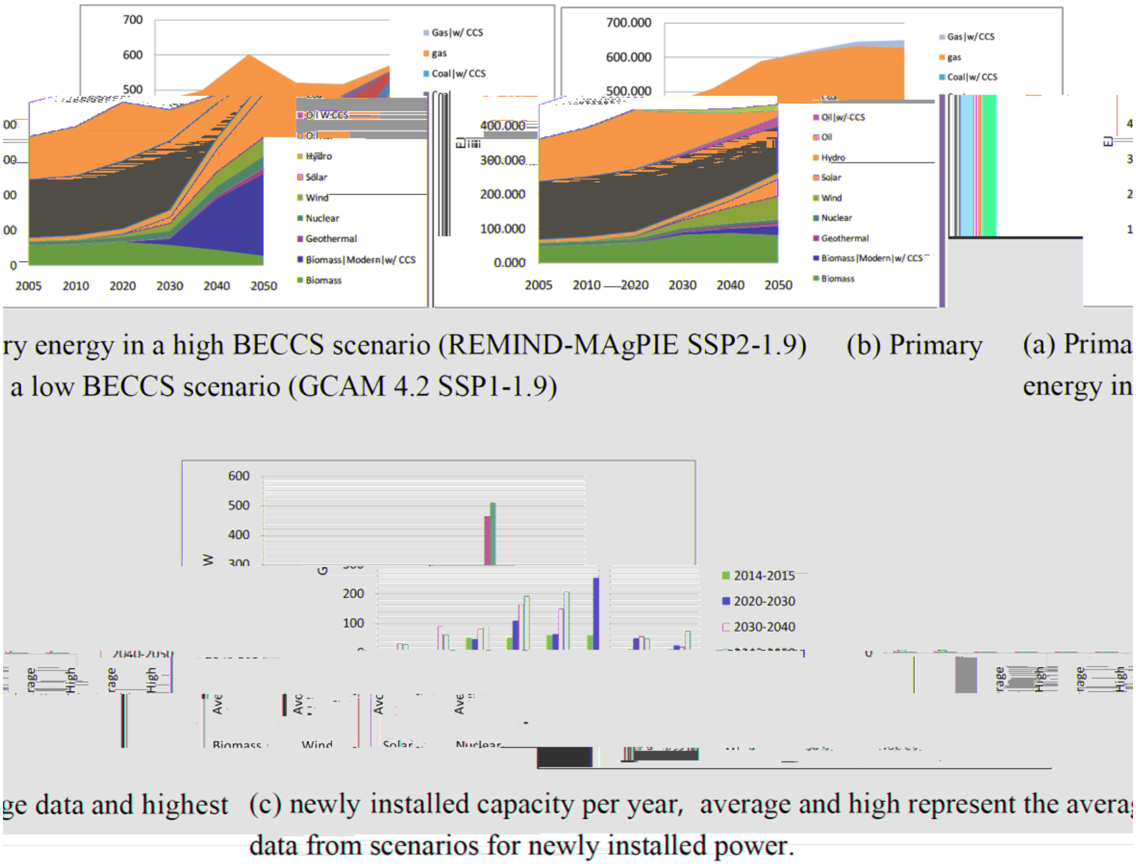


Figure 2.22: Variation in primary energy mix for two different illustrative 1.5°C scenarios (panels a, and b), and newly installed nameplate capacity per year (panel c; note that capacity factor is typically lower for wind and solar than for nuclear). Newly installed capacity per year for selected sources in 1.5°C scenarios.

2.4.3 *Energy end-use sectors*

In the following sections, the potential and challenges of CO_2 emission reduction towards the stringent temperature targets such as below 2°C and 1.5°C are discussed in each of energy end-use sectors (industry, buildings, and transport sectors). For this purpose, two types of scenarios are analysed and compared each other; IAM (integrated assessment modelling) studies and sectoral (detailed) studies. The data of IAM are extracted from the IPCC SR1.5 Scenario Database, and the sectoral data are taken from the recent series of IEA publications; “Energy Technology Perspectives” (ETP) (IEA, 2014, 2015, 2016a; International Energy Agency (IEA), 2017). The IAM scenarios are categorized in scenarios classes by the temperature rise over the 21st century (see Section 2.1). Since the number of scenarios for “Below 1.5°C 50” scenarios is small, the following analyses are focused only for the scenarios of Return 1.5°C scenarios (hereafter denoted as IAM-1.5DS) and Below 2°C scenarios (IAM-2DS). And the difference between data of subgroups with probability of 50% and 60% are small, then both data are aggregated into one group for simplicity.

The IEA ETP-B2DS (Below 2°C scenario) is the scenario with a 50% chance of limiting temperature rise below 1.75°C by 2100 (International Energy Agency (IEA), 2017). The comparison of CO_2emission trajectory between ETP-B2DS and IAM-1.5DS revealed that both trajectories are consistent each other up to 2050. IEA assumes that some level of BECCS can be deployed, which can help to offset emissions in difficult-to-decarbonize sectors, but that global energy-related CO$_2$emissions cannot turn net-negative at any time and stay zero after 2060 to 2100 (IEA, 2016a). Therefore, although its temperature rises in 2100 is below 1.75°C, this scenario can be considered to at least provide a point of comparison for 1.5DS up to 2050.

The CO$_2$ emissions of energy end-use sectors and carbon intensity of each sector are shown in Figure 2.23. The projections of IAM and IEA-ETP show rather different trends, especially in the carbon intensity. Although details are discussed later, these differences come from various factors, including the deployment of CCS, the level of fuel switching and efficiency improvement, and the effect of 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 [3.2–3.7: 25–75 percentile] between 2010 and 2050, the energy consumption of each end-use sector grows only by about 20% [minus20–40%] and 40% [10–60%] in 1.5DS and 2DS, respectively. This significant decoupling between energy use and economic growth is achieved by the efficiency improvement and demand reduction measures. The CO$_2$ emissions should be reduced further to achieve the stringent temperature targets. It is clearly shown that the CO$_2$emissions should be reduced more and quickly in 1.5DS than 2DS. This is largely made possible due to the decarbonisation, but its level differs among end-use sectors. While the carbon intensity of industry and buildings sector decreases to very low level of around 10 g–CO$_2$ MJ^{-1}, the carbon intensity of transport sector stays highest due to the higher reliance on the oil-based fuels. In the following subsections, the potential and challenges of CO$_2$emission reduction in each end-use sector are discussed in details.

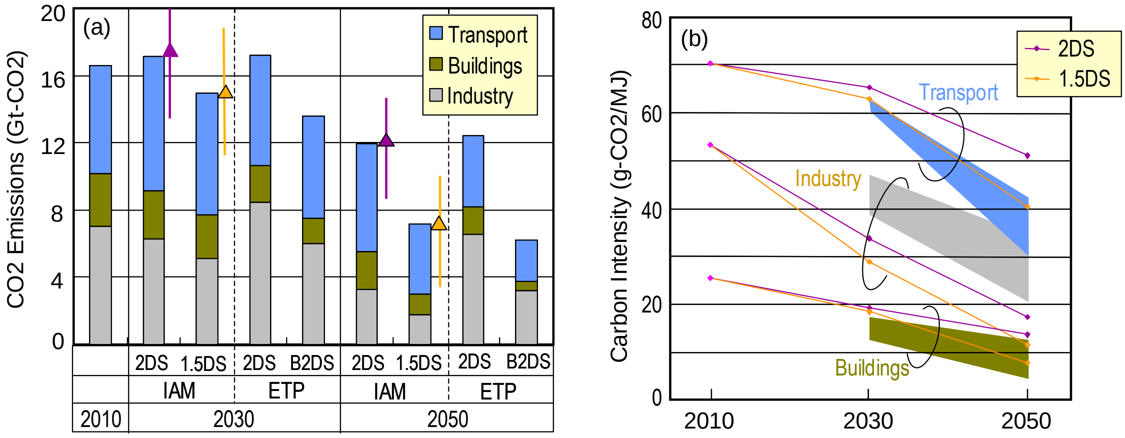


Figure 2.23: Comparison of (a) CO$_2$emissions and (b) carbon intensity in the energy end-use sectors (industry, buildings and transport sectors) between IAM and sectoral (IEA-ETP) studies. In panel (a), whiskers show the range of 25–75 percentile and solid triangles correspond to the median values. In panel (b), the data for IEA-ETP scenarios (2DS and B2DS) are shown by the coloured areas, where the upper and lower limits correspond the data of 2DS and B2DS, respectively (grey: industry, olive: buildings, and light blue: transport).

Note: for the data of IAM studies, there is rather large variation of projections for each indicator. Although these ranges of projections are not shown in the figure, 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 greenhouse gas emissions. Its direct CO$_2$ emissions currently account for about 25% of total man-caused fossil fuel and process CO$_2$emissions, and have increased with an average rate of 3.4% between 2000 and 2014, significantly faster than total CO$_2$ emissions (Hoesly et al., 2017). In addition to emissions from the combustion of fossil fuels, non-energy uses of fossils in petro-chemical industry and metal smelting, as well as non-fossil process emissions (e.g., from cement production) contribute 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 account for close to 66% of energy demand, and 72% of direct industry sector emissions in 2014 (International Energy Agency (IEA), 2017). In terms of end-uses, the bulk of energy in the manufacturing industries is required for process heating and steam generation, while most electricity (but smaller shares of total final energy) for industry is used for mechanical work (Banerjee et al., 2012; International Energy Agency (IEA), 2017).

As shown in Figure 2.23, a major share of the additional emission reductions required for 1.5°C pathways beyond those in 2°C pathways have to come from industry. Like other end-use sectors, industry contributes a relatively higher share to the additional CO_2emission reductions for strengthening ambition to 1.5°C, as supply side emissions reductions are almost fully exploited already in 2°C pathways (Luderer et al., 2017c; Rogelj et al., 2015a, 2017b).

The comparison of IAM and sectoral studies for the projections of final energy, CO_2emissions and carbon intensity are shown in Figure 2.24. The projections of final energy for both studies are consistent, but for the projections of CO_2emissions and carbon intensity, IAMs are more optimistic than sectoral (IEA-ETP) studies. This is largely due to the higher stringency of the climate target in integrated scenarios, and due to a different strategy on the CCS deployment. In IAM-1.5D scenarios, the share of electricity is relatively higher than IEA-ETP (36% [32–43%] vs. 25%) and hydrogen is also considered to have a share of about 4% [1–7%] (vs. 0%). In 2050, from REF reduction final energy is increased by 16% [5–22%] (35% [12–52%]) compared with the 2010 level (red dotted line) for 1.5DS (2DS), but CO2 emissions and carbon intensity are decreased by 75% [57–89%] (53% [39–70%]) and 76% [64–89%] (67% [59–77%]), respectively. This decarbonization is more significant in 1.5DS and brought by switching to low carbon fuels and CCS deployment.

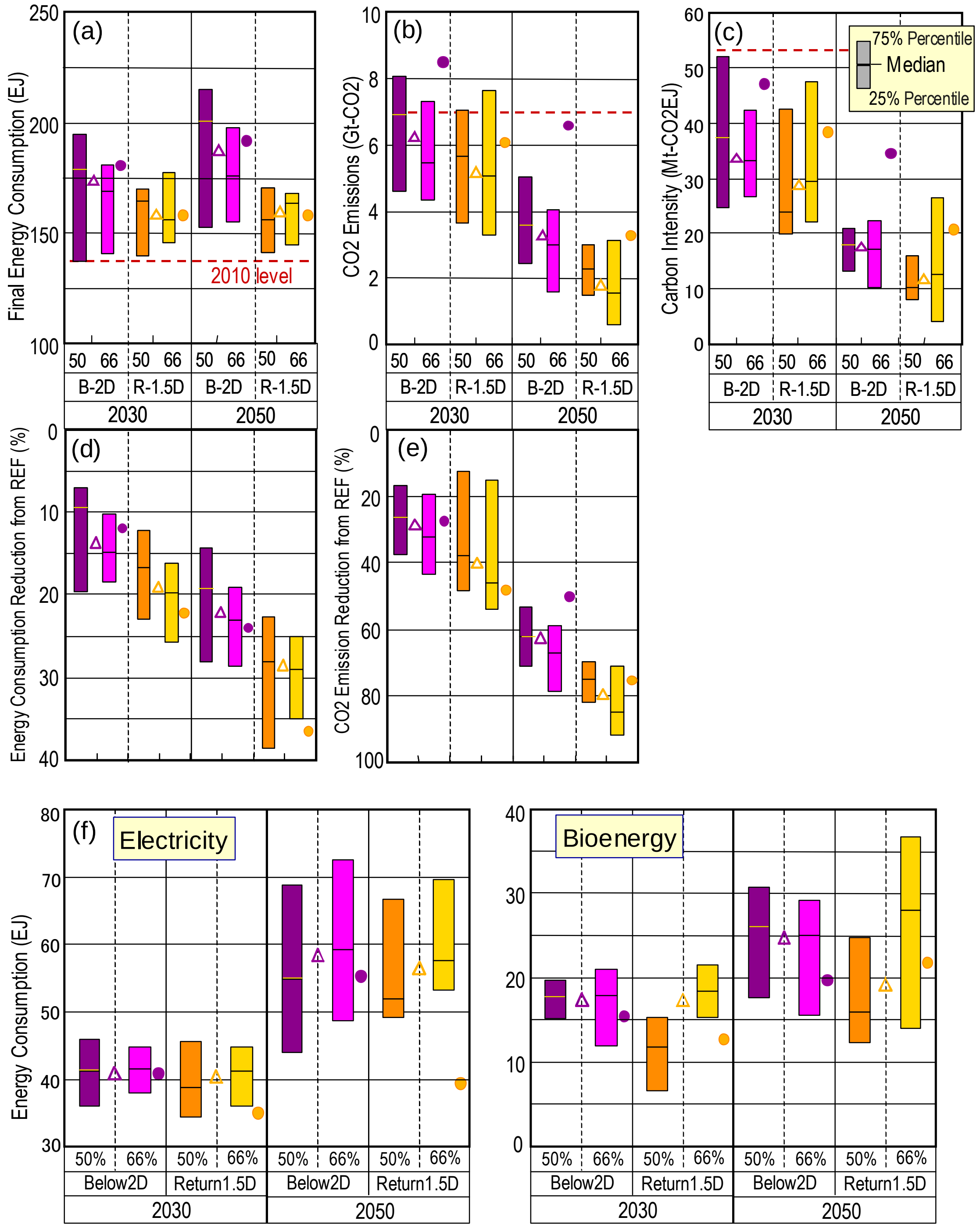


Figure 2.24: Comparison of (a) final energy, (b) CO2emissions, (c) carbon intensity, (d) reduction of energy consumption from reference scenario, (e) reduction of CO_2 emissions from reference scenario, (f) consumption of low carbon fuels in the industry sector between IAM and sectoral (IEA-ETP) studies. Open triangles indicate the median values of aggregated scenarios of 50 and 66% for B-2D: below 2°C and R-1.5D: return 1.5°C. Filled circles correspond to 2DS (purple) and B2DS (orange) of IEA-ETP studies. The red dotted line indicates the 2010 level.

Broadly speaking, the industry sector's mitigation measures can be categorized in terms of the following five strategies: (i) reductions in the demand of industrial products and materials, (ii) energy efficiency improvements in industrial production and processes, (iii) an increase of electrification of energy demand, (iv) reducing the carbon content of non-electric fuels, and (v) deploying innovative processes and application of carbon capture and storage. IEA ETP (International Energy Agency (IEA), 2017) estimates the relative contribution of different measures for the CO2emission reduction in their B2DS scenario compared with the reference scenario in 2050 as follows: energy efficiency 42%, innovative process and CCS 37%, switching to low carbon fuels and feedstocks 13% and material efficiency (include efficient production and use to contribute the demand reduction) 8%. The potential mitigation contributions of these strategies as well as their limitations will be discussed in the following.

2.4.3.1.1 Reductions in the demand of industrial products and material efficiency

Economic growth, structural change towards a more material or more service intensive economy, as well as the evolution of lifestyles strongly affects industrial energy demand and related mitigation challenges (Bauer et al., 2017a; Riahi et al., 2017). Beyond consumer demand reductions, reduction in the use of industrial materials, while delivering similar services, could help to reduce energy demand and overall system-level CO_2emissions by the strategies, such as using materials more intensively, extension of product lifetimes and so on. Also, material efficiency can be improved by producing materials in the most efficient way, increasing recycling, and increasing inter-industry material synergies, such as clinker substitution in cement production (Allwood et al., 2013; International Energy Agency (IEA), 2017). Demand reduction will also come from the synergy effects in the other sectors; for example. efficiency improvement due to light-weighting of automobiles. Related to material efficiency, industrial processes that use fossil-fuel feedstocks could shift to lower-carbon feedstocks such as oil to natural gas and biomass and also in the end-use, shift to more sustainable materials such as biomass-based materials could reduce the demand of energy-intensive materials(International Energy Agency (IEA), 2017).

2.4.3.1.2 Energy efficiency improvements in industrial production

Energy efficiency improvements are particularly important as short-term mitigation measures. 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. Although excess energy, usually as waste heat, would be inevitable, recovering and reusing this waste heat to economic levels benefits the overall energy system. Furthermore, demand-side management strategies could modulate the level of industrial activity in line with the needs of 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.

In the industry sector, energy demand increases more than 76% [51–97%] by 2050 in the baseline scenarios. However, in the IAM-1.5DS and 2DS, the increase is only 16% [5–22%] and 35% [12–52%], respectively (Figure 2.24). The reduction relative to the reference scenarios is 32% [29–39%] and 21% [11–35%] for 1.5DS and 2DS, respectively. It is important to note that these energy demand reductions encompass both efficiency improvements in production as well as reductions in material demand as discussed above, as most models do not discern these two factors.

2.4.3.1.3 Electrification of industry energy demand

In 2050, the CO_2 emissions in industry sector increases by 50% [8–75%] compared with 2010 level in the baseline scenarios. The emissions are significantly reduced by 80% and 60% from the baseline to 1.5DS and 2DS, respectively (Figure 2.24). This is largely due to the electrification as well as demand reduction. It is well understood that more rapid and deeper emission reductions can be achieved for electricity supply than for non-electric energy (Clarke et al., 2014; Krey et al., 2014a; Kriegler et al., 2014b). By mid-century, CO_2emissions per unit electricity are projected to decrease to near zero in both 2DS and 1.5 DS scenarios (see Section 2.4.2). An accelerated electrification of industry sector thus becomes an increasingly powerful mitigation option. In the IAM scenarios, the share of electricity reaches 36% [32–43%] by 2050 in 1.5DS scenarios (Figure 2.24). Not all industrial fuel use can be replaced with electricity, and electrification would have other effects on the process, including impacts on plant design, cost and available process integration options (International Energy Agency (IEA), 2017). It can thus be expected that even under stringent climate policies a substantial share of industry energy demand remains non-electric. Also, the change of demand by electrification of end-use sectors would affect the industry structure itself.

2.4.3.1.4 Reducing the carbon content of non-electric fuels

In 1.5DS scenarios, carbon intensity of non-electric fuels consumed in industry (calculated by division of total CO_2 emissions by the energy consumption excluding contributions from electricity) decreases to 17 g-CO_2 MJ^{-1} by 2050, compared to 26 g–CO_2 MJ^{-1} in 2DS. Considerable carbon intensity reductions are already achieved by 2030. These are largely made by a rapid phase out of coal. On the other hand, biomass becomes an increasingly important energy carrier in the industry sector in deep-decarbonization scenarios, in particular in the longer term. In 2050, biomass accounts only 12% [9–21%] of final energy consumption even in 1.5DS. In addition, in some scenarios also hydrogen plays a considerable role as a substitute for fossil-based non-electric energy demands.

2.4.3.1.5 Deployment of innovative technologies and application of carbon capture and storage

Progress over the next decade on sustainability-oriented industrial innovation is crucial to achieve longer-term climate targets in the industrial sector. Without major deployment of new low-carbon processes, the 1.5°C scenario will not be achievable. Bringing these technologies and processes to commercial deployment will require 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 (DRI), Inert anodes for aluminium smelting, full oxy-fuelling kilns for clinker production in cement manufacturing (International Energy Agency (IEA), 2017).

CCS plays a major role in decarbonizing the industry sector to meet a 2°C or 1.5°C target, especially in the industries with higher process emissions, such as cement and iron and steel industries. In 1.5DS, total account for CCS in industry project a contribution of 1.5 [0.8–1.8] Gt-CO_2 yr^{-1} by 2050.

Given project long-lead times and the need for technological innovation, early scale up of industry CCS is essential. In spite of the potential importance, the development and demonstration of such projects has been slow. As of now, only two large-scale industrial CCS projects outside of oil and gas processing are in operation (Global CCS Institute, 2016). The current cost of CO_2avoided (in USD) ranges from 19.7–27.3 USD tCO_2^{-1} for gas processing and bio-ethanol production, and $60-138/t-$CO_2$ for fossil fuel-fired power generation up to $104-188/tonne for cement production (Irlam, 2017). Carbon pricing is one of key enablers for mobilizing its large-scale implementation with the development of appropriate legal and regulatory frameworks and collaboration world-wide including international public-private collaboration.

All mitigation strategies discussed above have limitations. The scope for decreasing material inputs to the economy, and the willingness of consumers to pursue a less material-intensive lifestyle might be limited. Similarly, there are economic and thermodynamic limits to efficiency improvements (Saygin et al., 2011). However, this will be supplemented by the advanced energy management systems, especially for heat recovery, and shift to the innovative technologies. Electrifying some energy services has a substantial penalty as it converts a high-quality electricity into a low-quality heat, and thus reduces the overall efficiency of the system (Banerjee et al., 2012). The decarbonization of final energy is also limited by the fact that hydrocarbons often not only serve as energy sources, but also as material feedstocks to chemical processes. The industry sector competes with other demand sectors for a limited amount of sustainable biomass (Creutzig et al., 2015b; Rose et al., 2013). Finally, there are practical limits to the deployment of carbon capture and storage in smaller industrial facilities.

Furthermore, the industrial sector is also one of the most important sources of HFCs (Velders et al., 2015), which consequentially are also strongly reduced in stringent mitigation scenarios (Gernaat et al., 2015), and recent studies have confirmed significant potentials for their reduction (Purohit and Höglund-Isaksson, 2017; Velders et al., 2015). HFCs are being controlled under the Kigali Amendment to the Montreal Protocol, which mandates the phase-out of the consumption of these gases over the coming decades. Recent research estimates that compliance with the measures described in the amendment would lead to a reduction of HFC emissions of about 60% relative to a global pre-Kigali baseline (Höglund-Isaksson et al., 2017).

As a consequence, integrated modelling studies as well as sectoral studies suggest that no single mitigation option can serve as a silver bullet for reducing industry's emissions in line with 1.5–2°C stabilization, but that rather most or even all of the above listed options will have to contribute. The available studies show that energy demand reduction and the reduction of industrial coal use are near-term priorities for putting the industry sector on track for 1.5°C consistent decarbonization. Also, electrification, bioenergy as well as CCS play an increasingly important role for the deep decarbonization.

2.4.3.2 *Buildings*

In 2014 buildings sector accounts for 31% of total global final energy use, 54% of final electricity demand, and 8% of energy-related CO_2emissions (excluding electricity-related). When upstream electricity generation is taken into account, buildings are responsible for 23% of global energy-related CO_2emissions in 2014. One-third of those total buildings-related emissions, or roughly 8% is from direct fossil fuel consumption (International Energy Agency (IEA), 2017).

Past growth of energy consumption is 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 21% [6–45%] (42% [12–55%]) compared to 2010 in IAM-1.5DS (2DS) scenario (Figure 2.25). However, sectoral studies (IEA-ETP scenarios) show different trends. The energy consumption in 2050 decreases compared to 2010 in ETP-B2DS, and the reduction rate of CO_2emissions is higher than IAM scenarios (Figure 2.25). Mitigation options are often more fully represented in sectoral studies (Lucon et al., 2014), leading to higher energy consumption reduction and CO_2emission reduction.

The emission 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 61% [47–68%] in 1.5DS, compared with 50% [41–56%] in 2DS (Figure 2.25). The electrification contributes to the reduction of direct CO_2emissions in the building sector by replacing carbon intensive fuels, like oil and coal. Furthermore, when combined with a rapid decarbonization of the power system (see Section 2.4.2) it also enables further reduction of indirect CO_2emissions. In contrast to other dimensions, sectoral bottom-up models in general estimate lower electrification potentials for the buildings sector in comparison to global IAMs. Besides CO_2emissions, air conditioning in buildings also leads to emissions of HFCs. These gases have high global warming potential yet contribute currently only a small amount to the overall warming. However, their projected future impact can be significantly mitigated through efficiency measures and switching of cooling gases (Purohit and Höglund-Isaksson, 2017; Shah et al., 2015).

IEA-ETP (International Energy Agency (IEA), 2017) analysed the relative importance of various measures on the reduction of energy and CO_2emissions in the buildings sector. The largest energy savings potential, unsurprisingly, is in heating and cooling demand largely due to the 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 reduction 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_2emissions. In the ETP-B2DS, the direct CO_2emissions are 79% lower than reference scenario in 2050 and the remaining emissions come mainly from the continued use of natural gas.

The building 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 the substantial new construction is expected in the near future and retrofit of existing building stock in developed regions. This represents both a significant risk and opportunity for mitigation. 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 condensing boilers, heat pumps and more recently light-emitting diodes (LED) is also important for the reduction of energy and CO_2emissions (International Energy Agency (IEA), 2017).

Consumer choices, behaviour and building operation can lead to significant energy consumption differences in any region of the world. For instance, in China, studies have shown that occupant behaviour and building operations can vary energy consumption between two- and six-fold in residential households and between two- and ten-fold in office buildings (IEA, 2016a). A comprehensive policy framework is very effective to assists the various actors and stakeholders across the buildings and construction sectors to overcome barriers, including market failures, hidden and high upfront costs, and other behavioural and informational barriers. Public awareness is also critical to ensure market change (International Energy Agency (IEA), 2017).

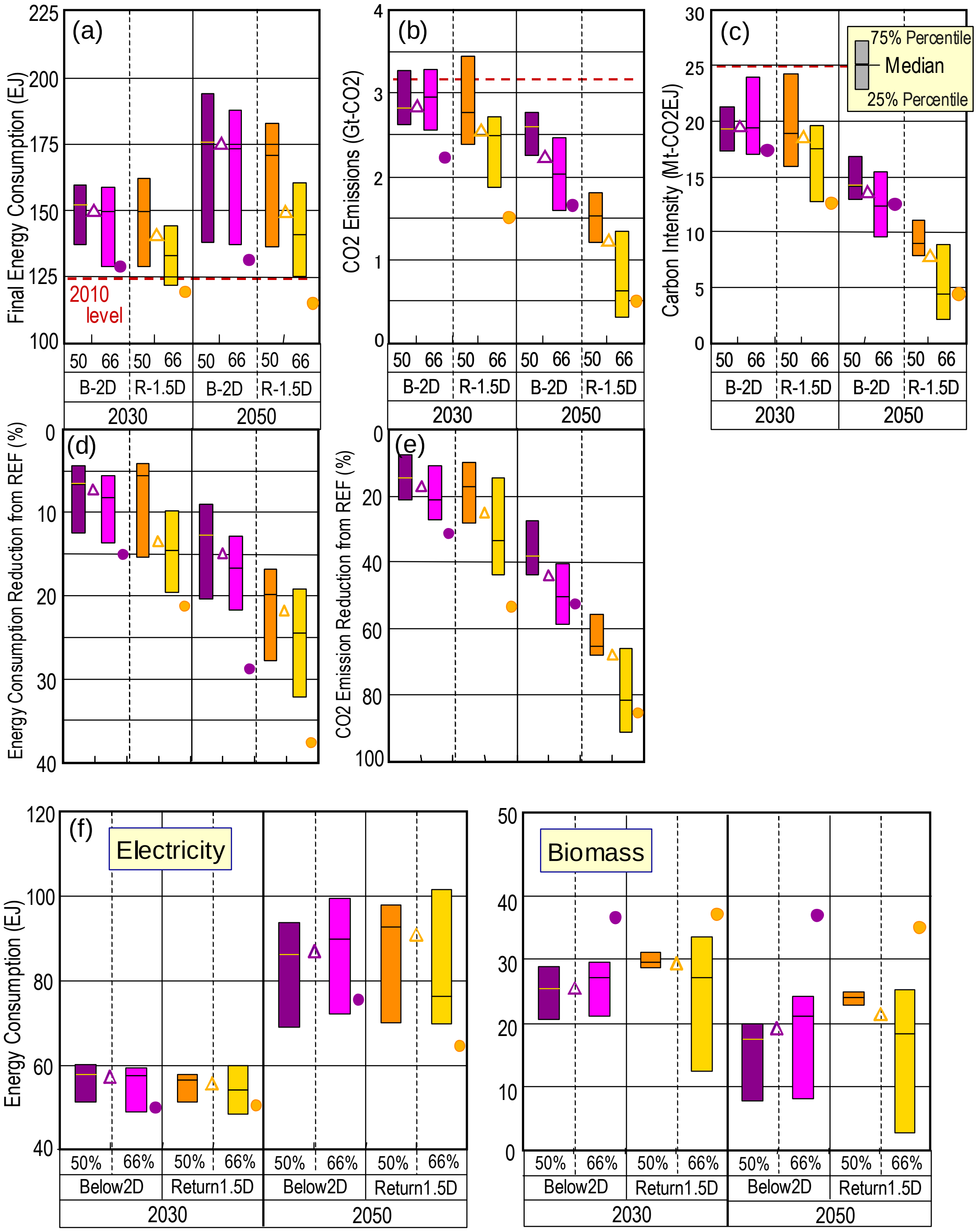


Figure 2.25: Comparison of (a) final energy, (b) CO_2 emissions, (c) carbon intensity, (d) reduction of energy consumption from reference scenario, (e) reduction of CO_2emissions from reference scenario, (f) consumption of low carbon fuels in the buildings sector between IAM and sectoral (IEA-ETP) studies. Open triangles indicate the median values of aggregated scenarios of 50 and 66% for B-2D: below 2°C and R-1.5D: return 1.5°C. Filled circles correspond to 2DS (purple) and B2DS (orange) of IEA-ETP studies. The red dotted line indicates the 2010 level.

2.4.3.3 *Transport*

Transport accounts for 28% of global final energy demand and 23% of global energy-related CO_2emissions, in 2014. Emissions increased by 2.5% annually between 2010 and 2015. Since the transport sector consumed 65% of global oil final energy demand, with 92% of transport final energy demand consisting of oil products (International Energy Agency (IEA), 2017), the transport sector is the least diversified energy end-use sector, suggesting major challenges for deep decarbonization.

Numerous transformation pathways have been developed in recent years to explore the question of how economy-wide greenhouse gas emissions could be reduced in line with the internationally agreed 2°C target (see, for example, Clarke et al., 2014; Sims et al., 2014). Yet, few of these studies investigate in a detailed way the transport sector's role in such an effort and in-depth study examining the more stringent target of 1.5°C. Developing a better understanding of this sector's role in meeting these targets is critical, given that over the past half century the sector has witnessed faster emissions growth than any other (reaching 6.7 Gt-CO_2yr^{-1} in 2010 – direct emissions; approximately 23% of total energy-related CO_2emissions (Clarke et al., 2014).

As discussed in Section 2.4.3, the IAM studies and sectoral studies (IEA-ETP) project rather different trends of energy consumption and CO_2emissions. The projections of final energy, CO_2emissions and carbon intensity are shown in Figure 2.26. The projections of IAMs are more conservative than IEA-ETP scenarios. Significant difference can be seen in the projection of energy consumption between IAM-1.5DS and ETP-B2DS; IAM-1.5DS projects a reduction of 39% [28–48%] compared to the baseline in 2050, while ETP-B2DS projects a reduction of 55% (Figure 2.26). Furthermore, IAM scenarios are generally more conservative in the projections of CO_2 emission and carbon intensity reduction. In AR5 (Clarke et al., 2014; Sims et al., 2014), similar comparisons between IAM and sectoral studies were performed and found that both projections are in good agreement each other. Considering what happened after AR5, two important changes can be identified; rapid growth of electric vehicles in passenger cars, and more attention towards the behavioural changes in this sector. The former contributes the reduction of CO_2 emissions and the latter reduction of energy consumption. According to the recent IEA-ETP scenarios, the contribution share of avoid (reduction of mobility demand) and shift (shifting to more efficient modes) measures in the reduction of CO_2emissions from the reference to B2DS scenarios in 2050 amounts to 20% (International Energy Agency (IEA), 2017).

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. Also important are behavioural measures such as avoid (reduction of mobility demand) and shift (shifting to more efficient modes). While the former solutions (technologies) tend always to figure into deep decarbonization pathways in a major way, this is not always the case with the latter, especially in IAM scenarios. Comparing different types of global transport models, (Yeh et al., 2016) find that sectoral (intensive) studies generally envision greater mitigation potential from behavioural solutions. 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 tele-commuting or integrated transport, land-use and urban planning), figure much less prominently. Whether these dynamics accurately reflect the actual mitigation potential of behavioural-related mitigation options is a point of investigation. One study (Creutzig, 2016) for instance, notes the diverse perspectives on transport mitigation solutions that are foreseen by different scientific communities.

The potential and strategies to reduce the energy consumption and CO_2emissions differ significantly among the transport modes. In ETP-B2DS, the shares of energy consumption and CO_2emissions in 2050 for each mode: LDV (light-duty-vehicles)/trucks/rail/aviation/shipping are 34/33/8/12/13% and 29/36/–1/14/21%, respectively, indicating the challenge of trucks, aviation and shipping to decarbonize. The reduction of CO_2emissions in the whole sector from the reference scenario to ETP-B2DS is 60% in 2050. The contributions of each mode for this reduction are LDV 36%, trucks 31%, aviation 13%, and shipping 10%. Since there is no silver bullet for the deep decarbonization, every possible measure would be required to achieve the stringent target. According to the analysis of IEA ETP (International Energy Agency (IEA), 2017), the contribution of various measures for the CO2 emission reduction from the reference scenario to the B2DS in 2050 can be decomposed to efficiency improvement (29%), biofuels (36%), electrification (15%), and avoid/shift (20%). It is noted that the share of electrification becomes larger compared with the older data, reflected by the recent growth of electric vehicle sales worldwide. Another new trend is the allocation of biofuels to each mode of transport. In B2DS, the total amount of biofuels consumed in the transport sector is 24EJ in 2060, and allocated to LDV (17%), trucks (35%), aviation (28%), and shipping (21%), that is to say more biofuels to the difficult-to-decarbonize modes.

In road transport, incremental vehicle improvements (including engines) are very important, 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 cars, especially plug-in hybrid electric vehicles (PHEVs). Electrification is a powerful measure to decarbonize for short-distance vehicles (passenger cars and 2- and 3- 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 have limited potential to decarbonize, while their demand growth is projected to be higher than other transport modes. Both modes have to pursue highly ambitious efficiency improvements and need low-carbon fuels. In near and medium term, this would be advanced biofuels and in long term could be hydrogen as direct use for shipping or an intermediate product for the synthetic fuels for both modes (International Energy Agency (IEA), 2017).

The share of low carbon fuels in the total transport fuel mix increases to 8% [4–14%] (16%) by 2030 and to 36% [18–47%] (58%) by 2050 in IAM-1.5DS (IEA-B2DS). The IEA-B2DS scenario is on the more ambitious side, especially in the share of electricity. Hence, there is wide variation among scenarios regarding changes in the transport fuel mix over the first half of the century. As seen in Figure 2.26, the projections of energy consumption, CO_2emissions, and carbon intensity are quite different between IAM and ETP scenarios. This difference would be explained as follows; more weight on the efficiency improvement and avoid/shift decreases the energy consumption, and higher share of biofuels and electricity accelerates the speed of decarbonization. Although the biofuel consumption and electric vehicle sales have increased significantly in the recent several years, their growth rate projected in these scenarios would be unprecedented and require to be far higher than has been experienced to date.

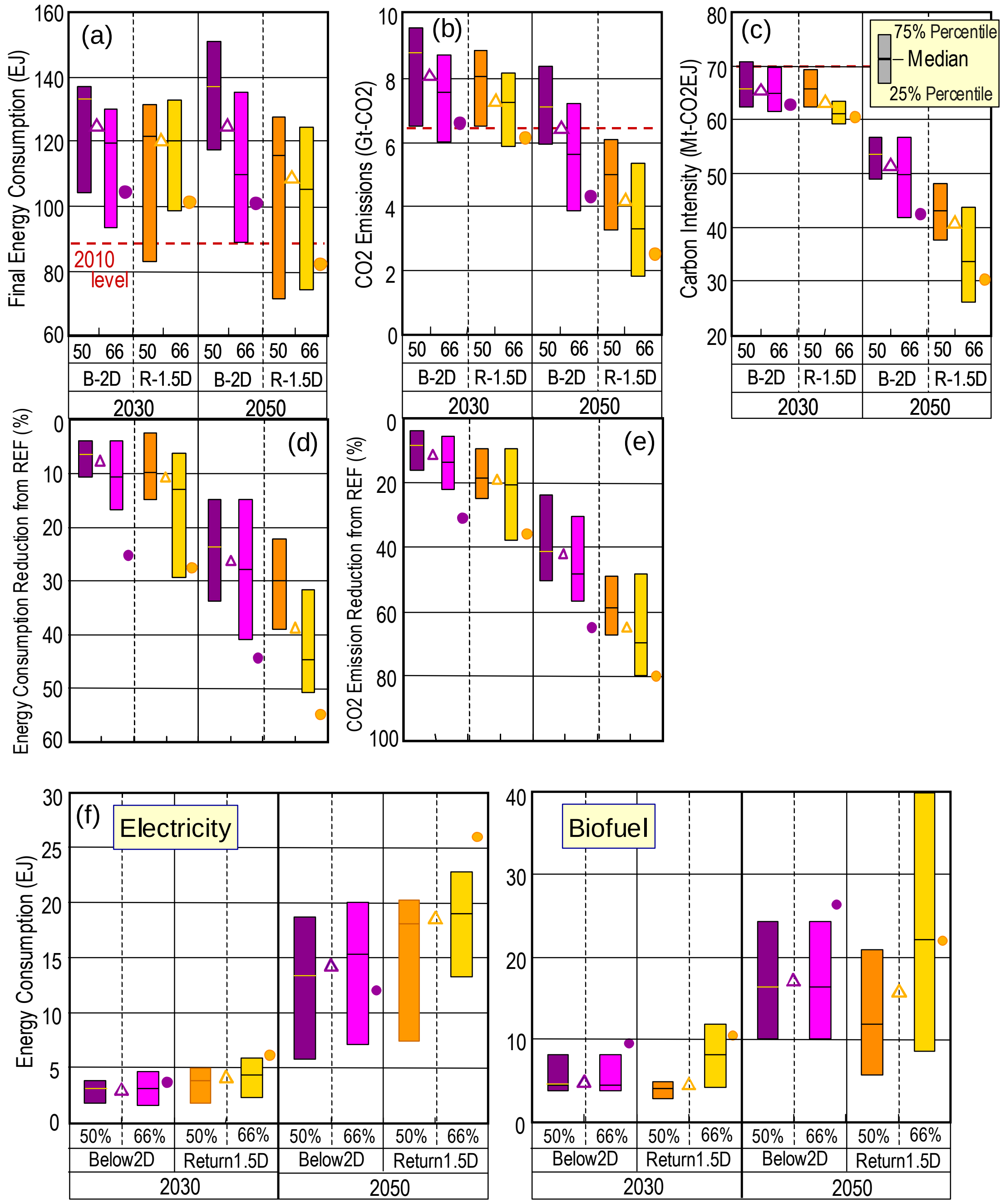


Figure 2.26: Comparison of (a) final energy, (b) CO_2emissions, (c) carbon intensity, (d) reduction of energy consumption from reference scenario, (e) reduction of CO_2emissions from reference scenario, (f) consumption of low carbon fuels in the transport sector between IAM and sectoral (IEA-ETP) studies. Open triangles indicate the median values of aggregated scenarios of 50 and 66% for B-2D: below 2°C and R-1.5D: return 1.5°C. Filled circles correspond to 2DS (purple) and B2DS (orange) of IEA-ETP studies. The red dotted line indicates the 2010 level.

Going beyond ‘well below 2°C’ in the direction of 1.5°C will require an acceleration of the mitigation solutions already featured in the deep decarbonization pathways discussed above (e.g., more efficient vehicle technologies operating on lower-carbon fuels), as well as those having received lesser attention in most global transport decarbonization pathways up to now (e.g., mode-shifting and travel demand management; Kauppila et al., 2017). Low-emitting automated vehicles combined with a high degree of on demand ride-sharing could also be critical to bridging the gap between 2 and 1.5°C while still allowing individuals’ travel needs to be adequately served (Kauppila et al., 2017). Current-generation, global scenario pathways generally do not include these newer transport sector developments, which in a sense leverage technological solution to induce shifts in travellers’ behaviour.

2.4.4 *Land-use transitions and changes in the agricultural sector*

The agricultural, forestry and other land-use sector (AFOLU) plays an important and possibly essential role in stringent mitigation futures (Clarke et al., 2014; Smith and Bustamante, 2014). On the one hand, its emissions need to be limited over the course of this century (see Section 2.2 and Section 2.3). On the other hand, the AFOLU sector has to meet the demands for food and feed of a growing global population, as well as supply biomass products for energy and other uses in a low-carbon society like carbon-dioxide removal (CDR). Meeting both demands together – and this in combination with limits to overall emissions – will require changes in land use, as well as in agricultural and forestry practices. A multitude of options are available to achieve this (Popp et al., 2017; Smith and Bustamante, 2014) (see Table 2.8 and Chapter 4, Section 4.3). This assessment mainly makes use of scenarios from integrated assessment models based on the quantifications of the SSPs that produce 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., 2017c; Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2017b; van Vuuren et al., 2017b). The IAMs used in the SSPs (Popp et al., 2017; Riahi et al., 2017) do not include spatially resolved climate damages to agriculture, nor damages due to ozone exposure or the effects of varying indirect fertilization due to N deposition from the atmosphere (e.g., Shindell et al. 2012; Mahowald et al. 2017). These models may thus have difficulty adequately capturing the differences in crop productivity between scenarios and in particular may underestimate the benefits of emissions reductions, especially for non-CO_2 warming agents that do not cause carbon fertilization (Shindell, 2016).

Transitions and changes in land use until mid-century are a feature of the large majority of SSP scenarios, both in stringent mitigation scenarios and baseline scenarios in absence of climate action (Figure 2.27). In the latter case, changes are mainly due to socio-economic drivers like growing demands for food, feed and wood products. Moreover, transitions in scenarios consistent with a global mean temperature increase of 1.5°C differ from the baseline scenarios in their land-use change fingerprint, depending on the underlying socioeconomic factors and the interplay with mitigation in other sectors (Figure 2.27) (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2017b).

General transition trends can be identified for many land types in 1.5°C scenarios. Due to schemes that avoid deforestation, mitigation that demands land (such as biomass production for BECCS and afforestation and reforestation) is mainly taking place at the cost of agricultural land for food and feed production. Besides that also marginal land is used and biomass is supplied from residues and waste, but at lower shares. Land for second generation energy crops expands by 2030 and 2050 in all available scenarios that assume a cost-effective achievement of a 1.5°C temperature goal (Figure 2.27), but the scale depends strongly on underlying socioeconomic assumptions (see later discussion of land pathway types). Avoided deforestation restricts agricultural expansion and forest cover can expand strongly in 1.5°C and 2°C scenarios alike, compared to its extent in no-climate policy baselines due to the use of afforestation and reforestation measures. However, the extent to which forest cover expands varies highly across models. In some cases, forest cover is projected to stay virtually constant or decline slightly. This is due to whether afforestation and reforestation is included in these scenarios as a mitigation technology (see Table 2.8 in Section 2.3). As a consequence of the expansion of various land uses, pasture land is generally reduced compared to both baselines in which no climate mitigation action is undertaken and 2°C consistent scenarios. Furthermore, cropland for food and feed production decreases in most 1.5°C scenarios, both compared to a no-climate baseline and relative to 2010. These reductions in agricultural land for food and feed production are facilitated by agricultural intensification on agricultural land and in livestock production systems (Popp et al., 2017) but also by changes in consumption patterns (Frank et al., 2017a; Fujimori, 2017). For example, in a scenario based on rapid technological progress (Kriegler et al., 2017c), global average cereal crop yields in 2100 are above 5 $tDMha^{-1}yr^{-1}$ in mitigation scenarios aiming at limiting end-of-century radiative forcing to 4.5 or 2.6 $W\ m^{-2}$, compared to 4 $tDM\ ha^{-1}\ yr^{-1}$ in SSP5-Baseline to ensure the same food production. Similar improvements are present in 1.5°C variants of such scenarios. This has to be seen in a historical context of cereal crop yields of 1 $tDM\ ha^{-1}\ yr^{-1}$ and ca. 3 $tDM\ ha^{-1}\ yr^{-1}$ in 1965 and 2010, respectively (calculations based on (FAOSTAT, 2017)).

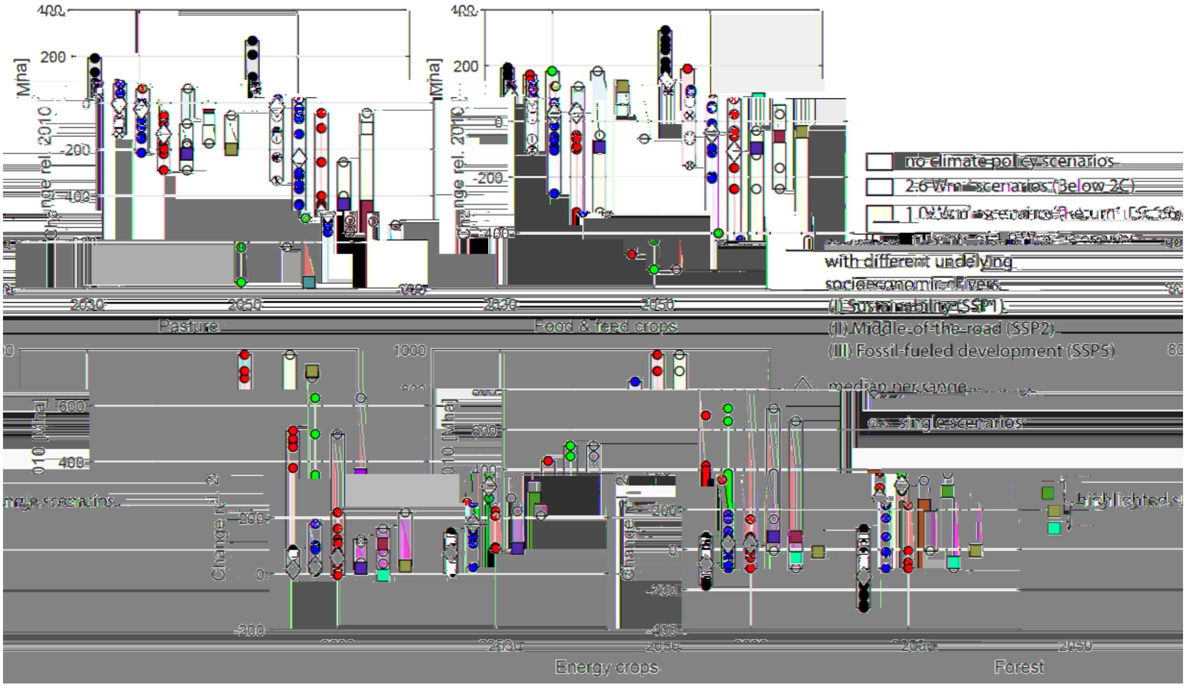


Figure 2.27: Overview of Land-Use Change transitions in 2030 and 2050, relative to 2010. Black and grey: baseline; green: 2.6 W m^{-2} scenarios; blue: 1.9 W m^{-2} scenarios. Pink: 1.9 W m^{-2} scenarios grouped per underlying socioeconomic assumption (from left to right: SSP1 (sustainability), SSP2 (middle-of-the-road), SSP5 (fossil-fuelled development), Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2017b). Ranges show the minimum-maximum range. Dots indicate single scenarios. White diamonds the median across scenarios. Coloured squares in the pink ranges indicate the position of the four highlighted scenarios presented in Figure 2.28. 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 scenarios, respectively. 2.6 W m^{-2} scenarios are mostly consistent with the ‘below 2C 66’ and ‘below 2C 50’ scenarios classes. 1.9 W m^{-2} scenarios are consistent with ‘return 1.5C 66’ scenario class.

An important aspect of these land transitions is the pace at which they are projected to take place over the coming decades in 1.5°C scenarios, especially in comparison to baseline scenarios without climate change mitigation and historical transitions (Table 2.11). 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).In 1.5°C scenarios between 2010 and 2030, pasture land is transformed at a pace of –15 to +3 Mha yr^{-1} (full range across scenarios, median: –7 Mha yr^{-1}), cropland for food and feed production is expanding or contracting at a pace of +9 to –16 Mhayr^{-1}(median: 1.4 Mha yr^{-1}), energy crops at 11 to 0 Mha yr^{-1} (median: 3 Mha yr^{-1}), while forest cover changes at a pace of –5 to +26 Mha yr^{-1}. In most cases, rates further increase for the 2030–2050 period. The median trend in decreasing pasture land in 1.5°C scenarios are amplified prolongations of historical (8.7 Mha yr^{-1} for 1970–1990 and 0.9 Mha yr^{-1} for 1990–2010) and baseline trends (median: 0.1 Mha yr^{-1} for 2010–2030), although single scenarios show both larger decreases or increases. Median total cropland increases in 1.5°C scenarios of 2.9 Mha yr^{-1} (2010–2030) and 5.1 Mha yr^{-1} (2030–2050) are significantly higher than reported changes of 0.5 Mha yr^{-1} for the time span of 1990–2010 but similar to 1970–1990 (4.6 Mha yr^{-1}). Forest cover increases due to REDD+ measures in stringent mitigation scenarios is a reversed dynamic compared to historical and baseline forest losses, and thus suggest that distinct policy and government measures would be needed to achieve this.

Changes of the AFOLU sector are driven by three main factors: demand changes, efficiency of production, and policy assumptions (Popp et al., 2017; Smith et al., 2013). Demand for agricultural products and other land-based commodities is influenced by societal consumption patterns (including dietary preferences and food waste affecting demand for food and feed), 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. 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), and trade.

Annual pace of land-use change [Mha yr^{-1}] Land type	**Scenario**	**Time window**		**Historical**	
		2010-2030	**2030-2050**	**1970-1990**	**1990-2010**
Pasture	1.9 W m^{-2}	-6.7 [-14.6/3.0]	-15.0 [-28.7/-1.9]	8.7 Permanent meadows and pastures (FAO)	0.9 Permanent meadows and pastures (FAO)
	2.6 W m^{-2}	-1.5 [-10.9/4.1]	-7.0 [-21.6/-0.7]		
	Baseline	-0.1 [-6.9/9.7]	-1.5 [-9.9/9.0]		
Cropland for food and feed	1.9 W m^{-2}	1.4 [-16.4/9.0]	-7.8 [-18.2/2.1]		
	2.6 W m^{-2}	1.3 [-12.9/8.3]	-2.2 [-16.8/2.6]		
	Baseline	4.4 [-5.3/9.6]	3.4 [-2.7/6.7]		
Cropland for energy	1.9 W m^{-2}	2.9 [-0.3/10.8]	13.2 [3.5/34.8]		
	2.6 W m^{-2}	1.3 [0.3/8.8]	7.2 [0.9/22.9]		
	Baseline	0.8 [0.2/4.2]	1.5 [-0.2/3.4]		
Total cropland (Sum of cropland for food and feed & energy)	1.9 W m^{-2}	5.4 [-10.2/12.8]	5.1 [-5.1/26.7]	4.6 Arable land and Permanent crops	0.9 Arable land and Permanent crops
	2.6 W m^{-2}	5.2 [-8.4/9.3]	4.4 [-7.1/17.8]		
	Baseline	5.7 [-2.7/9.9]	4.8 [0.6/9.6]		
Forest	1.9 W m^{-2}	1.3 [-4.8/26.0]	10.6 [-1.2/32.9]	N.A. Forest (FAO)	-5.6 Forest (FAO)
	2.6 W m^{-2}	1.4 [-4.7/22.2]	7.2 [-2.4/31.7]		
	Baseline	-3.4 [-9.0/3.3]	-2.7 [-6.5/4.1]		

Table 2.11: Annual pace of land-use change in 1.5°C scenarios. All values in Mhayr^{-1}, except when stated otherwise. 2.6 W m^{-2} scenarios are mostly consistent with the ‘below 2C 66’ and ‘below 2C 50’ scenarios classes. 1.9 W m^{-2} scenarios are consistent with ‘return 1.5C 66’ scenario class. Values: median [full range]. Based on land use developments projected by integrated assessment models under the assumptions of the Shared Socioeconomic Pathways (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2017b). FAO data are from FAOSTAT (2017).

A recent global study (Stevanović et al., 2017) finds that production (agricultural production measures in combination with avoided deforestation) and consumption side (diet change in combination with lower shares of food waste) measures have similar GHG reduction potentials of 43−44% in 2100 (compared to a baseline scenario without land-based mitigation). For livestock production, another study (Weindl et al., 2015)demonstrates that lower consumption of livestock products can substantially reduce deforestation (47–55%) and cumulative carbon losses (34–57%). On the supply side, already minor productivity growth in extensive livestock production systems leads 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. In addition to that, Havlík et al. (2014) show that even within existing livestock production systems, a transition from extensive to more productive systems bears substantial GHG abatement potential, while improving food availability. Many studies highlight the capability of agricultural intensification for reducing or even enhancing terrestrial carbon stocks (Popp et al., 2014a; Valin et al., 2013; 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 instance, the availability of affordable carbon-dioxide removal technologies that are not land based (like direct air capture – DAC, see also Chapter 4, Section 4.3.8) or either the ability of other sectors to achieve 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 2.27).

Scenarios that are consistent with 1.5°C rely on one or more of the three strategies highlighted in the previous paragraph (demand changes, efficiency gains, and policy assumptions), and can apply these strategies in different ways. Figure 2.28 provides examples of four illustrative AFOLU strategies and evolutions in 1.5°C pathways. For example, one approach can be to 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 (see scenario 1 in Figure 2.28). By contrast, in a scenario with higher baseline energy resource or energy demand and associated emissions, more land-based CDR is required in 1.5°C consistent scenarios (see scenario 2 in Figure 2.28). Land-based biomass supply is provided in this example by dedicated bioenergy crops and forest biomass supply (by 2050, about 15% of the required biomass comes from managed forests, which leads to a higher expansion of managed forests than in the other land pathway types). Mitigation in scenario 2 also affects the demand side (not shown in Figure 2.28). By 2050, global food production is reduced by 10% compared to a no-climate policy baseline – for livestock products this number is almost doubled (18%). In contrast, future land-use developments can look very differently under a resource- and energy-intensive future (including unhealthy diets with high animal shares and high shares of food waste (Springmann et al., 2016; Tilman and Clark, 2014), represented by scenario 3 in Figure 2.28) 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. Climate change mitigation strategies in such a future depend strongly on the availability of highly efficient CDR through BECCS (Humpenöder et al., 2014). As a consequence, significant amounts of biomass are provided by bioenergy crop expansion in combination with agricultural intensification in scenario 3 (Figure 2.28). Finally, also further policy assumptions can strongly affect land-use developments in 1.5°C scenarios, highlighting the importance for land use of making appropriate policy choices. For example, scenario 4 in Figure 2.28 strongly relies on a policy to incentivise afforestation and reforestation for CDR together with BECCS. This policy choice results in an expansion of natural forest area and a corresponding increase in terrestrial carbon stock.

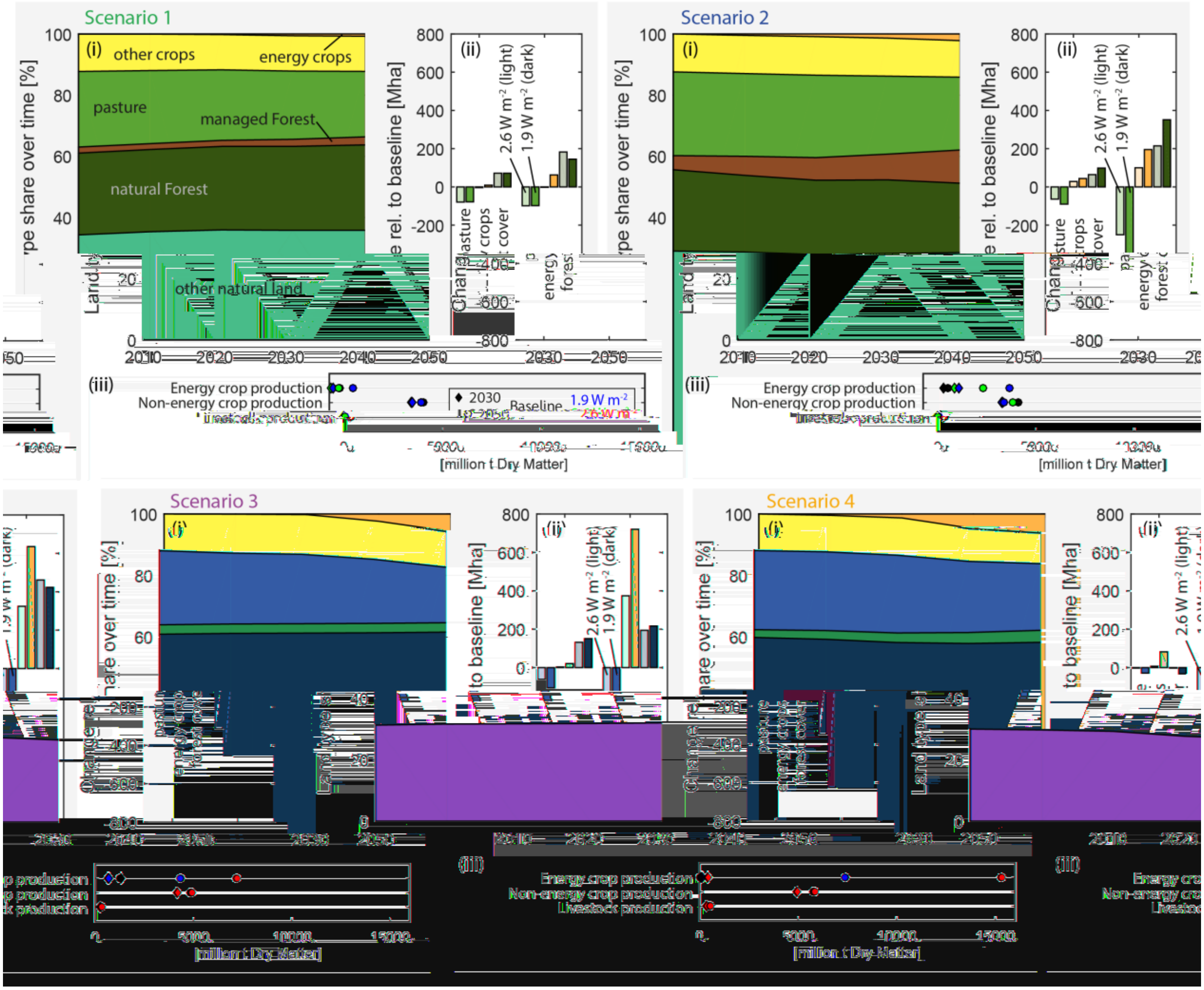


Figure 2.28: Four land pathway types for land transitions consistent with 1.5°C. 1.9 and 2.6 W m^{-2} are taken as a proxy for 1.5°C and 2°C scenarios, respectively. 2.6 W m^{-2} scenarios are mostly consistent with the 'below 2C 66' and 'below 2C 50' scenarios classes. 1.9 W m^{-2} scenarios are consistent with 'return 1.5C 66' scenario class. Each square illustrates the characteristics of one particular illustrative scenario and shows: (i) a temporal evolution until 2050 of the share of various land types in 1.9 W m^{-2} scenarios; (ii) change of land surface for three land types (pasture, energy crops, and forest cover) relative to a no-climate mitigation baseline for 2.6 W m^{-2} (lighter bars) and 1.9 W m^{-2} (darker bars) scenarios, respectively, in 2030 and 2050; (iii) production indicators in 2030 (diamonds) and 2050 (circles) for the baseline, 2.6 W m^{-2} and, 1.9 W m^{-2} scenarios. Data from (Riahi et al., 2017; Rogelj et al., 2017b). Colours of scenario names link back to the colour of single scenario symbols in Figure 2.27. Due to differences in base year data sources, and large uncertainties in historical data, land-use patterns differ between the models already in 2010 (Alexander et al., 2017; Popp et al., 2017; Prestele et al., 2016).

The choice of strategy or mitigation portfolio impacts the GHG dynamics of the land system (as well of other sectors, see Section 2.3) but also the extent to which synergies and trade-offs with other environmental and societal objectives can be materialised (see Section 2.5.3 and Section 5.4).

General lessons for GHG dynamics in the land-use sector can be learnt from stringent mitigation pathways: First, CO_2 emissions from deforestation can be abated at relatively low carbon prices if displacement effects into other regions (Calvin et al., 2017) or other land-use types such as soil-carbon-rich pastures (Calvin et al., 2014; Kriegler et al., 2017c; Popp et al., 2014a) can be avoided. Secondly, besides CO_2 reductions, the land system can play an important role for overall CDR efforts (Rogelj et al., 2017b) via BECCS, afforestation and reforestation, or both. Finally, also agricultural non-CO_2 emissions show large mitigation potentials at carbon prices below 100USDD tCO_2^{-1} (Frank et al., 2017b). However, at the same time, the level of non-CO_2 emissions from agriculture that is projected to remain by mid-century and beyond indicates that residual agricultural non-CO_2 emissions will play an important role for the achievement of deep climate targets in line with 1.5°C (Gernaat et al., 2015; Popp et al., 2017; Rogelj et al., 2017b; Stevanović et al., 2017) (see also Section 2.3). CH_4 emissions in these scenarios are already notably lower compared to the baseline cases without mitigation due to improved agricultural management (such as improved water management in rice production, improved manure management, better herd management and better quality of livestock through breeding and improved feeding practices) as well as dietary shifts away from emissions-intensive livestock products.N_2O emissions in these scenarios decrease due to improved N-efficiency and manure management. In contrast, high levels of bioenergy production can also result in increased N_2O emissions (Kriegler et al., 2017c).

Box 2.1: National pathway literature

National focused studies could better help to understand the pathway and feasibility toward the 1.5°C target. This box presents the studies from national analysis with looking into different background of country development, by selecting countries with consideration of economy development, regional balance, size and so on. There are not many studies published so far on emission pathways under 1.5°C. Four national-scale studies (Dhar et al., 2018; Jiang et al., 2017; Oshiro et al., 2017; Sferra et al., 2017) illustrate differences for India, China, Japan, and Finland.

These national studies use different approaches to construct national emission pathways for 1.5°C. China's analysis follows the carbon budget base on the ADVANCE project's results on regional budget, Japan and Finland's study takes zero emission by 2050 and 2040 as a constraint. India's share of global carbon budget for the 1.5°C scenario is apportioned in the same fraction as 2°C scenario.

National pathways are primarily built from the bottom up, and provide opportunities to link with national policy making process on energy, transport, building, industry planning, together with technology development. By using such kind of modelling method, feasibility issues could be better understood.

Bottom-up studies can provide more detail on technology transition and cost. The AIM/enduse model was used in Japan and China's study; the ANSWER MARKAL model was used in the India study, while Finland's study used different type model, with downscaling from global model by SIAMESE is not able to “predict” future policies at the country level. While downscaling the results, SIAMESE equalises the marginal cost of energy in all countries (cost-optimal solution) belonging to the same region (e.g., WEU). In a sense, SIAMESE assumes “uniform” policies in all countries. India's study focuses on the transport sector. The 1.5°C scenario in India's transport follows an emissions trajectory which starts at a lower level in the near-term and a sharp down turn in 2030 takes the emissions below emissions in 2015.

Key characteristics

The national studies have strong consistency with global IAM analyses of key options for mitigation towards 1.5°C pathways, which include zero or negative emission power generation, electrification in end use sectors, strong energy efficiency improvement, rapid reduction for fossil fuel in near term, and so on.

Technology options, Policy options, differences with respect to 2°C pathways

In energy sector, BECCS are key option in Japan and China's study, with share of total power generation 6% and 7.6% in 2050. Renewable energy (excludes BECCS) takes large share by around 70% and 53% in 2050. Nuclear is yet a major source in both studies, with 15% and 28% in 2050. Remaining fossil fuel power generation is equipped with CCS in 2050 in China. This makes power generation to be a source of negative emissions by 2050, of ~590million tonnes per year.

Concerning energy end use, electrification is the top option in in Japan, China, India, and Finland's studies. By 2050, electricity use in end use increases to be more than 50% in Japan, and 63% in China. In both Japan and China, there will be no fossil fuel use in building in 2050. In China's scenario, there is also almost no fossil fuel use in transport, with 55% electricity and 44% biofuels and hydrogen, to make transport nearly to be zero emission, while there will be 35% oil use in Japan, less than 30% in India by 2050.

Because of using bottom up type of model, policy options used in these scenarios are also wide range. Carbon taxes are used in all these countries' studies, they are USD2200USD tCO_2^{-1} in Japan, USD130USD tCO_2^{-1} in India, USD75USD tCO_2^{-1} in China. In China's case, there are more policies option including subsidies for electric car, FIT for CCS included, therefore the carbon price is relative low.

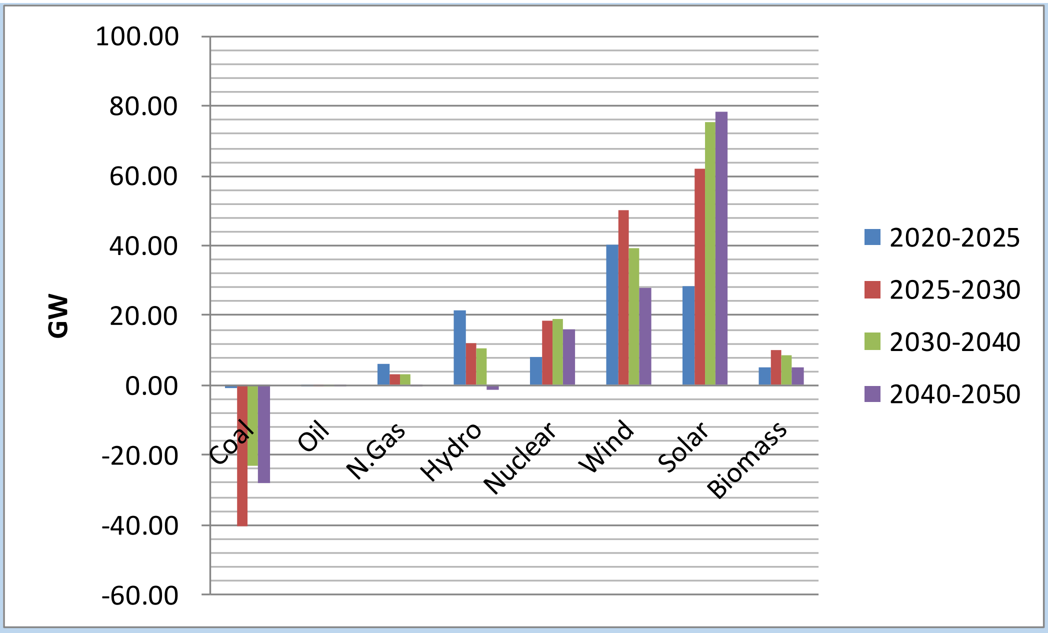
Technology progress is another key for lower carbon pricing. In China's case, technology learning curve are included, and electric car could be cheaper than gasoline car after 2025. Role of carbon price is mainly to trigger CCS implementation. Cost of CCS will also be reduced a lot with the scaling up of CCS technology in China.

Feasibility issues

There will significantly change of fossil fuel use, renewable energy, and CCS in the coming decades, especially in near term. If there is not near term rapid change, the carbon budget limitation will be easily broken. Rate of change in near term is an important issue for 1.5°C. Because coal use in China is more than half of world total in 2016, the change in China could be seen as a typical path for the world. Figure 1 gives the reduction for fossil fuels per year. The highest reduction rate for coal is 18.4million ton per year from 2020 to 2025, which is not a significant number, with 3% reduction rate annually. Coke will be reduced quickly after 2025 due to reduction of steel demand and increase of recycled steel. Oil reduction will mainly occur after 2030, with electric car dominate market after 2025, and fuel cell heavy duty vehicle and vessels will departure for market after 2030. Our understanding is the rate for coal, coke and oil reduction is acceptable for changing.

Box 2.1, Figure 1. Fossil fuel reduction per year in China.

Wind and solar power will increase rapidly in future. From 2025, newly installed capacity will be more than 60GW per year in China, and then go to more than 75GW per year after 2030, comparing with 34GW newly installed capacity in 2016. Wind power will also need to grow quickly, with newly installed capacity to be more than 40GW per year, comparing with that 32GW newly installed capacity in 2015 in China. Biomass power generation need to be 10GW newly installed capacity per year after 2025, in order to launch the BECCS in long term. All newly installed biomass power plants need to be with CCS, or CCS ready.



Box 2.1, Figure 2. Changing of capacity of power per year in China.

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, mitigation costs and co-impacts, including sustainable development issues, that can be derived from the existing integrated pathway literature and scenario comparison. Attention is also given to uncertainties and critical assumptions underpinning mitigation pathways and associated outcomes. The assessment indicates unprecedented intra- and intergenerational policy and geopolitical challenges. The challenges and opportunities identified in this section are further elaborated in Chapter 3 (e.g., social costs of carbon), Chapter 4 (e.g., policies and governance) and Chapter 5 (e.g., links with sustainable development goals).

2.5.1 *Policy narratives, enabling conditions and potential implications*

Experiments with IAMs most often create scenarios under idealised policy conditions which assumed that climate change mitigation measures are only undertaken where and when they are the most effective (Clarke et al., 2014). Such 'idealised implementation' scenarios assume that a global price on carbon emissions is implemented across all countries, all economic sectors, and rises over time through 2100 in a way that will minimise discounted economic costs. The carbon price is often used as a proxy of climate policy costs (see Section 2.5.2). As highlighted in AR5, scenarios developed under these assumptions are often referred to as 'least-cost' or 'cost-effective' scenarios because they result in the lowest aggregate global mitigation costs when assuming that global markets and economies operate in a frictionless, idealised way (Clarke et al., 2014).[1] However, in practice, the feasibility (see

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[1] Model experiments diverging from idealised policy assumptions aim to explore the influence of policy barriers to implementation of globally cost-effective climate change mitigation, particularly in the near term. Such scenarios are often referred to as 'second-best' scenarios. This include, for instance, (i) fragmented policy regimes in which some regions champion immediate climate mitigation action(e.g. 2020) while other regions join this effort with a delay of one or more decades (Blanford et al., 2014; Clarke et al., 2009; Kriegler et al., 2015b), (ii) prescribed near-term mitigation efforts (until 2020 or 2030) after which a global mitigation target is attempted to be achieved (Kriegler et al., 2015b; Luderer et al., 2013, 2016a; Riahi et al., 2015; Rogelj et al., 2013; Tavoni et al., 2012), or (iii) variations in technology preferences in mitigation portfolios (Edenhofer et al., 2010; Krey et al., 2014a; Kriegler et al., 2014b; Luderer et al., 2012; Riahi et al., 2015; Tavoni et al., 2012).

Chapter 1, Cross-Chapter Box 1.3) of a global carbon pricing mechanism deserves careful consideration (see Chapter 4). Scenarios from idealised conditions provide benchmarks for policy makers, since deviations from the idealized approaches capture important challenges for socio-technical and economic systems and resulting climate outcomes.

Socio-technical transitions literature points to multiple complexities in real-world settings that prevent reaching such 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-evolutionary processes reach beyond the role of policy only and include the role of citizens, businesses, stakeholder groups or governments, as well as the interplay of institutional and socio-political dimensions in shaping mitigation pathways. It has been argued that large system transformations, similar to those in 1.5°C mitigation 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.; Patt, 2017). As modelling approaches that quantify the potential effects of such evolutionary and behavioural processes are at early stages of model development (Holtz et al., 2015; Li et al., 2015), experiments with existing IAMs have been conducted that deviate from these idealised policy assumptions as described below. In several cases, the socio-technical transitions insights and models have complemented each other (Trutnevyte et al., 2015; Turnheim et al., 2015).

There has been substantial progress in coordination of scenario production and integrated assessment modelling in recent years, providing a better characterization of the influence of various factors affecting the transition to climate stabilisation.Modelling activities that use the framework of the SSPs (O'Neill et al., 2014), and for which also 1.5°C scenarios are available (Rogelj et al., 2017b), apply a structured set of climate policy assumptions that are consistent with the overall storylines of the respective SSPs. These are called 'Shared Climate Policy Assumptions' (SPAs), and play a key role in linking socioeconomic pathways to forcing and climate related outcomes (Kriegler et al., 2014a). All SPAs assume fragmented mitigation policies until 2020, and vary in global convergence thereafter (Riahi et al., 2017). SPAs aim to capture key policy mitigation issues related to the level of global cooperation in efforts to reduce emissions, the level of stringency over time, the sectoral coverage and the level of effectiveness of land-use mitigation (Kriegler et al., 2014a; Riahi et al., 2017). Through a combination of a set of policy assumptions for the reduction of fossil fuel and industry emissions (F), and for the land-use sector (L), five distinct policy contexts (SPAs) are defined in line with each respective SSP (see Table 2.12).The combination of these five SPAs and corresponding SSPs specifies expected mitigation challenges (see last column Table 2.12; Riahi et al., 2017).

SSP-based scenario studies underline that socio-economic (SSPs) and climate policy assumptions (SPAs) strongly influence mitigation pathway characteristics and the economics of achieving a specific climate target (Bauer et al., 2017a; Riahi et al., 2017; Rogelj et al., 2017b). In terms of enabling conditions, SPAs indicate that policy-driven scenarios that encompass lower energy intensity and limit energy demand reduce the risks of climate targets becoming unreachable (Clarke et al., 2014; Riahi et al., 2015). Another enabling condition is early and cooperative global mitigation action on the long-term climate goals. On the contrary, policy assumptions which lead to climate change mitigation action being delayed from what would be possible in a fully cooperative world, strongly influence the achievability of stringent mitigation targets (Luderer et al., 2013; Rogelj et al., 2013). Furthermore, it has also been shown that fragmented policy scenarios also exhibit 'carbon leakage' via energy and capital markets (Arroyo-Currás et al., 2015; Kriegler et al., 2015b). These are major factors for why SSP1/SPA1 translates into relatively low mitigation challenges whereas SSP3/SPA3 and SSP5/SPA5 describe futures that pose the highest socio-technical and economic mitigation challenges. This is reflected in the stringent mitigation scenarios in line with 1.5°C that have recently been modelled based on the SSPs (Rogelj et al., 2017b). An overview of participating models, successful (feasible) scenarios and related combinations of SSPs and SPAs is provided in Table 2.13.

Energy transition governance dominated by the government, market drivers or the wider society has been also shown to lead to potentially different mitigation outcomes (Chilvers et al., 2017; Trutnevyte et al., 2015).

Note that none of the IAMs contained in the SR1.5 database (see Section 2.1.3) could produce a 1.5°C scenario under SSP3/SPA3 assumptions, due to the impossibility under its policy assumptions to achieve globally coordinated mitigation action before mid-century (see Chapter 4 for institutional feasibility aspects in practice). Elements preventing the models to limit warming to 1.5°C include, for instance, climate policy fragmentation, lack of carbon pricing mechanisms, limited control of land use emissions, and heavy reliance on fossil fuels in the baseline. By mid-century, cumulative CO_2 emissions much larger than the carbon budget for limiting warming to 1.5°C are already emitted. Combined with the small technological capacity to reduce or offset CO_2 emissions and the high GHG emissions from the land-use sector, reaching the low forcing levels required to be in line with a warming of 1.5°C is not possible under these policy and socioeconomic assumptions. Under other socioeconomic and policy assumptions achieving the stringent forcing targets in line with 1.5°C can also be very challenging. For example, in the very unequal yet environmentally conscious world of SSP4, some models cannot limit radiative forcing to low levels due to the inability to control emissions from land-use under the assumptions of this SSP. Policy assumptions can also be varied further within one socioeconomic world. For example, one multi-model inter-comparison study (Luderer et al., 2016b) explored the effect on 1.5°C pathways of assuming implementation of the current NDCs until 2030 and stringent reductions thereafter, and finds that this delay in globally coordinated actions leads to many models finding no 1.5°C options during the 21st century.

SSP-SPA combination	Policy stringency in the near term and timing of regional participation	Policy Coverage of land use emissions	Energy Systems (Supply & Demand in baseline scenarios)	Mitigation challenge
SSP1-SPA1	F1: Early accession with full regional cooperation on climate policies targeting emissions from fossil-fuel use and industry after 2020	LP: Effective coverage (at the level of emissions control in the energy and industrial sectors) Price all land use emissions at the level of carbon prices in the energy sector	Increasing shares of renewables and other low-carbon energy carriers. Decoupling of energy demand from economic growth due to energy efficiency measures and behavioural changes. Effective energy access policies, reducing the use of coal and traditional biomass in households.	Low mitigation challenge due to the combination of low baseline fossil fuel emissions, low energy demand, no delays beyond 2020, favourable conditions of technology development and full participation of land mitigation
SSP2-SPA2	F2: Some delays in climate policies targeting emissions from fossil-fuel use and industry and fragmentation until 2020 with regions transitioning to global cooperation between 2020–2040 and linear transition to a globally uniform carbon price by 2040	LD: Intermediately effective coverage (limited REDD, but effective coverage of agricultural emission) Price all land use emissions at the level of carbon prices in the energy sector, without leading to afforestation or stopping deforestation before 2030	Continuation of the current fossil-fuel dominated energy mix. Energy demand roughly doubles in 2100. Effective energy access policies, reducing use of coal and traditional biomass in households	Intermediate mitigation challenge due to intermediate assumptions for i) baseline emissions, ii) energy demand, iii) delays, and iv) land participation
SSP3-SPA3	F3: Late accession and fragmentation in climate policies targeting emissions from fossil-fuel use and industry – higher income regions (with an average per capita income of 12600 USDUSDyr^{-1} or higher in 2020) join global regime between 2020–2040, while lower income regions start the transition during the period 2030-2050	LN: Very limited coverage and limitedpricing of land use emissions, due to implementation barriers and high transaction costs	Heavy reliance on fossil fuels with an increasing contribution of coal to the energy mix. Energy demand roughly doubles in 2100	High mitigation challenge due to high baseline emissions, major delays, limited technological progress and very limited participation of land in mitigation
SSP4-SPA4	F1: Early accession with full regional cooperation on climate policies targeting emissions from fossil-fuel use and industry after 2020	LD: Intermediately effective coverage and pricing of land use emissions (limited REDD, but effective coverage of agricultural emissions)	Increasing shares of renewables and other low-carbon energy carriers Decoupling of energy demand from economic growth due to energy efficiency measures and behavioural changes	Low mitigation challenge due to no delays beyond 2020, relatively low energy demand combined with intermediate assumptions for land mitigation and intermediate assumptions for baseline emissions. Challenges in SSP4 will most likely be between SSP1 and SSP2

SSP5-SPA5	F2: Some delays in global action and fragmentation in climate policies targeting emissions from fossil-fuel use and industry until 2020 with regions transitioning to global cooperation between 2020–2040 and linear transition to a globally uniform carbon price by 2040	LP: Effective coverage (at the level of emissions control in the energy and industrial sectors) Price all land use emissions at the level of carbon prices in the energy sector	Heavy reliance on fossil fuels with an increasing contribution of coal to the energy mix. More than tripling of energy demand over the century. Effective energy access policies, reducing use of coal and traditional biomass in households	High mitigation challenge due to the combination of high fossil fuel baseline emissions, very high energy demand, and delays in mitigation

Table 2.12: Summary of Shared Policy Assumptions (SPAs) assumed for climate change mitigation pathways according to the overall storylines of the respective SSPs and their associated mitigation challenges. From a global sectoral perspective, SPAs address fossil fuels and industry emissions and the land-use sector with respect to policy implementation. There are three generic SPAs for fossil fuel and industry emissions (F1, F2, F3) that represent low/intermediate/high levels of global cooperation respectively. There are also three SPAs for the land user sector (LP/LN/LD) that vary according to the pricing of emissions of land-use sources. When these specific SPAs are combined, the mix of F and L policy narratives result in five main SPAs with their respective SSPs and resulting mitigation challenges (last column). Source: (Riahi et al., 2017).

Model	Methodology	Reported scenario				
		SSP1-SPA1	SSP2-SPA2	SSP3-SPA3	SSP4-SPA4	SSP5-SPA5
AIM	General Equilibrium (GE)	1	1	0*	0	0
GCAM4	Partial Equilibrium (PE)	1	1	X	0	1
IMAGE	Hybrid (system dynamic models and GE for agriculture)	1	1	0*	X	X
MESSAGE-GLOBIOM	Hybrid (systems engineering PE model)	1	1	0*	X	X
REMIND-MAgPIE	General Equilibrium (GE)	1	1	X	X	1
WITCH-GLOBIOM	General Equilibrium (GE)	1	1	0	1	0

Table 2.13: Summary of models attempting to create scenarios with an end-of-century forcing of 1.9W m^{-2}, consistent with limiting warming to below 1.5°C in 2100, and related SPAs. Notes: 1= successful scenario consistent with modelling protocol; 0= unsuccessful scenario; x= not modelled; 0*= not attempted because scenarios for a 2.6 W m^{-2} target were already found to be unachievable in an earlier study. SSP3-SPA3for a more stringent 1.9 W m^{-2} radiative forcing target has thus not been attempted anew by many modelling teams. Marker implementations for all forcing targets within each SSP are indicated in blue. Source: Rogelj et al. (2017b).

2.5.1.1 *Policy regimes in line with 1.5°C scenarios*

The available literature indicates that policy-driven mitigation pathways in line with a 1.5°C (or 2°C) temperature goal require highly robust, stringent and urgent transformative policy regimes. Scenarios that encompass weak and fragmented policy regimes are unable to limit global warming below a 1.5°C or 2°C limit with high likelihood (Blanford et al., 2014; Clarke et al., 2014; Luderer et al., 2016a). Such regimes also include the current NDCs (Fawcett et al., 2015; Hof et al., 2017; Rogelj et al., 2017a). In other words, relatively weak short-term policy mitigation efforts and fragmented scenarios use up a large share of the long-term carbon budget before 2030–2050, increasing the probability of exceeding the budget in line with limiting warming to below 1.5°C or 2°C (Bertram et al., 2015a; van Vuuren et al., 2016). Weak (or lack of integrated) policy portfolios also increase the risks of trade-offs between mitigation approaches and sustainable development objectives (See Chapter 5 Section 5.4).

Modelled policy options allow global emissions to peak by 2020 and can drive the complete decarbonisation of the energy-economy system by approximately mid-century. Note thatCO_2 emissions from fossil fuel and industry remained relatively flat between 2014and 2016 (Peters et al., 2017b). Emissions growth resumed in 2017, however. Despite inherent levels of uncertainty attached to modelling studies (e.g., related to climate sensitivity, carbon-cycle response), all policy-driven pathways stress the urgency for transformative policy efforts to reduce GHG emissions in the short term (Riahi et al., 2015). Highly ambitious policies targeting both the decarbonisation of the supply side and the reduction of energy use on the demand side play a major role across mitigation pathways (Clarke et al., 2014; Kriegler et al., 2014b; Riahi et al., 2015). Important mitigation options outside the energy supply and end-use sectors include reduced deforestation, the expansion of forest land cover (afforestation and/or reforestation) and the reduction of the greenhouse gas intensity of agriculture (Bauer et al., 2017a; Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2017b). Studies also show that technology policies can have an important role with regards to development and uptake of zero-carbon technologies in the shorter term but that in the longer term, strong carbon pricing mechanisms can be necessary to ensure efficient reductions in GHG emissions (high confidence; Kriegler et al., 2015b).Model results underscore the need for an integrated and ambitious global response to climate change mitigation (for feasibility aspects of global multilateral policy regimes, see Chapter 4). Even if values of lower probability of equilibrium climate sensitivity (ECS) and transient climate response (TCR) are considered (see Section 2.6.2), the urgency for robust mitigation policies for temperature goals more stringent than 2°C remains (Rogelj et al., 2014a).

Whereas the integrated assessment literature is mostly focused on the role of carbon pricing to reduce emissions (Clarke et al., 2014; Weyant, 2017), there is an emerging body of studies (including bottom-up approaches) that focuses on the interaction and performance of various policies (e.g., regulation, subsidies and taxes; Bertram et al., 2015b). Results show that regulatory policies could serve as an entry point to strengthening mitigation and thus complement carbon pricing to drive the deep decarbonisation of the economy consistent with the 1.5°C limit (Kriegler et al., 2017d).Other studies suggested that carbon pricing is needed but insufficient on its own to drive the required changes in line with 1.5° (or well below 2°C) scenarios (Pollitt, 2017; Stiglitz et al., 2017). However, a carbon tax can become a significant source of governmental revenue and facilitate the transition towards deep mitigation pathways via recycling effects (e.g., using revenues to reduce social impacts and support low-carbon infrastructure investments; Stiglitz et al., 2017). The effect on public budgets is particularly important in the near term, but less prominent in the long term as emission fall (Pollitt, 2017).

Assuming a global implementation of regionally existing policies mixes (e.g., regulation across various end-use sectors) and a moderate carbon pricing (e.g., 5USDUSD tCO_2^{-1} in 2025 and average prices between 22–27USDUSD tCO_2^{-1} in 2030), early action mitigation pathways are generated that close a large part of the emissions gap to cost-effective 1.5°(or below 2°C) scenarios in 2030 (Kriegler et al., 2017d). Furthermore, a mix of stringent energy efficiency policies (e.g., minimum performance standards for appliances, building codes), combined with a carbon tax (e.g., 27USDUSD tCO_2^{-1} in 2040) has been shown to generate cost-effective mitigation scenarios in some studies (Brown and Li, 2017). As a single policy option, a carbon tax shows higher mitigation risk values across different sustainability areas compared to scenarios that entail a wider policy mix (e.g., regulation addressing phase out of fossil fuels subsidies; Bertram et al., 2017; see also Section 2.5.3 and Chapter 5). The decarbonisation of residential heating is also shown to be more cost-effective when a policy mix (e.g., carbon tax, technology subsidies, and building codes) is implemented (Knobloch et al.). Delays in implementing a policy mix, comprising for example taxes, subsidies and direct regulation across power, residential heating and transportation sectors leads to global warming above 1.5°C but that can still be below 2°C (Pollitt, 2017). To keep the 1.5°C (or below 2°C) target within reach, the stringency, diversity (beyond carbon pricing) and effectiveness of policy portfolios are of prime importance in the short-term (Kriegler et al., 2017d; Mundaca and Markandya, 2016; Roelfsema et al., 2017; UN Environment, 2017).

The near-term stringency of the policy portfolios also has implications for the use and deployment of CDR options (e.g., to compensate for residual emissions in the long-term) (see Chapter 4 for details). Delayed mitigation policies increase the need for the full portfolio of mitigation measures, including CDR (Clarke et al., 2014; Riahi et al., 2015; Xu and Ramanathan, 2017). At the same time, CDR deployment is already substantial in immediate policy scenarios (see Sections 2.3 and 2.4). Policies driving bioenergy use show a similar or higher share of bioenergy when BECCS is excluded than when it is allowed (Klein et al., 2014).Ambitious demand-side policies reduce the need for CCS (Wachsmuth and Duscha.). Scenarios in which CDR options are restricted emphasise the strengthening of near-term policy mixes and show that a 1.5°C target can be achieved even in the absent of coordinated carbon pricing post 2020 (Kriegler et al., 2017d; Luderer et al., 2013). Likewise a rich and effective policy mix in the near term leads to emission reductions that are much less dependent on CDR options (Pollitt, 2017).

Moving from a 2°C to a 1.5°C target implies higher socio-technical transition speeds, larger deployment scales and bold policies in the short term (very high confidence; Kriegler et al., 2017d; Rockström et al., 2017). This requires higher levels of transformative policy regimes in the near term, which allow deep decarbonisation pathways to emerge and a net zero energy-economy system to be achieved by 2040–2060 (Bataille et al., 2016; Rogelj et al., 2015a). It also requires higher levels of technological deployment and innovation (very high confidence; Sections 2.3 and 2.4) and assumes more profound behavioural, economic and political transformation (See Chapter 4 for socioeconomic and technical transformation in practice). Aggressive policies addressing energy demand appear to be central in keeping 1.5°C within reach during this century and lowering mitigation costs (Luderer et al., 2013; Rogelj et al., 2013, 2015a). Model assumptions indicate that effective behavioural and societal change are critically needed for achieving a 1.5°C pathway (details in Chapter 4, Section 4.4.3).

Multiple factors can affect the efficiency and effectiveness of stringent policy options. Stringent mitigation policies can 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 (see Chapter 4). Furthermore, policies may also not exclusively address mitigation but also target other objectives (e.g., public health, energy security) (Jewell et al., 2016; Shindell et al., 2012, 2016). Climate impacts can also influence the effectiveness of mitigation policies, but are generally not taken into account in IAMs. These aspects generate interactions and frictions over time so overlaps and synergies exist. In addition to stringent policy options which are tightened over time, critical issues driving results in mitigation pathways relate to compliance levels, international cooperation and political acceptability (Blanford et al., 2014; Kriegler et al., 2013; Peters, 2016; Riahi et al., 2017).

Implementation limits and hurdles that mitigation pathways entail from a policy point of view in practice have to be addressed explicitly (e.g., stringency levels, political acceptability, monitoring and evaluation) (Elmar Kriegler et al. 2014; Mundaca and Markandya 2015). Whereas the policy issues identified in this section pertain to the theoretical dimension of mitigation pathways, aspects related to 1.5°C mitigation policies in practice are of prime importance. For instance, questions and solutions related to institutional capacity, public acceptance, distributional equity, consumption preferences, economic conditions, market development, behavioural change, cognitive implications of policy measures, and intra- and inter-generational issues need to be confronted with policies and measures in practice; including historical precedents. These issues are discussed in detail in Chapters 3, 4 and 5.

2.5.1.2 *Limitations of Integrated Assessment Models in examining policy options*

Although model-based assessments project drastic near, medium and long-term transformations in 1.5°C scenarios, projections also often struggle to capture a number of hallmarks of transformative change, including disruption, innovation, and nonlinear change in human behaviour (Rockström et al., 2017). Regular revisions and adjustments are standard for expert and model projections, for example, to account for new information such as the adoption of the Paris Agreement. Costs and deployment of mitigation technologies will differ in reality from the values assumed in the full-century trajectories of the model results. CCS and nuclear provide examples of where real-world costs have been higher than anticipated (Grubler, 2010; Rubin et al., 2015) while solar PV is an example where real-world costs have been lower (Creutzig et al., 2017; Figueres et al., 2017; Haegel et al., 2017)[2]. Such developments will affect the consistent carbon price trajectories for achieving stringent mitigation targets. This shows the difficulty of adequately estimating social and technological transitions and illustrates the challenges of producing scenarios consistent with a quickly evolving market (Sussams and Leaton, 2017).

As mentioned previously, behavioural and institutional frameworks affect the market uptake of mitigation technologies and socio-technical transitions (see Section 2.6.3 and Chapter 4). These aspects co-evolve with technology change and determine, among others, the adoption and use of low-carbon technologies (Clarke et al., 2014), which in turn can affect both the design and performance of policies (Kolstad et al., 2014; Wong-Parodi et al., 2016). A foreseeable technological change in models can preclude the examination of policies that aim to promote disruptive technologies (Stanton et al., 2009). In addition, knowledge creation, networks, business strategies, transaction costs, microeconomic decision-making processes and institutional capacities influence (no-regret) actions,

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[2] FOOTNOTE The International Energy Agency (IEA) estimates that for OECD countries, total primary energy supply (TPES) from renewable sources has grown on average 2.5% per year between 1990 and 2016. For the same period, TPES from non-renewable energy sources (coal, gas, oil and nuclear) shows 0.4% growth. See Chapter 4 (section 4.3.2) for details about the role of renewable energy in accelerated transitions.

policy portfolios and innovation processes (and vice versa) (Geels et al., 2017; Lucon et al., 2014; Mundaca et al., 2013; Patt, 2015; Wong-Parodi et al., 2016); however, they are difficult to capture in equilibrium or cost-minimisation model-based frameworks (Ackerman et al., 2009; Brunner and Enting, 2014; Geels et al., 2017; Grubb et al.; Laitner et al., 2000; Mundaca et al., 2010; Patt, 2015; Patt et al., 2010; Rockström et al., 2017; Turnheim et al., 2015; Ürge-Vorsatz et al., 2009; Wilson and Dowlatabadi, 2007). It is argued that assessments that consider greater end-user heterogeneity, realistic market behaviour, and end-use technology details can address a more realistic and varied mix of policy instruments, innovation processes and transitional pathways (Geels et al., 2017; Lucon et al., 2014; McCollum et al., 2016; Mundaca et al., 2010; Trutnevyte et al., 2015; Ürge-Vorsatz et al., 2009; Wilson et al., 2012).

Some studies (see Table 2.14) describe the transitions that are deemed necessary in the short term at the sector level to keep the door open for a 1.5°C pathway (Climate Action Tracker, 2016; Rockström et al., 2017). They indicate that the pace should be governed by novel governance schemes rather than by inertia imposed by incumbent (predictable) technologies (Rockström et al., 2017). These studies also aim at providing signs that a transition of the magnitude required for a 1.5°C transition is in principle possible, and in some cases, is already happening (Climate Action Tracker 2016; Figueres et al. 2017; Sussams and Leaton 2017; IRENA 2017; IEA/IRENA 2017).

	Energy	Cities & Infrastructure	Transport	Industry	Food Systems	Land use
A roadmap for rapid decarbonisation (Rockström et al., 2017)	Coal exits the global energy mix by the end of 2020. By 2040, oil will be about to exit the global energy mix. Polycentric power grids using superconductive cables will start supplying energy in developing countries, and radical new energy generation solutions will enter the market. Natural gas still provides some backup energy, but CCS ensures its carbon footprint is limited. By 2050 global economy powered by carbon-free energy.	By 2020, all cities in the industrialised world should have decarbonisation strategies in place. All building construction must be carbon-neutral or carbon-negative after 2030. Improving energy efficiency alone would reduce emissions 40 to 50% by around 2030 in many residential cases.	Phase-out of internal combustion engines in new cars by 2030. By 2040 internal combustion engines for personal transport will have become rare on roads worldwide and aircraft fuel should be entirely carbon neutral.	By 2020, all major corporations in the industrialised world should have decarbonisation strategies in place. Emissions-free concrete and steel after 2030 (or replaced by zero- or negative-emissions materials). Improving energy efficiency would reduce emissions 40 to 50% by around 2030 in many industrial cases.	Agro-industries, farms, and civil society should develop a worldwide strategy for sustainable food systems to drive healthier, low-meat diets and reduce food waste. By 2050 global economy fed from carbon-sequestering sustainable agriculture.	
Carbon Action Tracker[3]	The growth of renewables and other zero and low carbon electricity technologies needs to be sustained until 2025 and to reach 100% by 2050. No new coal power plants should be built and the emissions from coal should be reduced by at least 30% by 2025.	To transform the entire standing building stock before 2050 and complete phase-out of direct emissions from buildings by 2050.	Zero-emissions vehicles would have to constitute 100% of newly-sold vehicles worldwide before 2035.	New installations in emissions-intensive sectors (steel, cement, ammonia, petrochemicals) are low-carbon after 2020, and start development and deployment of new near-zero emission technology.	Up to 20% emissions reduction from adopting best practices. e.g. healthy diets, food waste reduction.	Stop net deforestation by 2020s. Afforestation of degraded land before 2030. Reduce forestry emissions and other land use to 95% below 2010 levels by 2030.

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[3] FOOTNOTE The analyses conducted for energy supply and end-use sectors in this report refer to the sector-specific results of Rogelj et al. (2015a) and Kuramochi et al., (2017) as the point of departure. Technology-specific assessments are based on various technical studies including IPCC (2014b), IEA Energy Perspectives 2016 (IEA, 2016), and the Climate Action Tracker's own calculations.

Low Carbon Technology Partnership Initiative (LCTPi)[4]	1.5 TW of additional renewable energy capacity by 2025.	Reduce projected energy use in buildings by 50% by 2030 through energy efficiency in buildings.	Use sustainably produced biofuels for 27% of total transport fuel by 2050. Achieve CO_2 neutral freight transport within the 21st century;	Cement industry emission reductions in the range of 20-25% in 2030 compared to business-as-usual. 0.4 $GtCO_{2-eq}$ reduction per year in the chemical industry's emissions by 2030 through new breakthrough technologies	Reduce agricultural and land-use change emissions from commercial agriculture by 50% by 2030. Achieve a 65% emissions reduction by 2050.	Increase forest carbon stocks by 3 $GtCO_2\,yr^{-1}$.
Mission 2020 (Figueres et al., 2017)	By 2020 Renewable make up at least 30% of the world's electricity supply. No coal-fired power plants are approved beyond 2020, and existing ones are retired.	By 2020 Cities are upgrading at least 3% of their building stock to zero- or near-zero emissions structures each year, to fully decarbonise buildings and infrastructures by 2050.	Electric Vehicles (EV) make up >15% of new car sales globally by 2020. Doubling of city mass-transit utilisation, 20% increase in fuel efficiencies for heavy-duty vehicles and 20% decrease in GHG emissions from aviation per km travelled	Heavy industry goal of halving emissions well before 2050	Sustainable agricultural practices can reduce emissions and increase CO_2 sequestration in healthy, well-managed soils.	Emissions from deforestation and land-use changes to be cut to zero by 2020 decade. Afforestation and reforestation create a carbon sink by 2030
Expect the Unexpected. (Sussams and Leaton, 2017)	Solar PV could supply 23% of global power generation by 2040 and 29% by 2050. Coal is phased out of the power mix by 2040.		EVs account for 35% of the road transport market by 2035 and over two-thirds by 2050			
Drawdown http://www.drawdown.org/	246.14 Gt reduced CO_2 by 2050. Wind 25.6% of world electricity use. Utility-scale solar PV grows to 10% and Rooftop solar PV grow to 7% of electricity generation by 2050. Fossil fuels represent 30% of electricity generation by 2050	54.5 Gt reduced CO_2 by 2050. 9.7% of new buildings will be net zero by 2050.	51 Gt reduced CO_2 by 2050. EV rises to 16% of total passenger miles and Hybrid vehicles to reach 6% of the market in 2050. Mass transit represents 40% of urban travel.	15.6 Gt reduced CO_2 by 2050	321.7 Gt reduced CO_2 by 2050. Combined plant-rich diet and reduced food waste solutions mitigate 5.0 (6.5) Gt per year by 2050. 7.3 Gt per year for agricultural bio-sequestration	84 Gt reduced CO_2 by 2050 through temperate and tropical forest restoration. 18.1 Gt reduced CO_2 by 2050 (afforestation on 204 million acres of marginal lands)

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[4] FOOTNOE Available at lctpi.wbcsd.org/wp-content/uploads/2015/11/LCTPi-PWC-Impact-Analysis.pdf

Table 2.14: Transitions and enabling conditions that need to take place in key sectors in the short term for a 1.5°C pathway, based on available studies.

At the same time, modelling of individual sectors, instead of pursuing systemic horizontal approaches, fails to capture cross-sectoral efficiencies and synergies. This is particularly relevant for urban systems and food systems (Lucon et al., 2014; Smith and Bustamante, 2014). Urban areas could achieve lower emissions if the role of urban planning and density were captured (e.g., see Güneralp et al. 2017). Urban planning could also reduce GHG emissions from urban transport between 20% and 50% (Creutzig, 2016). Regarding food systems, technical GHG reduction potentials related to behavioural changes, such as dietary shifts toward more healthy nutrition, improved livestock managements, and food waste reduction, strongly exceed the potentials of supply-side mitigation options in this sector (Gerber et al., 2013; Smith and Bustamante, 2014). Although consumption-based approaches and demand-side solutions are relevant in policy and mitigation terms (Davis and Caldeira, 2010; Lucon et al., 2014; Peters, 2010; Steininger et al., 2014), they are not given the same level of attention as technological supply-side solutions in assessments, modelling efforts, and research and development in general (Mundaca et al., 2015; Wilson et al., 2012). This is partly because demand-side solutions are often embedded in a complex network of social institutions and practices, and thus less prone to quantitative analysis and clear-cut implementation and system boundaries. Comparability between economic potentials at the supply side and technical potentials at the demand side is limited because demand-side options are difficult to judge in terms of cost-benefit analyses (Creutzig et al., 2016) partly due to complications of how to define their scope when determining required investments (Grubler and Wilson, 2014) and because of endogenous preferences that render benefits and costs are context-dependent (Mattauch et al., 2016).

Furthermore, there are also substantial uncertainties in mitigation options which depend, on the one hand, on model development and the inclusion of options (see Section 2.3.1) and, on the other hand, on modellers' beliefs and preferences. For example, in addition to the aforementioned behavioural changes and their effects on methane from agriculture, there are substantial uncertainties in the mitigation potential of HFCs (Purohit and Höglund-Isaksson, 2017) and several air quality-related pollutants because of uncertainties in the baseline emission trajectories. In the case of HFCs, current emissions are very low, so the mitigation potential depends almost entirely on hypothetical reference emissions against which low emission scenarios are compared. Similar considerations apply for several air quality related pollutants. IAMs often assume, in line with historical experience, that economic growth leads to a reduction in local air pollution as populations become richer (i.e. an environmental Kuznets curve) (Rao et al., 2017). In such cases, the mitigation potential is small because reference emissions that take into account this economic development effect are already low in scenarios that see continued economic development over their modelling time horizon. Other studies do not apply this historically observed relationship arguing that it would not necessarily hold in the future, and air pollution emissions or control standards are kept constant at some historical level, absent of technological or societal economic development (Amann et al., 2013). Assumptions about reference emissions are important because high reference emissions lead to high perceived mitigation potentials and potential overestimates of the actual benefit, particularly in the context of mitigation for HFCs and BC-rich sectors, while low reference emissions lead to low perceived benefits of mitigation measures and thus less incentive to address these important climate and air pollutants (Amann et al., 2013; Gschrey et al., 2011; Rogelj et al., 2014b; Shah et al., 2015; Shindell et al., 2012; Velders et al., 2015).

Cross-Chapter Box 2.1: 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 greenhouse gas (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). 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 (NASEM, 2016, 2017; Rose, 2012).

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 (Nordhaus 2007; Pizer et al. 2014; Kolstad et al. 2014; Adler and Treich 2015; Adler et al. 2017; National Academies of Sciencesand Medicine 2016).

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. 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 only 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 uncertainties in SCC estimates 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 combine with uncertainties in the climate damage functions assumed, including their empirical basis (Pindyck, 2013; Revesz et al., 2014b; Stern, 2013). 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 (Calvin et al., 2017; Thomson et al., 2011), IMAGE (van Vuuren et al., 2011b, 2017b), MESSAGE-GLOBIOM (Fricko et al., 2017; Havlík et al., 2014; Riahi et al., 2011), REMIND-MAgPIE (Kriegler et al., 2017c; Luderer et al., 2013; Popp et al., 2010) 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.

CBA IAMs such as DICE (Nordhaus, 2013, 2017b; Nordhaus and Boyer, 2000), PAGE (Hope, 2006) and FUND (Anthoff and Tol, 2009; Tol, 1999) 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; NASEM, 2017; Revesz et al., 2014a). 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 wellbeing, labour productivity, value of capital stock, ecosystem services and the risks of catastrophic climate change for future generations (Ackerman and Stanton, 2012; Moore and Diaz, 2015; Revesz et al., 2014a; 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. The CBA literature on SCC estimates is briefly assessed in Chapter 3 to the extent it pertains to the subject of 1.5°C warming.

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 (Cai et al., 2015; Lemoine and Traeger, 2014; Lontzek et al., 2015), a low social discount rate (Nordhaus, 2005; Stern, 2007) and inequality aversion (Adler et al., 2017; Dennig et al., 2015; Schmidt et al., 2013).

The SCC and the shadow price of carbon are not merely theoretical concepts (Pizer et al., 2014; Revesz et al., 2014a; Stiglitz et al., 2017). In a frictionless world with no uncertainty, no financial constraints and compensation schemes to guarantee that emissions pathways do not exacerbate existing inequalities in income distribution, they could be translated into a carbon price. 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.

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 carbon dioxide 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), should be included in social costs (Sarofim et al., 2017; Shindell et al., 2017c). This would require linking emissions of different pollutants at the activity level, as for example attempted by the concept of Social Value of Mitigation Activities (SVMA) mentioned in Paragraph 108 of the Paris Agreement decision. Most importantly, a consistent valuation of the SCC or the SVMA in a sustainable development framework would require accounting for the SDGs in the social welfare formulation.

2.5.2 *Economic and financial implications of 1.5°C Scenarios*

2.5.2.1 *Carbon prices*

The economic implications of a particular 1.5°C scenario can be approached in a variety of ways. These include the macro-economic costs expressed as the reduction in consumption or economic output between scenarios with and without climate policy, required investments in specific sectors, social costs or marginal or average carbon prices in line with an efficient implementation of the emission reduction objective. An overview of (cost) metrics to capture the economic impact of mitigation pathways is given in AR5 (Clarke et al., 2014; Krey et al., 2014b) and a discussion of macro-economic impacts of mitigation is provided in Box 2.2. Investments in the energy supply system are discussed in Section 2.5.2.2. Furthermore, the social costs of carbon and avoided externalities due to mitigation measures are discussed in Chapter 3 and 5. We hence focus here on the carbon price characteristics of different mitigation scenarios as a metric to investigate the potential economic implications of stringent mitigation pathways. Under a cost-effective analysis (CEA) framework, carbon prices (mitigation costs) reflect the stringency of mitigation requirements at the margin (i.e., cost of mitigating one extra unit of emission) (see Cross-Chapter Box 2.1)). Emissions prices are usually expressed in carbon (equivalent) prices using the GWP-100 metric as exchange rate for pricing emissions of non-CO_2 greenhouse gases controlled under internationally climate agreements (like CH_4, N_2O and fluorinated gases, see Cross-Chapter Box 1.2 on Balance and Metrics in Chapter 1).[5] The carbon prices assessed here are fundamentally different from the concepts of optimal carbon price in a cost-benefit analysis, or the social cost of carbon (SCC, see also Chapter 3, Section 3.5.2), but can be used as a point of comparison (see Box 2.2).

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

Carbon prices vary substantially across models and scenarios, and their value increase with mitigation efforts (Clarke et al., 2014; Guivarch and Rogelj, 2017; Stiglitz et al., 2017). Based on carbon pricing data available for this special report (discounted to 2020 using a 5% rate), scenarios ‘Below 2°C’ with a greater than 50 and 66 percent probability show carbon prices (median values) in the range of USD30–70USD$_{2010}$ tCO_2^{-1} in 2050, respectively (see Figure 2.29). For scenarios that can return global warming to 1.5°C with a greater than 50 and 66 percent probability, carbon prices range from 90–105USDUSD$_{2010}$ tCO_2^{-1} in 2050, respectively. Then, for scenarios that limit global warming below 1.5°C with a greater than 50 percent probability, carbon prices are estimated to be 240USDUSD$_{2010}$ tCO_2^{-1} in 2050 approximately. Note that the latter scenario is the lowest models can represent (see Section 2.3). Despite the variety of model methodologies and approaches, carbon prices between ‘Below 1.5°C 50%’ and ‘Below 2°C 50% or 66%’ scenarios differ by about a factor of three to seven by 2050 across models and socioeconomic assumptions. The range of model results give this finding medium confidence. CEA-based IAM studies reveal no unique carbon pricing path (Akimoto et al., 2017; Bertram et al., 2015a; Kriegler et al., 2015b; Riahi et al., 2017).However, and consistent with the literature (Hof et al., 2017; Luderer et al., 2013; Rogelj et al., 2013), the estimates show that carbon prices need to increase significantly when a higher level of stringency is pursued.

The widespread range of values depends on numerous aspects, including model methodologies, projected energy demand, resulting emissions, mitigation potentials, technology availability, abatement costs and interactions with other policy instruments, amongst other aspects (Clarke et al., 2014; Kriegler et al., 2015b; Riahi et al., 2017; Rogelj et al., 2015c). The characteristics of the technology portfolio, particularly in terms of costs, availability and performance been shown to play a key role (Clarke et al., 2014; Luderer et al., 2013, 2016a; Riahi et al., 2015; Rogelj et al., 2015c). Technology limitations increase mitigation costs and technology improvements or breakthroughs reduces costs (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 mitigation flexibility from a technology perspective (Kriegler et al., 2015a) (see also Chapter 4, Section 4.3). Scenarios 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 options (e.g., BECCS). The distribution of carbon prices highlights the importance of being aware of potential sampling bias in scenario ensembles towards outcomes derived from models which are more flexible, have more mitigation options, and have cheaper cost assumptions and thus can provide feasible scenarios in contrast to other who are unable to do so (Kriegler et al., 2015a; Tavoni and Tol, 2010).

Irrespective of the stringency of the climate objective, socioeconomic conditions and policy interactions also strongly influence carbon price levels. For instance, and considering the limited number of scenarios, carbon prices in a ‘Below 2°C 50%’ scenario range from 10–17USDUSD$_{2010}$ tCO_2^{-1} in 2050 with SSP1 (‘sustainability’) assumptions, and 45USDUSD$_{2010}$ tCO_2^{-1} in 2050 with SSP5 (‘fossil-fuelled development) assumptions. With due limitations, this suggests lower economic mitigation challenges under SSP1 assumptions compared to SSP5. Also earlier, demand-side measures that increase energy efficiency or limit energy demand have been identified as a critical enabling factor reducing mitigation costs for stringent mitigation scenarios across the board (Bertram et al., 2015a; Clarke et al., 2014; Riahi et al., 2012). Combined with a carbon tax (e.g., 27USDUSD$_{2010}$ tCO_2^{-1} in 2040), a mix of ambitious energy efficiency policies can reach a mitigation scenario in line with a 1.5°C target more cost-effectively than a carbon tax alone (Brown and Li, 2017). In the absent of complementary policies (e.g., fuel standards, energy efficiency subsidies), carbon taxes alone can generate mitigation pathways consistent with 1.5°–2°C; however, at a much higher tax rate (Pollitt, 2017). Delayed near-term mitigation policies and measures, including limited extent of international global cooperation, increases total economic mitigation costs, corresponding carbon prices and transitional challenges (Clarke et al., 2014; Luderer et al., 2013). This is because stronger efforts are required in the period after the delay to counterbalance the higher emissions in the near-term. Mitigation challenges are further increased by failures to adopt strong and effective policies in the near term (2020-2030), as more fossil-based capacity investments are stranded (Bertram et al., 2015a; Johnson et al., 2015; Luderer et al., 2016a) and mitigation pathway in line with 1.5°C become more dependent on costlier CDR options (Smith et al., 2015). Staged accession scenarios produce higher carbon prices than immediate action mitigation scenarios under the same stringency level of emissions (Kriegler et al., 2015b).

Box 2.2: Macro-economic impacts of mitigation

Studies using cost-effectiveness analysis (CEA, see Cross-Chapter Box 2.1. on the Economics of 1.5°C pathways) estimate macro-economic impacts of mitigation pathways in terms of variation in economic output or consumption levels over the long term (Krey et al. 2014, Annex II.3.2, pg. 1292), without considering the benefits of limiting climate change as well as co-impacts on other sustainable development goals (von Stechow et al., 2015). Some global integrate assessment models and many country models also report on variations of employment levels and trade balances. Those variations are measured against a hypothetical baseline without mitigation policy or a policy reference scenario (Section 2.5.2) at various points in time or discounted over a given time period.

If GDP and consumption variations fall below the baseline, they are reported as losses or macro-economic costs[6]. This is a frequent source of misunderstanding. Such cost estimates give an indication how economic activity slows in the long-term relative to the baseline, they do not describe a reduction of output and consumption levels relative to previous years. Macro-economic costs of mitigation need to be clearly distinguished from the marginal abatement costs that describe the cost of reducing the last unit of emissions (Paltsev and Capros, 2013). Macro-economic mitigation costs aggregate the cost of all emissions abatement that took place up to the level of marginal abatement costs. A country with a large abatement potential at low marginal abatement cost levels may spend more on overall abatement than a country with high marginal abatement costs and low abatement potential. If the marginal abatement cost is equated throughout the world, a country with a high dependence to carbon intensive industry (developing countries in a catch-up phase) can be more impacted than a country relying on services and low carbon intensive activities (Tavoni et al., 2013, 2014).

Aggregate mitigation costs depend strongly on assumptions about the baseline which serves as yardstick against which policy costs are measured. The baseline is therefore a critical concept in CEA. When assuming well-functioning, forward-looking and globally integrated markets in the baseline – a situation Working Group 3 called “idealised implementation environment” in the IPCC Fifth Assessment Report (Clarke et al., 2014; Krey et al., 2014b) – the least cost strategy to internalise a climate goal constitutes a globally uniform emissions price minimising the discounted sum of mitigation costs over time. In a real-world setting, perfect expectations and perfect markets do not exist; rather climate policies interact with existing policies and other distortions in labour, energy, capital, and land markets (see Chapter 4). In this case, the optimal policies in a so called first-best world no longer apply (Lipsey and Lancaster, 1957).

Starting from a non-optimal baseline might lead either to more pessimistic conclusions about the macro-economic costs of climate policies (in case of absence of compensating transfers or of market imperfections slowing down the adaptation of economic actors) or to more optimistic conclusions if policy reforms are conducted synergistically with the climate objective. A strand of literature has explored ways of using the revenues of carbon prices (principally carbon taxes) to conduct fiscal reforms that reduce more distortionary taxes and offer, under certain conditions, a “double dividend” by providing both environmental benefits and an aggregate economic gain especially in the form of higher employment (Bovenberg, 1999; Bovenberg and De Mooij, 1994; Bovenberg and Goulder, 1996; Bovenberg and van der Ploeg, 1994; Goulder, 1995, 2013). Yet, the magnitude of these effects depends on country specific circumstances, notably implementation and revenue recycling schemes (Fullerton and Metcalf, 1997), behaviour of labour markets (Guivarch et al., 2011), the price elasticity of imports, and exports and the capacity to reduce tax evasion (Liu, 2013).

In the aftermath of the 2008 financial crisis, a strand of literature developed, sometimes referring to the notion of green growth (GCEC, 2014), to examine how the low carbon transition could open a new long-term growth cycle (Stern and Rydge, 2012) and new development opportunities (Jakob et al., 2016) (see Chapter 5). Whether new economic opportunities might be unlocked (OECD, 2017) will depend upon the capacity to avoid a crowding out effect between carbon saving investments and other investments (Pollitt and Mercure 2017) and to maximise spill-over effects (Popp and Newell, 2012). This capacity will also depend upon the possibility of using the low carbon transition to reduce the ‘savings glut’ (Hourcade and

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[6] FOOTNOTE An in-depth discussion about macro-economic mitigation cost metrics is provided in Annex II, Section A.II.3.2 of the IPCC Fifth Assessment Report of Working Group III (Krey et al., 2014b). Here we only summarise a few key concepts relevant for the assessment of the economics of 1.5°C pathways in Chapter 2.

Shukla, 2013) that has been associated with the risk of 'secular stagnation' (Krugman, 2009; Summers, 2016).

Ultimately, the macro-economy of climate policies concerns primarily their short- and medium-term impacts in a world far from an equilibrium, whereas the mitigation pathways literature assessed in Chapter 2 of this report conveys important information about the long-term economic equilibrium of low carbon development paths.

Considering incomplete and uncertain information, an optimal carbon price of the magnitude estimated by in modelled mitigation pathways needs to be compared with what is politically feasible at the international, national, and sectoral level.Carbon pricing is becoming an increasingly important and expanding instrument of climate and energy policy around the world (see details in Chapter 4). Over 42 national and 25 subnational initiatives have created a price for carbon emissions (World Bank, Ecofys, 2017). Approximately 15% of global GHG emissions were priced directly via a tax or emissions trading system (ETS) in 2016 (World Bank, Ecofys, 2017). As of August 2017, observed carbon prices in practice ranged from 1 USD tCO_2^{-1}(e.g., Chonqing pilot ETS) to about 140 USD tCO_2^{-1} (Sweden carbon tax), with approximately three quarters of emissions being priced below 10 USD tCO_2^{-1} (World Bank, Ecofys, 2017). The value of carbon markets worldwide was about USD52 billion USD in 2016 (World Bank, Ecofys, 2017). In most cases, emissions taxes and emission market price levels, respectively, are considerably lower than carbon prices estimates for the near term in least-cost 1.5°C and 2°C mitigation pathways (e.g., 40–80USD$tCO_{2\text{-eq}}^{-1}$ in 2020 and 50–100USD$tCO_{2\text{-eq}}^{-1}$ in 2030) (Stiglitz et al., 2017). The gap may reflect political economy considerations, a low prioritisation for climate mitigation, or an emphasis on trade-offs with other societal and economic objectives (see discussion in Chapter 4).

Emissions tax levels or emissions targets are usually chosen based on a multitude of considerations beyond a long-term climate goal or an estimated social welfare impact of climate change (Baranzini et al., 2017; Newell et al., 2014; Stern, 2007). In practice, carbon markets also operate simultaneously with pre-existing taxes and other policy options such as tradable green certificates, , feed-in-tariffs, energy efficiency obligations, emissions standards and early retirement of fossil-fuel installations (see details in Chapter 4) (Goulder and Parry, 2008; Goulder and Schein, 2013; Koch et al., 2014; Mundaca, 2008; Sorrell and Sijm, 2003). If emissions abatement is partly achieved by those measures, emissions prices will only reflect the marginal abatement costs of remaining emissions reductions under the target, which are lower than the marginal costs of the full emissions abatement (Bertram et al., 2015b). Carbon market prices can also be affected by a variety of factors, such as information asymmetries across markets actors, market risks, credibility, emission uncertainties, market power and regulatory uncertainty (Cramton and Kerr, 2002; Fan et al., 2010; Goulder and Schein, 2013; Jiang et al., 2014; Mundaca and Richter, 2013; Newell et al., 2014; Rannou and Barneto, 2016; Zachmann and Hirschhausen, 2008) (see Chapter 4).

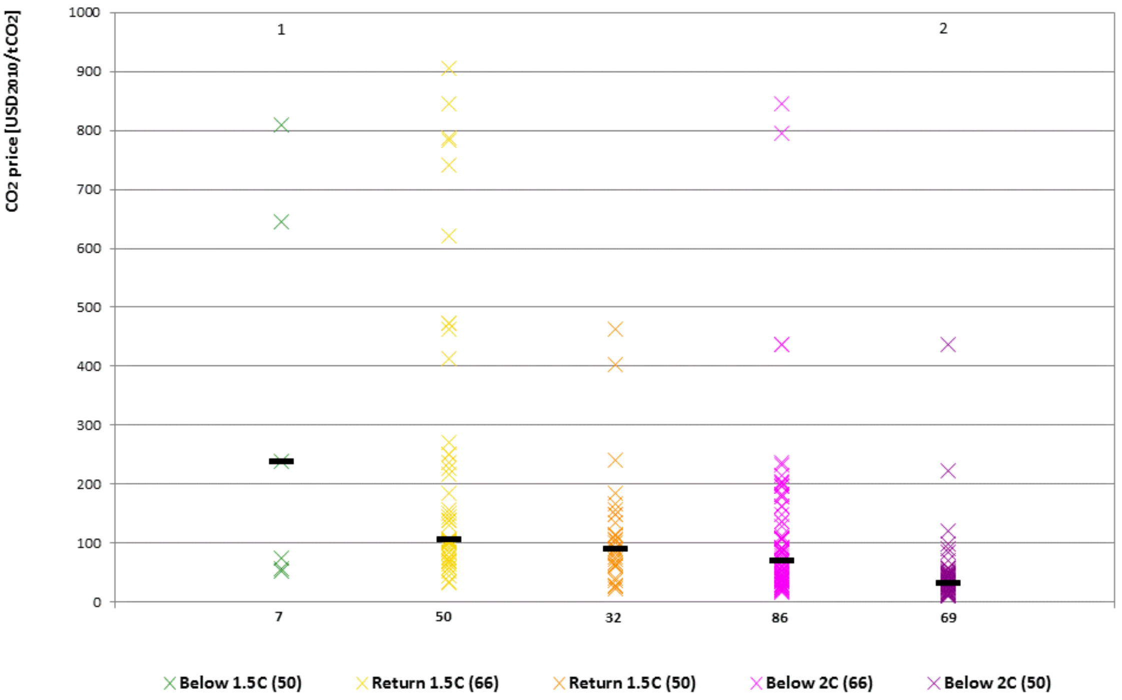


Figure 2.29: Global carbon prices in 2050 consistent with selected mitigation pathways. Median values in floating black dash. The number of scenarios included is indicated at the bottom of the panel. The number of scenarios outside the figure range is noted at the top.

2.5.2.2 *Investments*

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

Global energy system investments in the year 2016 are estimated at approximately 1.7 trillion USD (2.2% of global GDP approximately), with oil and gas representing two fifths of global investments(IEA, 2017). 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.). Between 2000 and 2012, global energy investments grew almost continuously (approximately a three times increase); they then levelled off for three years before declining in 2015, and declined again by 12% in real terms in 2016 (IEA, 2017). Estimates of demand-side investments are more uncertain, mainly due to a lack of reliable statistics and definitional issues about what exactly is counted towards a demand-side investment (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. These definitions differ in which components are counted towards being relevant to the energy part of demand-side investments. Based on these two definitions, demand-side energy investments for the year 2005 were estimated to be of the order of 1 to 3.5 trillion USD (central estimate 1.7 trillion USD) using the broad definition and 0.1 to 0.6 trillion USD (central estimate 0.3 trillion USD) using the narrower definition. Due to these definitional issues, demand-side investment projections are uncertain, often underreported, and difficult to compare in an appropriate way. Global IAMs often do not fully represent, for example, incremental efficiency investments for end-use technologies or systemic design choices, for example, mass transit or alternative urban form.

Research carried out by six global IAM teams in the framework of the CD-LINKS project (www.cd-links.org/) found that climate policies in line with limiting warming to 1.5°C would require a marked upscaling of energy system supply-side investments between now and mid-century, reaching levels of between 1.4–3.8 trillion USD yr^{-1} globally on average over the 2016-2050 timeframe (McCollum et al.) (Figure 2.30), cumulative CO_2 emissions over the 21st century in these scenarios fall in the range of the 'return 1.5C 66' or 'return 1.5C 50' classes used in this report). Supply-side investments here refer to resource extraction, power generation, fuel conversion, pipelines/transmission, and energy storage. How these investment needs compare to those in a policy baseline scenario is uncertain: they could be higher, quite a bit higher, or lower. Corresponding investments in the policy baselines from these same models are 1.3–2.7 trillion USD yr^{-1}. Much hinges on the reductions in energy demand growth embodied in the 1.5°C pathways, which will require investing in energy efficiency. Studies suggest that annual supply-side investments by mid-century could be lowered by around 10% (McCollum et al.) and in some cases up to 50% (Grubler et al., 2017) were strong energy demand growth limitations to be successfully implemented. The degree to which these supply-side reductions would be partially offset by an increase in demand-side investments is not clear.

Some trends are robust across scenarios. First, pursuing efforts to limit global temperature increase to 1.5°C will require a major reallocation of the investment portfolio, implying a system aligned to mitigation challenges (high confidence). The path laid out by countries' current NDCs until 2030 will not be the driver for these structural changes; and while low-carbon investments have been increasing in recent years (Frankfurt School-UNEP Centre/BNEF, 2017; IEA, 2016c), much more will needed to align investments with 'return 1.5C 66' or 'return 1.5C 50' pathways. Specifically, annual investments in low-carbon energy (across the entire supply side) overtake fossil investments globally already in the 2020–2025 timeframe in 1.5°Cpathways (McCollum et al.). Low-carbon supply-side investments are projected to average 0.8–2.9 trillion USD yr^{-1} globally to 2050. Under middle-of-the-road assumptions of future socioeconomic and technological development (Fricko et al., 2017), the bulk of these investments are projected to be for clean electricity generation, particularly solar and wind power (0.09–1 trillion USD yr^{-1} and 0.1–0.4 trillion USD yr^{-1}, respectively) as well as nuclear power (0.1–0.23 trillion USD yr^{-1}). The precise apportioning of these investments depends on societal preferences related to mitigation strategies and policy choices (see Section 2.3). Another critical area where investments are scaled up for 1.5°C pathways is for electricity transmission and distribution and storage (0.3–1.4 trillion USD yr^{-1}), since a cornerstone of a low-carbon world is likely to be 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 0.2–0.7 trillion USD yr^{-1} in total over the 2016–2050 period). Investments in unabated coal are halted by 2030 in most 1.5°C consistent projections, while the literature is less conclusive for investments in unabated gas (McCollum et al.). This illustrates how mitigation strategies vary between models, but in the real world should be considered in terms of their societal desirability (see Chapter 4).Furthermore, some fossil investments made over the next few years – or those made in the last few – come with a risk that they will need to be 'stranded' at some point in the future (i.e., retired prior to fully recovering their capital investment)(Bertram et al., 2015a; IEA / IRENA, 2017; Johnson et al., 2015). Early retirement of infrastructure is a standard feature of several well-established IAMs (Bertram et al., 2015a; Johnson et al., 2015). Modelling studies have also shown how the reliability of institutions influences investment risks and hence climate mitigation investment decisions (Iyer et al. 2015), and find that a lack of regulatory credibility or policy commitment fails to stimulate low-carbon investments (Bosetti and Victor, 2011; Faehn and Isaksen, 2016). Another key insight emerging from the scenarios literature is that the incremental effort to move beyond limiting global mean temperature increase to 2°C and pursue 1.5°C instead requires a step-change in low-carbon investments per tonne of CO_2 avoided (Figure 2.30).

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.) are the following (average over 2016-2050 timeframe): 0.3-1.3 trillion USD yr^{-1}(ASIA), 0.3–0.8 trillion USD yr^{-1} (OECD), 0.08–0.5 trillion USD yr^{-1} (MAF), 0.07–0.2 trillion USD yr^{-1} (LAM), and 0.05-0.2 trillion USD yr^{-1} (REF) (regions are defined consistent with their use in AR5 WGIII, see Table A.II.8 in Krey et al., 2014b).

Assumptions in modelling studies indicate a number of challenges. For instance, access to finance and mobilisation of funds are critical (Fankhauser et al., 2016). In turn, policy efforts need to be effective in re-directing financial resources towards mitigation investments (UNEP, 2015) and reduce transaction costs for bankable mitigation technology projects (Brunner and Enting, 2014; Mundaca et al., 2013). Furthermore, 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, 2016; EC, 2017; Mundaca et al., 2016). Assumptions also overlooked the different time horizons that actors have in the competitive finance industry (Harmes, 2011). See Chapter 4 (Section

4.4.2) for details of climate finance in practice. Studies suggest that policies that re-direct existing financial resources towards mitigation investments and reduce transaction costs for bankable low-carbon energy technology projects, particularly on the demand side, are needed. There are risks of fossil-based asset stranding, hence financial stress tests for future energy infrastructure are needed. Delayed action or weak near-term policies, increase the risk of exceeding the 1.5°C target and the amount of stranded investment in fossil-based capacity, leading to higher long-term mitigation challenges (high confidence). Further, a lack of near-term policy commitment and regulatory credibility hinders mitigation investments and increases abatement costs (high confidence).

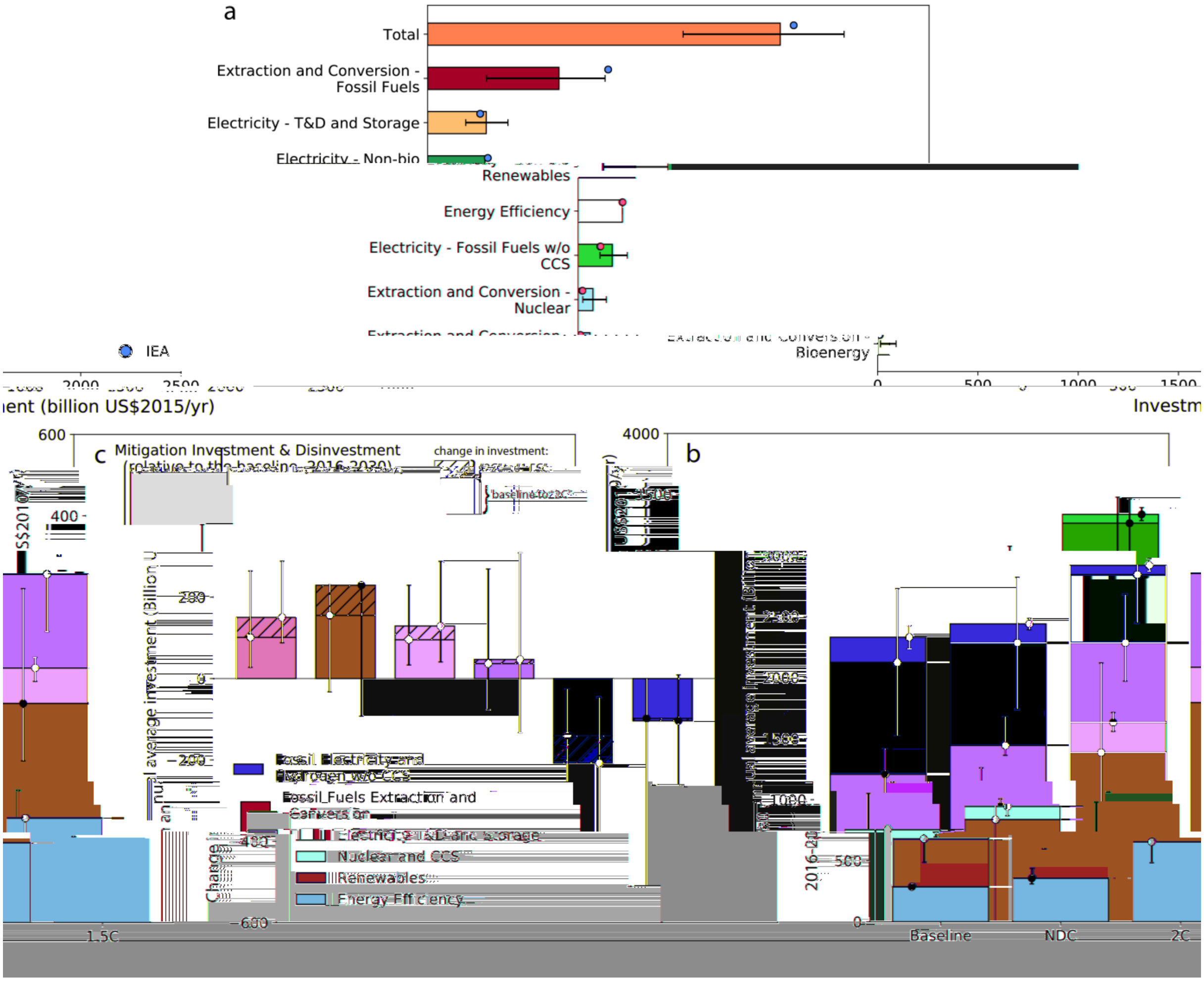


Figure 2.30: Historical and projected global energy investments. (a) Investment estimates across six global models from (McCollum et al.) (bar = mean, whiskers full model range) compared to historical estimates from IEA (International Energy Agency (IEA) 2016) (blue dots). (b) Average annual investments over the 2016–2050 period in no-climate policy “baselines”, scenarios which implement the NDCs (“NDC”), scenarios consistent with the “below 2C 66” scenario class (“2C”), and scenarios in line with the “return 1.5C 66” scenario class (“1.5C”). Whiskers show the range of models around the internally consistent estimate by the MESSAGEix model. (c) Average annual mitigation investments and disinvestments for the 2016–2030 periods relative to the baseline. The solid bars show the values for “2C” scenarios, while the hatched areas show the additional investments for the scenarios labelled with “1.5C”. Whiskers show the full range around the multi-model mean. T&D stands for transmission and distribution, and CCS stands for carbon capture and storage.

2.5.3 *Sustainable development features of 1.5°C pathways*

Since AR5, an increasing number of modelling studies and literature show that sustainable development objectives and climate policy targets are interrelated, interact with each other and that synergies and trade-offs can be identified (Jakob and Steckel 2016; von Stechow et al. 2016; Epstein et al. 2017; Wüstemann et al. 2017). Synergies include aspects related to air quality, ocean acidification, water use, biodiversity, as well as poverty alleviation, job creation, improved energy security, public health, and so on. Trade-offs often arise from the large-scale deployment or restrictions of certain mitigation technologies and their related risks (e.g., nuclear or CCS), the impact of policy instruments (e.g., on fuel poverty Moss et al. 2014; Cameron et al. 2016), and risks associated with direct climate impacts or resource use by mitigation measures (e.g., water scarcity and cooling water (Fricko et al., 2016), food production and land-based mitigation measures or bioenergy production (Popp et al. 2017; Jakob and Steckel 2016; von Stechow et al. 2016), or air quality and use of CDR relative to reducing residual emissions (Shindell et al., 2017b).

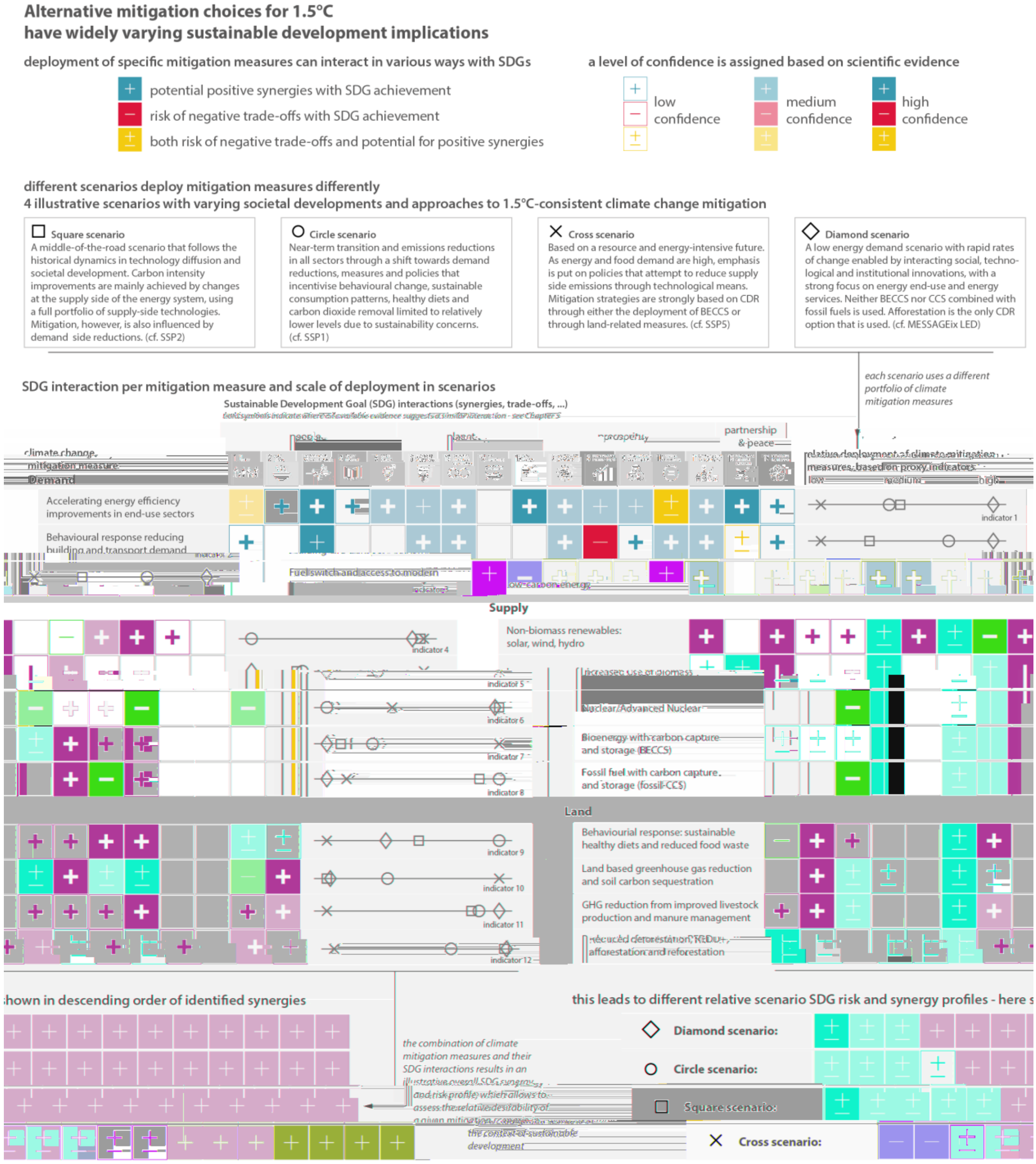
Potential synergies between climate and development policies are an emerging and active field of research. The SSP framework also allows for first steps in the exploration of these interactions between climate and other development goals. The SSP1 ‘sustainability’ scenario is an example of a scenario in which climate policy is implemented alongside other goals such as a focus on providing sufficient food, providing modern energy, avoiding deforestation and reducing local air pollution. For its quantification, achievement by 2030 of full access to modern energy (consistent with SDG7), significant reductions of global air pollution for health reasons (SDG3), and significant gains in access to food (SDG2) have been assumed (van Vuuren et al., 2017b). While the SDGs have not been targeted in SSP1, the scenario leads to significant improvement in access to modern energy and food, reductions in air pollutants (Rao et al., 2017), and overall low food and energy demand facilitating climate change mitigation (Popp et al., 2017; Riahi et al., 2017).

It is also increasingly suggested in international climate policy that many countries are willing to support climate policies that can deliver other societal goals, such as the Sustainable Development Goals (SDGs) or other local or national priorities like energy security or public health (e.g., see Kennel, F. et al. 2012; Jewell et al. 2016). Integrating development and climate policies can contribute to achieve 2030 goals more effectively, efficiently and sustainably, if synergies are enhanced and trade-offs minimized (Nilsson et al. 2016; Peters and Tanner, 2016). Mitigation costs, for example, can vary significantly when climate and sustainability scenarios are simultaneously assessed (Jakob and Steckel, 2016). However, a policy mix addressing various sustainability issues can compensate for most mitigation risks when moving from a 2°C to a 1.5°C target (Bertram et al., 2017). Studies call for an integrated assessment framework to simultaneously evaluate climate and sustainable development policies (Griggs et al., 2014; von Stechow et al., 2016) (see details in Chapter5).

A qualitative assessment of the synergies and trade-offs of individual mitigation measures and SDGs across relevant SDGs’ outcomes has been carried out in Chapter 5. Those insights have been synthesized in this chapter (see Figure 2.31), showing the interactions of three groups of measures – demand side measures, supply side measures and land based measures – with sustainable development dimensions, represented along every SDG (see Chapter 5). The assessment is based on the potential positive synergies and the risks of negative trade-offs of individual mitigation measures with SGD achievement. However, the scale of deployment of individual measures and different combinations of mitigations measures – that is to say. ‘mitigation portfolios’ – will also influence the extent and balance of the synergies and trade-offs. The choice of mitigation portfolio can have wide-ranging implications for the achievement of other societal objectives.

Pathways come with distinct features and deploy mitigations measures differently, which in turn influence the extent of the synergies and trade-offs with other societal objectives, such as poverty eradication, food security, or clean air. Thus, the assessment here maps the interactions of different scenarios and their respective mitigation portfolios (see Section 2.3) with all SDGs. This mapping provides a relative assessment of scenario SDG synergies, based on the relative deployment of each mitigation measure in the scenarios. Four illustrative scenarios with varying societal developments and different mitigations portfolios consistent with returning warming to 1.5°C by the end of the century were selected to assess how their distinct features and mitigations portfolios perform across other societal goals, specifically across all SDGs. A brief description of each scenario is included on top of Figure 2.31. Three of the four scenarios are based on the SSPs (SSP1, SSP2, and SSP5) (Fricko et al., 2017; Kriegler et al., 2017c; Riahi et al., 2017; Rogelj et al., 2017b; van Vuuren et al., 2017b); a fourth is drawn from an independent modelling exercise, which puts particular emphasis on demand reductions (Grubler et al., 2017). Finally, interactions are weighted and aggregated for each SDG at scenario level, with a level of confidence based on the scientific evidence, resulting in an illustrative sustainability profile of alternative mitigation pathways towards the same 1.5°C objective in the context of sustainable development.

Understanding the potential linkages and interactions between climate mitigation and other societal objectives is an important first step (Section 5.4).Only recently integrated studies have started to explore these interactions with multiple societal objectives in depth(Clarke et al., 2014; Jakob and Steckel, 2016; Krey et al., 2017; von Stechow et al., 2015). This literature already suggests that energy efficiency and other mitigation strategies can provide near-term synergies with multiple other societal objectives, like energy security and air quality co-benefits. However, it also highlights that these co-benefits are neither automatic nor assured but result from conscious and carefully coordinated policies and implementation strategies (Clarke et al., 2014; Krey et al., 2017; Shukla and Chaturvedi, 2012). This highlights the importance of mitigation portfolio choices, particularly when also considering the achievement of sustainability objectives.



☐ Square scenario
A middle-of-the-road scenario that follows the historical dynamics in technology diffusion and societal development. Carbon intensity improvements are mainly achieved by changes at the supply side of the energy system, using a full portfolio of supply-side technologies. Mitigation, however, is also influenced by demand side reductions. (cf. SSP2)

○ Circle scenario
Near-term transition and emissions reductions in all sectors through a shift towards demand reductions, measures and policies that incentivise behavioural change, sustainable consumption patterns, healthy diets and carbon dioxide removal limited to relatively lower levels due to sustainability concerns. (cf. SSP1)

✕ Cross scenario
Based on a resource and energy-intensive future. As energy and food demand are high, emphasis is put on policies that attempt to reduce supply side emissions through technological means. Mitigation strategies are strongly based on CDR through either the deployment of BECCS or through land-related measures. (cf. SSP5)

◇ Diamond scenario
A low energy demand scenario with rapid rates of change enabled by interacting social, technological and institutional innovations, with a strong focus on energy end-use and energy services. Neither BECCS nor CCS combined with fossil fuels is used. Afforestation is the only CDR option that is used. (cf. MESSAGEix LED)

Figure 2.31: 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.[7]

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[7] FOOTNOTE Proxy indicators are: 1) Compound annual growth rate of primary energy (PE) to final energy (FE) conversion from 2020 to 2050; 2) % change in FE between 2010 and 2050; 3) Year-2050 carbon intensity of FE; 4) Year-2050 PE that is non-bio RE; 5) Year-2050 PE from biomass; 6) Year-2050 PE from nuclear; 7)

2.6 Assessment tools and knowledge gaps

The literature on mitigation pathways assessed in this chapter is based on a range of tools. Many of these tools are similar to those underlying the IPCC Fifth Assessment Report. However, to provide readers with relevant context for the assessment in this chapter, key tools and their applicability, strength and limitations will be briefly assessed in this section, focussing on the most relevant topics for this report.

The chapter draws on global mitigation pathway studies with full coverage of sectorial emissions over the 21st century, and also upon the wider mitigation literature which looks at specific mitigation options in more isolated settings. While the former type of studies is typically based on global integrated assessment models (IAMs), the latter type often uses more detailed sector- or region-specific models with a time horizon until mid-century. This chapter also describes the geophysical tools of the assessment that are needed to relate emissions pathways to climate response. Finally, the chapter also aims to place the quantitative literature on mitigation pathways into the context of the transition and development literature where possible and relevant. This section gives a short overview on how this literature relates to 1.5°C mitigation pathways.

2.6.1 *Integrated and sector-specific assessment models*

Integrated assessment models (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 emissions from different sectors. Over time, the system coverage of integrated assessment models has also increased. Many of the IAMs that contributed mitigation scenarios to this assessment now include a process-based description of the land system in addition to the energy system (e.g., Wise et al. 2014; Kriegler et al. 2017; Fricko et al. 2017), and some have been extended to cover air pollutants, water, and material use. These features make them increasingly apt to explore questions beyond those that touch upon climate mitigation only (von Stechow et al., 2015). In addition to the process-based IAMs that provide integrated scenarios, this chapter also draws from insights from sector specific assessment models. Such models typically focus on a specific sector, such as the energy (Bruckner et al., 2014), buildings (Lucon et al., 2014) or transport (Sims et al., 2014) sector. Sectorial decarbonization strategies projected by IAMs in 2°C pathways have been found to be consistent with sector-specific studies in AR5 (Clarke et al., 2014). A growing body of literature on 100% renewable energy scenarios has emerged (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., 2017b; Pietzcker et al.), none of the IAM projections identify 100% renewable energy solutions for the global energy system as part of cost-effective mitigation pathways. 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 as has been found in the IAM literature on 1.5°Cpathways assessed in this chapter (Luderer et al., 2017c).

The IAMs used in the mitigation pathway assessment in this chapter are detailed process-based models, with limited to no coverage of climate impacts. The scenarios generated by these models are defined by the choice of long-term 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, e.g., represented by different Shared socio-Economic Pathways, especially those pertaining to energy and

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Year-2050 $GtCO_2$ BECCS; 8) Year-2050 $GtCO_2$ Fossil-CCS; 9) Year-2050 share of non-livestock in food energy supply; 10) Cumulative CO_2 AFOLU over 2020-2100 period; 11) CH_4 and N_2O AFOLU emissions per unit of total food energy supply; 12) Change in global forest area between 2020 and 2050. Values of Indicators 2, 3, and 11 are inverse related with the deployment of the respective measures. The scenario values are displayed on a relative scale from zero to one where the lowest scenario is set to the origin and the values of the other indicators scaled so that the maximum is one.

food demand (Clarke et al., 2014). Since AR5, the scenario literature has expanded the exploration of these dimensions much beyond the addition of 1.5°C pathways. This included low demand scenarios (Grubler et al., 2017; van Vuuren et al., 2017d), scenarios taking into account a larger set of sustainable development goals (Bertram et al., 2017; Krey et al., 2017), scenarios with restricted availability of carbon dioxide removal technologies (Bauer et al., 2017b; Strefler et al., 2017; van Vuuren et al., 2017d), scenarios with near-term action dominated by regulatory policies (Kriegler et al., 2017d) and scenario variations across the Shared Socio-economic Pathways (Riahi et al., 2017; Rogelj et al., 2017b).

Detailed process-based IAMs use greenhouse gas (GHG) pricing mechanisms to induce emissions reductions and associated changes in energy and land uses consistent with the imposed climate goal. Those mechanisms are often augmented by assumptions about regulatory and behavioural climate policies in the near- to mid-term (Bertram et al., 2015b; Kriegler et al., 2017d; van Sluisveld et al., 2016). The choice of mechanism to adapt the GHG price trajectory to the climate goal formulation varies across IAMs and can affect the shape of mitigation pathways. For example, assuming exponentially increasing CO_2 pricing to stay within a limited CO_2 emissions budget is consistent with efficiency considerations in an idealized economic setting, but can lead to temporary overshoot of the carbon budget if carbon dioxide removal technologies are available. The pricing of non-CO_2 greenhouse gases is often pegged to CO_2 pricing using their global warming potentials (mostly GWP_{100}) as exchange rates (see Chapter 1 Cross-Chapter Box 1.2). This leads to stringent abatement of non-CO_2 gases in the medium- to long-term, but also incentivizes continued compensation of these gases by carbon dioxide removal even after their full abatement potential is exploited, thus further contributing to the peak and decline temperature pattern of some mitigation pathways. The choice of economic discount rate is usually reflected in the increase of GHG pricing over time and thus also affects the timing of emissions reductions. For example, the deployment of capital intensive abatement options like renewable energy can be pushed back by higher discount rates. However, as overall emissions reductions need to remain consistent with the choice of climate goal, mitigation pathways from detailed process-based IAMs are typically only moderately sensitive to the choice of discount rate (Rogelj et al., 2013). This is fundamentally different for much more aggregated cost-benefit IAMs (see Box 6.1 in Clarke et al. 2014) which balance monetised costs of mitigation and climate damages to identify cost-benefit optimal emissions pathways. Such models are, in contrast, quite sensitive to the choice of discount rate (e.g. Pizer et al. 2014; Kolstad et al. 2014; Adler et al. 2017). A detailed discussion of the strengths and weaknesses of cost-benefit IAMs is provided in AR5 (Clarke et al., 2014; Kolstad et al., 2014; Kunreuther et al., 2014), and an overview discussion comparing contributions of both process-based and cost-benefit IAMs is provided in Weyant, (2017) (see also Box 2.2).

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. Ultimately, the set of process-based IAMs that provided input to this assessment is not fundamentally different from those underlying the IPCC AR5 assessment of transformation pathways (Clarke et al., 2014) and an overview of these integrated modelling tools can be found there. However, there have been a number of model developments since AR5, in particular improving the sectorial detail of IAMs (Edelenbosch et al., 2017b), the representation of solar and wind energy (Johnson et al., 2017; Luderer et al., 2017b; Pietzcker et al.), the description of bioenergy and associated sustainability trade-offs (Bauer et al., 2017b; Humpenöder et al., 2017), the representation of a larger portfolio of carbon dioxide removal technologies (Strefler et al., 2017), the accounting of behavioural change (McCollum et al., 2016; van Sluisveld et al., 2016; van Vuuren et al., 2017c) and energy demand developments (Edelenbosch et al., 2017a, 2017c; Grubler et al., 2017; Levesque et al., 2017), the consideration of climate impacts (Schultes et al., 2017), and the modelling of sustainable development implications (Bertram et al., 2017; Krey et al., 2017), for example. relating to water demand (Fricko et al., 2016; Mouratiadou et al., 2016), access to clean water and sanitation (Parkinson et al., 2017), material use (Luderer et al., 2017a), energy access (Cameron et al., 2016), air quality (Rao et al., 2017) and food security (Fujimori et al., 2017). Furthermore, since AR5, a harmonised model documentation of IAMs and underlying assumptions has been established within the framework of the EU ADVANCE project: http://themasites.pbl.nl/models/advance/index.php/ADVANCE_wiki.

2.6.2 *Geophysical assessment tools*

The geophysical assessment in this chapter draws upon results from a range of climate models and simple climate model emulators. The most complex earth system models (ESMs) simulate the fully coupled Earth system, including its atmospheric and ocean circulations, and include vegetation feedbacks and multiple biogeochemical cycles, including the carbon and/or or the nitrogen cycle. Earth system models of intermediate complexity (EMICs) employ the most important processes simulated in the full ESMs but with a reduced level of detail allowing a greater number of simulations to be performed. ESM and EMIC results are the principal method employed in making climate projections. For traceability to AR5 most of the projections of global mean surface temperature in this report are made with a simple climate model emulator of the more complex ESMs. For these simulations the MAGICC (Meinshausen et al., 2011a) reduced complexity carbon-cycle and climate model is used in the same model variant used to inform the WGIII assessment in AR5. These different classes of geophysical assessment tools come with their own strengths and limitations but take up complementary roles. ESMs reflect our most detailed up-to-date understanding of the Earth system, but the computational cost of such tools is excessively high to simulate a large ensemble of scenarios. Simple climate model emulators are developed to closely emulate ESMs based on physical principles, they can be run multiple thousands of times, but make simple approximations and typically do not simulate climate responses other than global mean surface temperatures.

The IAM pathways considered in this chapter and throughout the report have used estimates of radiative forcing and global mean surface temperature derived from the MAGICC model, calibrated to previous CMIP phases of coupled model results (Meinshausen et al., 2011a). The same model was extensively employed to assess scenarios within IPCC AR5 WG3 (Clarke et al., 2014). The spread of equilibrium climate sensitivity (ECS) simulated by MAGICC is similar to that exhibited by CMIP5 models, but the AR5 assessment of ECS had a smaller likely lower bound (1.5°C) than seen in the models (Collins et al., 2013). Tuning to CMIP4 would suggest a larger sensitivity to rising CO_2 compared to CMIP5 models, although a multi-model inter-comparison indicated that the default MAGICC calibration is close to the median of other model approaches (Joos et al., 2013). However, the uncertainty range of its carbon cycle response is likely underestimated (see Bodman et al. 2013 and below). The MAGICC model was able to represent the range of temperature projections exhibited by the CMIP5 models, across most RCP scenarios (see Collins et al. 2013, Figure 12.8 and Clarke et al. 2014, Figure 6.12), both in terms of its median temperature response and 5–95% uncertainty range. This good fit was not true of RCP2.6, where MAGICC underestimated the spread in climate response compared to CMIP5 models. This can be traced to: 1) a single treatment of short-lived climate forcers within MAGICC compared to a diversity within CMIP5 models, and 2) a lack of internal variability in MAGICC (Collins et al., 2013).

The geophysical choices in the MAGICC setup are based on pre-AR5 science. Since publication of AR5 updated understanding of radiative forcing, climate sensitivity and the carbon cycle will all affect the robustness of the MAGICC setup for quantifying best estimates and uncertainty ranges of global mean surface temperature responses for a given emission scenario. For high emission scenarios uncertainties in the climate sensitivity and carbon cycle response dominate (Friedlingstein et al., 2014b; Frölicher, 2016; Myhre et al., 2015; Tokarska et al., 2016). For the low emission pathways that are the focus of this report, the carbon-cycle feedbacks on temperature and less important and the uncertainty in aerosol radiative forcing and in equilibrium climate sensitivity are more-or-less equally important in evaluating future temperatures (Mauritsen and Pincus, 2017; Smith et al., 2018).

However, other uncertainties associated with Earth system feedbacks might induce an asymmetry of the temperature change to rising and decreasing CO_2 (Zickfeld and MacDougall, 2016). Such asymmetry also known as path-dependence of the TCRE can lead to a slightly higher temperature outcome for a given carbon budget when it is achieved by net CDR after a carbon budget overshoot. So far, idealized experiments carried out with a model of intermediate complexity, Zickfeld and MacDougall (2016) estimate that the asymmetry between rising and decreasing CO_2 is about 7% for the TCRE. However, other studies carried out with CMIP5 models (Boucher et al., 2012; Jones et al., 2016; Séférian et al., 2017) show response in the opposite direction (illustrated with one ESM in Figure 2.32). Each model's asymmetrical response is the result of many factors that can counter-balance one another. Part of it has been attributed to the lagged response of slow components of the Earth system to past CO_2 emissions and ensued warming, such as the deep ocean-induced legacy warming (Held et al., 2010). The turnover times of the various carbon cycle reservoirs, as well as their sensitivity to environmental conditions such as atmospheric CO_2 and climate, also likely determine each model's response. However, in a situation where the global mean temperature exceeds 1.5°C by mid-century and returns below this threshold by 2100, MAGICC exhibits for 89 mitigation pathways out of 108 (~80%) a reduction in 2100 carbon budget due to asymmetrical response of the TCRE. In comparison, available ESM overshooting simulation shows that 5 out 6 ESMs (~80%) suggest an increase in 2100 carbon budget (Jones et al., 2016), a similar response is illustrated in Figure 2.32 by simulations of the CNRM-ESM1. As a consequence, we assign a greater geophysical uncertainty in TRB than in TPB as discussed in Section 2.2.2.

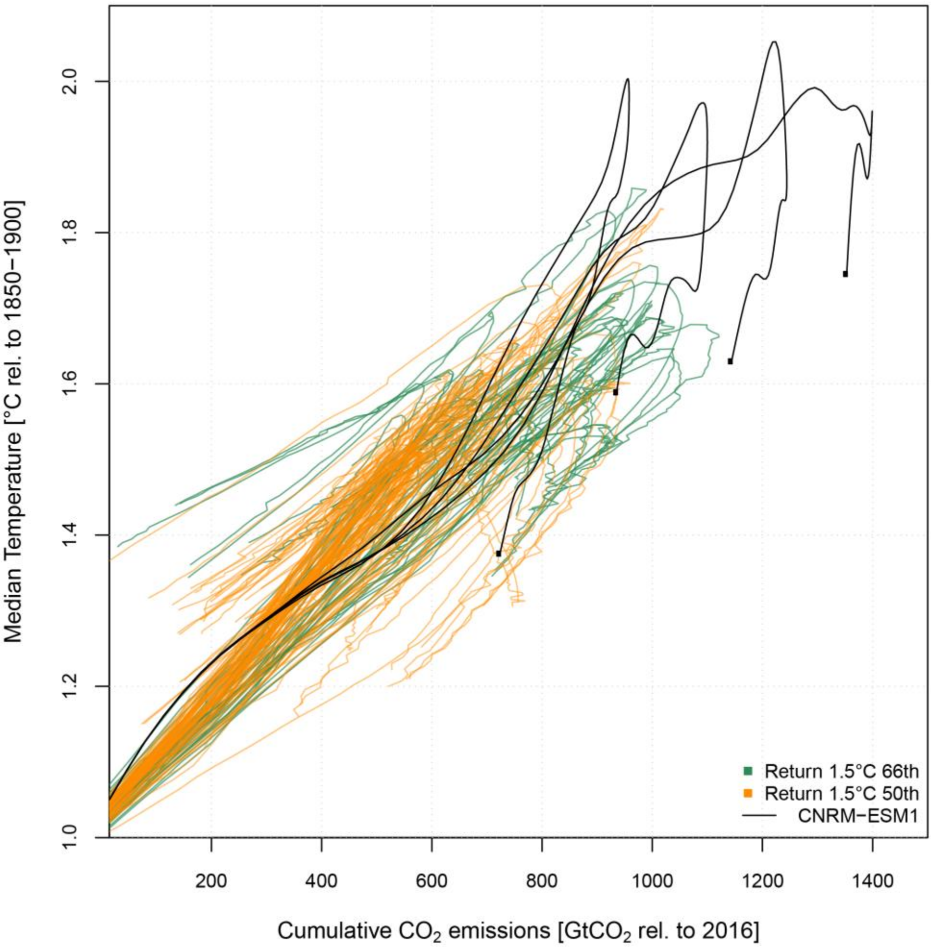

Figure 2.32: Uncertainties on the threshold return carbon budgets due to Earth system feedbacks in the context of mitigation pathways exceeding 1.5°C by mid-century and returning below 1.5°C by 2100, in terms of cumulative CO_2 emissions and global mean temperature relative to 2016. MAGICC results (coloured lines) are represented for the two classes of mitigation pathways retuning below 1.5°C with a 50% and 66% likelihood whereas results from simulations of CNRM-ESM1 model are given by black lines.

Permafrost thawing can release both carbon dioxide and methane as the Earth warms. However, vegetation gains in previously frozen regions can lead to more carbon uptake countering some of the released carbon flux. In the version used here, MAGICC is run in the same setup as for AR5, which did not include MAGICC's permafrost module for carbon dioxide (Schneider von Deimling et al., 2012), so these effects are not accounted for. Given the size of the permafrost carbon pool (1460 to 1600 Gt of carbon; Hugelius et al., 2014; Schuur et al., 2015; Strauss et al., 2017) even small changes to this will reduce the remaining carbon budget for 1.5°C or 2°C. Using an EMIC, MacDougall et al. (2015) estimate that this feedback reduces the CO_2-only carbon budget for 2°C (4650 $GtCO_2$) by 550 $GtCO_2$ under RCP4.5. Cumulative CO_2 emissions from newly thawed permafrost carbon under low warming scenarios (RCP2.6 or A1B from AR4) range from 59 to 378 Gt CO_2 by the end of 2100 (Burke et al., 2012; MacDougall et al., 2012; MacDougall and Knutti, 2016; Schaefer et al., 2011; Schaphoff et al., 2013; Schneider von Deimling et al., 2012; Schneider Von Deimling et al., 2015). Burke et al. (2017) estimated annual carbon flux from permafrost under RCP2.6 to range from –0.1 to 0.63 Gt CO_2 per year by 2100 depending on the model used. Field, laboratory and modelling studies estimate that the vulnerable fraction in permafrost is about 5–15% of the total budget (Schuur et al., 2015) and that carbon emissions are expected to occur beyond 2100 because of the inert system and the large proportion of slowly decomposing carbon in permafrost (Schädel et al., 2014).

Carbon release from permafrost in the form of methane is less commonly represented in models due to its complexity and the small magnitude of methane release. Cumulative methane 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; Schneider Von Deimling et al., 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). A meta-analysis of laboratory incubation studies showed that carbon release from permafrost might be dominated by CO2 emissions rather than methane even when soil conditions are wet (Schädel et al., 2016).

Gains in vegetation carbon by the end of the century are predicted from the same set of models that predict carbon emissions but they may not offset carbon losses from permafrost in the long-term. MacDougall et al. (MacDougall et al., 2012) showed that under RCP2.6 the transition of the terrestrial land surface from a carbon sink to a carbon source will occur in 2053 (2013–2078), which is on average 26 years earlier than without consideration of the permafrost carbon feedback. Differences in the offsetting capacity of plant carbon uptake in the permafrost zone between field and modelling studies indicate the potential for over or underestimation of the plant carbon uptake offset.

Taking the permafrost evidence together, the MAGICC model as employed in this chapter possibly underestimates the future temperature response to the scenarios in Section 2.3 and 2.4 by a small amount. The remaining carbon budget could be overestimated in Section 2.2. This missing feedback is expected to be more important in 2100 than the near term but likely small. Using the (Burke et al., 2017) upper range and a mid-range TCRE as a guide the likely bias on 2100 temperature is assessed to be < 0.1°C, corresponding to a remaining carbon budget overestimate of less than 200 Gt CO_2 (Section 2.2.2).

Several feedbacks of the Earth system, involving the carbon cycle, non-CO_2 greenhouses gases and/or aerosols, may also impact the future dynamics of the coupled carbon-climate system's response and hence the carbon budgets compatible with 1.5°C or 2°C. Nutrient limitation due to change in reactive nitrogen or phosphorus deposition over land and ocean (Duce et al., 2008; Mahowald et al., 2017), impact of ozone exposure (de Vries et al., 2017) or fire CO_2 emissions (Narayan et al., 2007) on land net carbon uptake, release of nitrous oxide from thawing permafrost Voigt et al. (Voigt et al., 2017a, 2017b) and feedbacks associated with natural aerosols (Scott et al., 2017) are an indicative list of feedbacks that might influence carbon budgets and projections that are not explicitly included within the MAGICC setup. Such simple models are also not able to account for multiple geophysical climate targets beyond global mean temperature rise (such as ocean acidification, and net primary production on land). These can be simultaneously used as constraints for estimating emission budgets. For any given likelihood of meeting such combined targets, carbon budgets would need to be greatly reduced due to counteracting mechanism and processes in the geophysical system (Steinacher et al., 2013).

For highly ambitious mitigation pathways the aerosol radiative forcing is a considerable source of uncertainty (Samset and Myhre, 2017; Smith et al., 2018). Published modelling studies (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 (Jones et al., 2017; Smith et al., 2017a) as this affects the estimate of the mitigation potential from different sectors that have aerosol pre-cursor emission sources. Reducing black carbon emissions is an important part of highly ambitious mitigation scenarios (Jones et al., 2017; Shindell et al., 2017a). Most of these types of scenarios rapidly phase out SO_2 emissions, whereas NO_x and NH_3 emissions often continue to increase leading to more nitrate aerosol. The amount of aerosol cooling that is attributable to sulphate and nitrate aerosol precursors therefore affects temperature projections. Generally, we expect the mitigation-driven reduction in aerosol precursor emissions to warm the climate with the reduction of SO_2 from coal fired power stations having the largest effect (Rogelj et al., 2015b). The magnitude of this aerosol-warming effect depends on how much of the aerosol cooling is attributable to SO_2, particularly the cooling associated with aerosol-cloud interaction. 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 uncertainty range, future temperature increases will be stronger (Smith et al., 2017a).

Estimates of greenhouse gas forcing are also undergoing revisions. A recent revision (Etminan et al., 2016) increases the methane forcing by 25%, this revision is not currently accounted for in the MAGICC setup meaning the effects of methane on temperature will be underestimated. As a result there is medium confidence that the MAGICC setup employed in Sections 2.2, 2.3 and 2.4 will underestimate both the temperature increase avoided from methane mitigation and the temperature change increase expected from remaining methane emissions. Further, there is medium confidence that the revision of methane radiative forcing will reduce (depending on scenario) the remaining carbon budget evaluated with the AR5 MAGICC setup in Section 2.2.

Understanding of climate sensitivity, the carbon cycle, and radiative forcing of greenhouse gases and aerosols are continuously being improved. AR5 assessed ECS to be with a likely (18% to 83%) range of 1.5–4.5°C. This is a lower low-estimate compared to the range of CMIP5 models (Collins et al., 2013), and also the MAGICC ECS distribution has not explicitly been selected to reflect this but is nevertheless consistent with the AR5 assessment (Rogelj et al., 2014a). This caveat could skew the range of MAGICC results quoted here towards smaller remaining carbon budgets and higher temperature change. However, work since AR5 has suggested that the inferred climate sensitivity from energy budget changes over the historical period has been lower than the 2xCO_2 climate sensitivity for known reasons (Armour, 2017; Ceppi and Gregory, 2017; Forster, 2016; Gregory and Andrews, 2016; Knutti et al., 2017; Proistosescu and Huybers, 2017; Rugenstein et al., 2016). The evidence for the 1.5°C lower bound on ECS in AR5 came from uncorrected historical estimates. 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 (Brown and Caldeira, 2017; Knutti et al., 2017; Sherwood et al., 2014; Tan et al., 2016; Zhai et al., 2015) suggest that the lower bound of ECS could be revised upwards arguably making the low probability density at the lower bound of the MAGICC ECS range used in this chapter more appropriate. 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) and increasing (Brown and Caldeira, 2017) the bound presented in the literature.

The impacts of inhomogeneously distributed forcers on global mean temperature may also depend on the spatial distribution of the forcing (Marvel et al., 2016; Myhre et al., 2013; Rotstayn et al., 2015; Shindell, 2014).These effects are not typically well captured in simple models, although MAGICC has the facility for forcing-specific efficacies, they are not currently well known for most forcing agents (Myhre et al., 2013).

For this report, we adopt the MAGICC setup as employed in WG3 IPCC AR5 to assess carbon budgets and determine the evolution of atmospheric composition and global mean temperature from the scenario literature. Although its setup is not based on current science there is no clear evidence of a major inaccuracy in either its climate sensitivity or carbon cycle response. However, it does likely underestimate the role of methane, both in terms of the temperature increase avoided from its mitigation and the temperature change expected from recalcitrant emissions. Therefore, any methane-specific conclusions should be considered an underestimate (high confidence). Overshoot pathways heavily reliant on negative emission technologies may not be modelled correctly and the permafrost response is excluded but it is currently difficult to gauge how they may bias the models carbon cycle response. Both these biases are assessed to be small based on current knowledge. However, the MAGICC model spread does not capture the full uncertainty of carbon cycle responses. As a result of these underestimates of uncertainty by the AR5 MAGICC setup employed in this chapter, the MAGICC 5–95% range of responses is taken as the likely (18% to 83%) range of responses for the overall assessment of the remaining carbon budget (Section 2.2) and scenario response (Sections 2.3 and 2.4). Improvements in the geophysical knowledge of climate sensitivity, carbon cycle responses and in radiative forcing are expected for IPCC AR6 which could further alter this report's findings (see Sections 2.2.2 and 2.6.4). There is medium confidence that the remaining carbon budgets presented in this section will be revised downward rather than upward in the future.

2.6.3 *Sociotechnical transitions literature*

Sociotechnical literature puts primary attention to the role of actors, such as citizens, businesses, stakeholder groups or governments, as well as the interplay of technical, behavioural, institutional and socio-political dimensions in shaping mitigation pathways. The sociotechnical literature thus complements insights from integrated and sector-specific assessment models that primarily point to the mitigation solutions involving technology, fuel switching, efficiency improvements, infrastructure, and to some extent behaviour change. Sociotechnical literature is a very diverse body of research with two broad strands: behavioural studies on mitigation (Dietz et al., 2009; Wilson and Dowlatabadi, 2007) and sociotechnical transitions theory (Geels et al., 2017; Sovacool and Hess, 2017). Behavioural studies focus on individuals and households in terms of their energy and food demand, transportation behaviour, dietary choice, food wastage, and other actions. As compared to the supply-side research on mitigation, the body of demand-side focused research is much smaller (Wilson et al., 2012; Wilson and Dowlatabadi, 2007). As the difference between a low consumption sustainability-focused society (SSP1) and an energy intensive and technologically focused society (SSP5) is large with respect to cumulative mitigation to move to a 1.5°C consistent pathway, insights from behavioural literature are of high importance.

Sociotechnical transitions theory can complement the insights from integrated assessment models because the latter operate in an optimization or equilibrium framework of economic theory and primarily point to policy drivers of mitigation. Transformations that are consistent with 1.5°C pathways are so fundamental and systematic that they also require an evolutionary sociotechnical framework to investigate non-policy drivers. To date, sociotechnical transitions literature revolves around historical case studies, such as the conceptual analysis of German and UK energy transitions in 1990-2014 (Geels et al., 2016) that help elaborate future transitions (Verbong and Geels, 2010), but do not specify how such future transitions could potentially unfold (Turnheim et al., 2015). As historically-informed sociotechnical transitions literature cannot provide quantitative or global-level estimates of future mitigation pathways, some efforts have been undertaken to develop sociotechnical transition models (Holtz et al., 2015; Li et al., 2015). These models, however, are still at very early stages of development and validation. As integrated and sector-specific assessment models and methods from sociotechnical transitions literature appear complementary, there have been experiments to combine these approaches for deriving joint transition insights and mitigation solutions (Kinn, 2016; Trutnevyte et al., 2014; Turnheim et al., 2015), but these experiments are still very rare.

2.6.4 *Knowledge gaps*

The literature on 1.5°C pathways has increased substantially over the past two years, but significant knowledge gaps still exist. There continues to be large uncertainty about the role of land use change, agricultural emissions and land-use based mitigation options in 1.5°C pathways. Also, the role of lifestyle changes and behavioural policies to foster deep emissions reductions needs to be further explored. On the supply side, the consideration of speculative technologies to capture and use carbon, to support a fully electrified, hydrogen-based, or carbon-neutral liquid fuel-based economy, and to strongly reduce the land footprint of meat (especially beef) and dairy production could significantly alter the shape of mitigation pathways. The future emissions of short-lived climate forcers and their temperature response remain a large source of uncertainty in the climate response in 1.5°C pathways. Their global emissions, their sectorial and regional disaggregation and their climate response are generally less well quantified than for CO_2 (Section 2.3 and 2.6.2). These uncertainties play an important role in 1.5°C pathways in which mid-century projections of methane and N_2O emissions vary by more than 50% around the mean within 1.5°C scenario classes. Emissions from the agricultural sector constitute the main source of uncertainty here (Gernaat et al., 2015) and are an important gap in understanding the potential achievement of stringent mitigation scenarios. Particularly important to understand is how mitigation of aerosol precursors will affect the radiative forcing from aerosol cloud interaction. It is also important to better quantify the potential co-benefits of mitigating air pollutants and how the reduction in air pollution may affect the carbon sink by modifying diffuse radiation and ozone levels (Section 2.5).

Climate sensitivity and carbon cycle responses remain important sources of uncertainty but are less important than they would be under high emission scenarios (Section 2.6.2). Progress on constraining climate sensitivity and understanding its evolution over time and how it might vary between forcing agents would help to constrain future projections of temperature and reduce the uncertainty in the carbon budget. Quantifying how the carbon cycle responds to negative emissions and understanding how emissions from permafrost respond are important gaps in understanding for strong mitigation pathways (Section 2.2.2 and

2.6.2).

A critical knowledge gap relates to short-term entry points to the long-term emissions developments in 1.5°C pathways. While it has been established that the NDCs in 2030 are insufficient to keep the 1.5°C target in reach without strongly disruptive changes, more information is needed on what realistic policy trajectories until 2030 could strengthen near-term climate action sufficiently to significantly reduce the post-2030 mitigation challenges of limiting warming to 1.5°C.

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. Their main limitations are that climate damages, avoided impacts and societal co-benefits of the modelled transformations remain largely unaccounted for. Furthermore, rapid technological changes and uncertainties about input data present continuous challenges (high confidence). In several cases, sectorial assessment models have identified different (and often larger) mitigation potentials for single sectors than what is realized in global IAMs (for example, see Lucon et al. 2014). A certain lag in the integration of the latest knowledge in global IAMs is to be expected and highlights the importance of continuously updating models with the latest sectorial insights. Moreover, a general underrepresentation of studies and research exploring behavioural change and end-use measures to climate mitigation has been identified in the literature (Wilson et al., 2012), and recent IAM studies have started to explore this gap (Grubler et al., 2017; McCollum et al., 2016; van Sluisveld et al., 2016; van Vuuren et al., 2017d). In recent years, IAMs have shifted from modelling scenarios for ideal worlds (so-called first-best worlds) to also exploring scenarios in which important barriers are explicitly assumed. These barriers can come under the form of unavailable or limited mitigation technology options (e.g., Krey et al. 2014b; Kriegler et al. 2014a), delayed or fragmented mitigation policies (e.g., Riahi et al. 2015; Kriegler et al. 2015a), or variations in the regional risk to investments (Iyer et al., 2015a), amongst other aspects. Also the various socioeconomic developments as explored with the Shared Socioeconomic Pathways (O'Neill et al., 2017; Riahi et al., 2017) follow this general evolution, and include narratives with relatively low barriers to mitigation as well as narratives with high mitigation challenges. Finally, IAMs typically do not include climate impacts on societal subsystems (van Vuuren et al., 2012) and related adaptation measures. This affects both baselines (in which climate impacts can, for example, affect the efficiency of power generation and agricultural productivity), and mitigation scenarios (which, for example, can rely on larger bioenergy shares that can be affected by climate impacts). Recent work has shown that accounting for new climate damage estimates below 2°C can significantly alter the near-term development of 2°C pathways(Schultes et al., 2017). A full coupling of IAMs and ESMs can also lead to shifts in optimal mitigation pathways (Thornton et al., 2017). IAMs typically employ GWP-100 to relate GHG emissions from different species (see Chapter 1, Cross-Chapter Box 1.2). Alternative metrics could be employed that are better suited to evaluate the temperature response of strong-mitigation pathways which may alter the trade-offs between CO_2 and non-CO_2 emissions, including the deployment of net negative CO_2 emissions in the second half of the century. Studies have shown that the choice of GHG metric affects the trajectory of the overall temperature response, and can also affect carbon prices and mid-term methane emissions, and increasing overall mitigation costs by up to 1/3rd though impacts are typically smaller (Harmsen et al., 2016; Strefler et al., 2014).

The important energy demand reductions assumed in the mitigation pathways assessed in this chapter raise issues of potential rebound (Barker et al., 2009; Blanco et al., 2014; Chackravarty et al., 2013; Chan and Gillingham, 2015; Fouquet and Pearson, 2012; Kolstad et al., 2014; Lin and Tan, 2017; Roy, 2000; Saunders, 2017, 2008, 2015; Sorrell, 2007; Turner, 2013), which would make the achievement of low energy demand futures more difficult than anticipated. Rebound results, for example, in energy efficiency improvements leading to smaller reductions in energy demand than one would otherwise assume. Empirical (Barker et al., 2009; Chackravarty et al., 2013; Lin and Tan, 2017; Roy, 2000; Saunders, 2015, 2017; Sorrell, 2007) and theoretical (Saunders, 2008; Sorrell, 2007, 2014) evidence indicates that current modelling approaches that underlie the pathways literature might underestimate the potential rebound effect. Reasons for this potential underestimation are diverse, and different models are subject to different limitations (Saunders, 2008, 2015). These limitations indicate that although limiting energy demand is identified as a key characteristic in 1.5°C pathways, its future evolution is less certain than model results alone would suggest. Rebound following efficiency improvements makes attaining low levels of energy use more challenging, but in itself increases economic welfare (Chan and Gillingham, 2015; Saunders, 1992). This has led to some arguing that rebound is not a trade-off but rather the opposite as it enhances development and therewith improves the capacity of populations to deliver energy system decarbonisation (Nordhaus, 2017a).

Understanding from the sociotechnical transition literature needs to be usefully incorporated and compared to global integrated assessment approaches to better inform and constrain possible transition pathways. Under strong mitigation trajectories, transitions will need to be pushed towards global societal limits, and such limits have not yet been clearly identified (Section 2.5).

Mitigation assessments need to improve the representation of micro-economic decision making processes and resulting choices. There is a need to integrate the growing research and empirical findings about consumer behaviour from neuroscience, behavioural economics, environmental psychology and new institutional economics (among other disciplines) in scenario studies, particularly when representing the demand-side of energy systems. To better understand the effects of mitigation pathways compatible with a 1.5°C world, it is critical to increase our knowledge on how social preferences, energy-use behaviour and value-based choices respond to stringent climate and energy policies in modelling studies. Parameterization is a key challenge.

Modelling studies indicate that a major shift in investment patterns is required to achieve global warming of 1.5°C. Whereas studies concentrate on the amount, allocation and timing of needed investments resources, assumptions stress the importance of having a more explicit representation and understanding of the financial sector itself. A better representation of financial crises is needed in mitigation studies, including the distinction between public and private funding sources. Assumptions in modelling studies imply 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, credit rating agencies) and financial products also needs to be taken into account. Furthermore, a better representation of the mobilisation of capital and financial flows between countries/regions are important to increase the resolution on international distribution of wealth. The risks of fossil-based asset stranding need to go beyond energy infrastructure but also include implications for stock markets and pension funds, for instance.

Frequently Asked Questions

FAQ 2.1: Are we on track to keep global warming below 1.5°C?

Warming of the planet due to human activity has reached around 1°C above pre-industrial levels, which means we are already two thirds of the way to 1.5oC of warming. If the current pace continues, scientists estimate global mean warming would exceed 1.5°C in the 2040s, or earlier if warming continues to accelerate. Countries' pledges to cut emissions under the Paris Agreement are insufficient to limit warming to 1.5°C. Keeping 1.5°C on the table would require strong policy action and international cooperation in the near term.

Before the Paris Agreement, countries submitted proposals for how they could each address climate change, known as Intended Nationally Determined Contributions (INDCs). With the Paris Agreement now adopted and countries formally joining up, these pledges have become known as Nationally Determined Contributions (NDCs).

A number of different analyses have shown that combining all national pledges still leads to emissions by 2030 that are well above what would be required to limit warming to 1.5°C. As things stand, annual global emissions under the current pledges are projected to reach 49–56 gigatonnes (1 gigatonne = 1 billion tonnes) of carbon dioxide equivalent (CO2e) in 2030. This is compared to present day emissions of about 50 GtCO2e. In contrast, global emissions in scenarios that hold global warming to 1.5°C decline substantially, with emissions below about 35 GtCO2e by 2030. Higher 2030 emissions suggest that warming will exceed 1.5°C, at least for a period of time.

Most modelling has found that reducing emissions in line with the NDCs – but no more – makes holding warming to 1.5°C by the end of the 21st century extremely unlikely because emissions after 2030 would have to fall faster than models assume is technically achievable. In contrast, stringent emissions cuts by 2020 or 2030 open up more possibilities in the models for limiting warming to 1.5°C.

The basic requirement for limiting warming to 1.5°C is that emissions of long-lived greenhouse gases, primarily CO2, would need to drop to net zero by around mid-centur–y. This is a concept known as 'carbon neutrality'. It means that if some emissions can't be avoided (i.e., in agriculture or transport), these would need to balanced out by taking carbon dioxide out of the air, such that overall or 'net' emissions remain zero. The extent to which carbon dioxide can be removed from the air is uncertain, however. This is because several of the 'negative emissions technologies' that would be required to achieve it are still in their infancy, or the consequences and means of deploying them at large scale are still being explored.

Holding warming to 1.5°C by 2100 would also require stringent cuts in emissions of substances other than CO2 that warm Earth's climate. Known as non-CO2 climate forcers, this group includes methane, nitrous oxide, black carbon and hydrofluorocarbons.

The question of whether it is feasible to limit warming to below 1.5°C has many dimensions. Models can reveal some of the characteristics of a future world in which warming is held to 1.5°C. These characteristics include: stringent policies that encourage emissions to fall rapidly in the near term, rapid scale up of technologies with low or zero emissions, lower energy demand, lower demand for foods with high carbon footprints, and slower global population growth.

All of these conditions involve underlying policy choices about socio-economic development and technology. A world that is consistent with holding warming to 1.5°C requires highly ambitious policies and strong international cooperation. In contrast, delayed action, limited international cooperation, and weak or fragmented policies risk making mitigation more expensive in the long run and make holding warming to 1.5°C increasingly unlikely.

*[**Figure suggestion:** Annual CO2 emissions associated with scenarios in which global mean temperatures exceed 2°C, including estimates based on current national pledges, those in which global mean temperatures have a 50% probability of remaining below 1.5°C throughout the 21st century and those with a 66% probability of returning below 1.5°C by 2100.]*

FAQ 2.2: How can we limit global warming to 1.5°C?

Holding warming to 1.5°C requires that net global CO2 emissions fall to zero by the middle of the century. Scenarios that achieve this see coal phased out, renewables become the dominant source of energy by 2050 and rapid cuts to non-CO2 drivers of warming, including methane, nitrous oxide, black carbon and hydrofluorocarbons. Different pathways – including those that see warming temporarily overshoot 1.5°C and return later in the century – will have different implications for climate impacts, sustainable development and equity.

Since warming is directly proportional to total cumulative carbon dioxide (CO2) emissions, scientists can calculate what is known as a "carbon budget". This is the maximum total carbon that can be emitted as CO2 to still stay below a certain temperature threshold. Carbon budgets are normally expressed with a likelihood of success (e.g., a 66%, or two-in-three, chance of staying below a given temperature).

To have at least a 50% chance of holding warming below 1.5°C throughout the century, the remaining carbon budget is 580 gigatonnes (1 gigatonne = 1 Gt = 1 billion tonnes,) of CO2 from 2016 onward, with a range across model scenarios of 490 to 640 Gt (accounting for the variations in emissions other than CO2). Keeping a higher probability of staying below 1.5°C would further limit this remaining carbon budget. There are also uncertainties about some parts of the climate system that could impact the size of the remaining carbon budget, such as the potential release of carbon from thawing permafrost. These uncertainties are almost exclusively expected to shrink remaining carbon budgets, rather than to expand them.

Global CO2 emissions are currently about 40 GtCO2 per year. If the current rate continues, this would exhaust the remaining carbon budget for 1.5°C in 10 to 15 years. Without stringent emissions in the next five to ten years, this would set the world up for either the impossible task of instantaneously dropping emissions to zero once the budget is exhausted or to exceed the 1.5°C carbon budget. The scientific literature discusses such a possibility of temporarily exceeding the 1.5°C carbon budget and returning to within its limits later in the century. In fact, most model pathways aim at holding warming below or close to 1.5°C in 2100 and see global temperature 'overshoot' 1.5°C around mid-century, before peaking and returning below 1.5°C before 2100.

But such 'overshoot' scenarios rely on removing CO2 from the air to bring global temperature back down to 1.5°C. This comes with the risk that the necessary Carbon Dioxide Removal (CDR) technologies and practices may not prove as practical, effective or economical as assumed, or that competition for land and water negatively affects sustainable development. The larger and longer the overshoot, the greater the reliance on CDR technologies and the greater the potential for irreversible climate impacts, such as the collapse of polar ice shelves.

To stay within the carbon budget for 1.5°C, models suggest global CO2 emissions would need to decrease to 'net zero' around mid-century. At this point, known as 'carbon neutrality', CO2 emissions would need to be at or approaching zero, with any remaining emissions balanced out using CDR, such that there is no overall flow of man-made CO2 emissions into the atmosphere. This may be necessary in sectors that cannot phase out emissions rapidly or fully, such as industry or transport. For this reason, all pathways consistent with 1.5°C rely on CDR to some extent. Beyond maintaining 'net zero' emissions in the long term, reliance on CDR in 1.5C pathways depends on the pace of emissions reductions in the next few decades and the degree to which it is deemed acceptable for temperature to overshoot 1.5°C. Limiting warming to 1.5°C would also require stringent reductions in substances other than CO2 that warm the climate, such as methane, nitrous oxide, black carbon and hydrofluorocarbons.

The main technique for removing CO2 in model pathways that limit warming to 1.5°C is a combination of Biomass and Carbon Capture and Storage (BECCS). The total amount of CDR in 1.5°C pathways is of the order of 380–1130 GtCO2 over the 21st century, with BECCS deployed in some scenarios as early as 2020. Some scenarios do not use BECCS at all. Instead, they include other land-based CDR methods, such as afforestation, alongside with assuming much lower demand for energy and resources in the future. Activities such as restoring carbon-rich mangroves and wetlands can also contribute to removing CO2, as well as enhancing biodiversity and ecosystem health. But there are questions about how permanent this method of removing CO2 would be and model scenarios that take into account the many interactions between sectors and regions typically haven't yet explored these options.

Holding warming to 1.5°C strongly depends on future population growth, economic development, energy demand, dietary choices, food wastage, forest management policies, and international cooperation. The main characteristics of pathways that successfully limit warming to 1.5°C are the phase out of coal in the energy sector and a rapid rise in energy coming from renewables. Coal usage declines in 1.5°C pathways at a rate of around 4–5% until the middle of the century. Or, in cases where coal use is not entirely phased out by 2050, between 40–100% of the emissions are captured before they enter the atmosphere and buried underground, a process known as Carbon Capture and Storage (CCS). The picture by mid-century is more mixed for other fossil fuels, with slowly declining use of oil and varying amounts of natural gas with CCS. Renewables, such as wind and solar, are the dominant source of energy by 2050 in most 1.5°C pathways.

The shifts required to limit warming to 1.5°C imply urgent and ambitious international cooperation, as well as coordination between different levels of government, civil society, academia and the private sector. In contrast, delaying emissions cuts would quickly see the remaining carbon budget exhausted and increase future reliance on CDR. All of this would, in turn, make it less likely that warming can be limited to 1.5°C, as well as more difficult and more expensive to return to below 1.5°C by 2100 after an overshoot.

The different pathways by which warming could stay below 1.5°C come with implications for sustainable development and global equity. In general, limiting climate change can enhance several dimensions of sustainable development, including human health and access to clean air and water. But pursuing stringent climate mitigation compatible with 1.5°C need to consider complex local and national contexts to avoid widening existing inequalities. Avoiding the highest estimates of population growth, and the low educational attainment for women that underpin such estimates, are critical for limiting warming to 1.5°C. Raising finance in at-risk countries remains a significant barrier.

*[**Figure suggestion**: A schematic showing cumulative CO2 emissions (billions of tons; Gt) through 2015 and median values in scenarios that are consistent with a 50% probability of holding warming to 1.5C.]*

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