

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

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

Coordinating Lead Authors: Kejun Jiang, Joeri Rogelj, Drew Shindell

Lead Authors: Solomon Fifita, Piers Forster, Veronika Ginzburg, Collins Handa, Haroon Kheshgi, Shigeki Kobayashi, Elmar Kriegler, Luis Mundaca, Roland Séférian, Maria Virginia Vilariño

Contributing Authors: Katherine Calvin, Oreane Edelenbosch, Johannes Emmerling, Sabine Fuss, Chenmin He, Daniel Huppmann, Gunnar Luderer, Anil Markandya, David L. McCollum, Malte Meinshausen, Alexander Popp, Evelina Trutnevyte

Review Editors: Jan Fuglestvedt, Latifa Redani

Date of Draft: 22 July 2017

1 **Table of Contents**

2

3 **Executive Summary..... 4**

4

5

6 **2.1 Introduction to Mitigation Pathways and the Sustainable Development Context 7**

7 2.1.1 Mitigation Pathways compatible with 1.5 °C 7

8 2.1.2 Socio-economics underlying 1.5°C scenarios 8

9 2.1.3 The Use of Scenarios to Answer Particular Questions 8

10 2.1.4 New scenario information since AR5..... 9

11

12

13 **2.2 Geophysical relationships and constraints 10**

14 2.2.1 Linking geophysical characteristics to mitigation pathways 10

15 2.2.2 The 1.5°C and 2°C carbon budget 10

16 2.2.2.1 Carbon budget computations 10

17 2.2.2.2 Remaining carbon budget and related uncertainties 12

18 2.2.2.3 Role of non-CO₂ GHGs and aerosols 14

19 2.2.3 Geophysical characteristics of mitigation pathways..... 15

20 2.2.3.1 Pathway classification 15

21 2.2.3.2 Near-term to 2050..... 16

22 2.2.3.3 Post-2050..... 19

23

24

25 **2.3 General characteristics of 1.5°C pathways and transitions in the near-to-medium term..... 20**

26 2.3.1 Overview of mitigation pathways..... 20

27 2.3.1.1 General scenario concepts 20

28 2.3.1.2 General characteristics of 1.5°C pathways 22

29 2.3.1.3 Mitigation options in 1.5°C pathways 25

30 2.3.2 Key characteristics of transitions in 1.5°C pathways from today until mid-century 28

31 2.3.3 Emissions evolution..... 29

32 2.3.4 Disentangling the whole-system transformation 33

33 2.3.4.1 Energy..... 33

34 2.3.4.1.1 Evolution of primary energy contributions over time 33

35 2.3.4.1.2 Deployment of CCS..... 34

36 2.3.4.1.3 Pace of change 36

37 2.3.4.2 End-use sectors 36

38 2.3.4.2.1 Industry 36

39 (i) Reductions in the demand of industrial products and material efficiency 37

40 (ii) Energy efficiency improvements in industrial production..... 37

41 (iii) Electrification of industry energy demand 38

42 (iv) Reducing the fossil carbon content of non-electric fuels..... 38

1	(v) Application of carbon capture and storage	38
2	2.3.4.2.2 Buildings.....	39
3	2.3.4.2.3 Transport.....	41
4	2.3.4.3 Land-use transitions and changes in the agricultural sector	44
5	2.3.4.4 Mitigation portfolios and investments	48
6	2.3.4.4.1 Mitigation portfolios.....	48
7	2.3.4.4.2 Investments	50
8	2.3.5 Delay and carbon lock-in.....	52
9		
10		
11	2.4 Properties of 1.5°C pathways after mid-century	52
12	2.4.1 Emissions development of 1.5°C pathways after mid-century.....	53
13	2.4.1.1 Short lived climate forcers and fluorinated-gases	53
14	2.4.1.2 Long-lived greenhouse gases.....	54
15	2.4.2 Carbon dioxide removal in 1.5°C pathways	56
16	2.4.2.1 Apportion of CDR to different uses in 1.5°C pathways	56
17	2.4.2.2 CDR technologies and deployment levels in 1.5°C pathways.....	60
18	2.4.2.3 Sustainability implications of CDR deployment in 1.5°C pathways.....	61
19	2.4.3 Energy use in 1.5°C pathways after mid-century	63
20	2.4.3.1 Energy demand.....	63
21	2.4.3.2 Energy Supply	64
22	2.4.3.3 Alternative visions of carbon neutral energy systems	66
23		
24		
25	2.5 Challenges, opportunities and co-impacts of transformative mitigation pathways	67
26	2.5.1 Policy narratives and potential implications.....	67
27	2.5.1.1 Policy regimes in line with 1.5°C scenarios	71
28	2.5.1.2 Limitations of IAMs in examining all policy options.....	72
29	Box 2.1: Economics of 1.5°C Pathways and the Social Cost of Carbon	75
30	2.5.2 Economic implications of 1.5°C Scenarios	77
31	Box 2.2: Macro-economic impacts of mitigation	77
32	2.5.3 Sustainable development features of 1.5°C pathways	81
33		
34		
35	2.6 Assessment tools and knowledge gaps	81
36	2.6.1 Integrated and sector-specific assessment models.....	82
37	2.6.2 Geophysical assessment tools.....	82
38	2.6.3 Sociotechnical transitions literature.....	83
39	2.6.4 Knowledge gaps	84
40		

1 **Executive Summary**

2

3 Limiting warming to 1.5°C above preindustrial levels requires a rapid phase out of global CO₂ emissions and
 4 deep reductions in non-CO₂ greenhouse gas emissions. This chapter assesses 1.5°C mitigation pathways to
 5 achieve this. In doing so, it will explore a set of key questions: What is the remaining budget of CO₂
 6 emissions to stay below 1.5°C and to what extent it is overshoot and returned to in 1.5°C pathways? {2.2, 2.6}
 7 How can this budget be distributed over the coming decades and the remainder of the century? {2.2, 2.3, 2.4,
 8 2.6} What are the underlying transformations in energy and land use in the context of sustainable
 9 development, both in the near term, and until and after 2050? {2.3, 2.4} And how do near term policies
 10 affect the ability to maintain pathways to limiting warming to 1.5°C degrees? {2.3, 2.5}

11

12 The assessment in this chapter is based on an emerging field of literature on 1.5°C pathways since AR5. To
 13 support the assessment, quantitative descriptions of the energy-land-emissions developments in these
 14 pathways from integrated assessment models were collected in a database and their temperature outcome
 15 evaluated with a reduced-complexity carbon-cycle and climate model.

16

17 **Climate outcomes and CO₂ budgets of 1.5°C pathways that account for all forcings.** Available pathways
 18 holding warming below or close to 1.5°C in 2100 all exhibit overshoot of that temperature level around mid-
 19 century, with a subsequent peak and return of temperatures below 1.5°C before 2100. {2.2.3.2}

20

21 To hold warming below 1.5°C by 2100 with at least 66% or 50% likelihood, the carbon budget (i.e., the
 22 cumulative amount of CO₂ emissions emitted from 2016 to 2100) is 280 (150-360) GtCO₂ and 330 (250-
 23 490) GtCO₂, respectively (interquartile range across scenarios between brackets). Net zero global CO₂
 24 emissions lead to halting further long-term warming. Until this peak in global mean temperatures, 1.5°C
 25 pathways project to emit 670 (620-750) GtCO₂ and 780 (690-950) GtCO₂, for the same respective
 26 likelihoods, indicating that CO₂ is actively removed from the atmosphere in the second half of the century to
 27 achieve a long-term temperature decline. For the 50% likelihood levels, the carbon budget until mid-century
 28 carbon neutrality in 1.5°C pathways is about 40% lower than the budget in 2°C pathways. {2.2.3}

29

30 1.5°C pathways require deep reductions in CO₂, reaching global net zero CO₂ emissions (i.e., carbon
 31 neutrality) around mid-century, together with stringent reductions in non-CO₂ climate forcings, primarily
 32 methane, nitrous oxide, black carbon and hydrofluorocarbons. Non-CO₂ climate forcings reduce carbon
 33 budgets by 2000 GtCO₂ per degree of warming attributed to them. {2.2.2.3, 2.3.3, 2.4.1}

32

33 **Near-term policies consistent with 1.5°C pathways.** 1.5°C pathways require highly robust, ambitious,
 34 internationally cooperative, and urgent transformative policy regimes. In contrast, weak near-term policy
 35 efforts and fragmented scenarios quickly exhaust a large share of the compatible carbon budget, decreasing
 36 the probability of limiting warming to 1.5°C or returning it to below 1.5°C by 2100 after a temporary
 37 overshoot. {2.5.1}

38

39 The Nationally Determined Contributions (NDCs) submitted by Parties to the Paris Agreement result in
 40 global greenhouse gas (GHG) emissions on the order of 49-58 GtCO₂-eq yr⁻¹ in 2030, whereas 1.5°C
 41 scenarios available to this assessment show an interquartile range of 25 to 41 GtCO₂-eq yr⁻¹. When starting
 42 from 2030 GHG levels in line with the national pledges, most integrated energy-economy-land models
 43 cannot produce scenarios in line with limiting warming below 1.5°C over or at the end of the 21st century,
 44 because the modest emissions reductions until 2030 imply subsequent reductions and transformations that
 45 are too steep and too abrupt to be achieved by the mitigation options in the models. {2.3.5}

46

47 Stringent near-term targets by 2020 or 2030 imply higher near-term mitigation costs, carbon prices and
 48 investments, but lower long-term mitigation costs, carbon prices, and investments. Delayed action, limited
 49 international global cooperation, or weak near-term policies promote carbon lock-in, and lead to higher long-
 50 term mitigation costs. Failure to achieve near-term emissions reductions increases the subsequent required
 51 rates of change as well as the amount of stranded investment in fossil-based capacity. It also leads to
 52 generally higher cumulative CO₂ emissions until carbon neutrality and therewith a higher and longer
 53 exceedance of the 1.5°C temperature limit. {2.3.5, 2.5.1.1, 2.5.2}

54

55 **Properties of transitions in mitigation pathways before mid-century.** There are multiple, distinctly
 56 different pathways compatible with 1.5°C that depend on underlying societal choices and preferences and

1 that come with different implications for sustainable development. {2.3.1.1, 2.5.3}

2
3 Scenarios consistent with 1.5°C show large reductions of per capita energy demand, rapid electrification of
4 energy end use, and rapid decreases in the carbon intensity of electricity and of the residual fuel mix. These
5 transitions are greater and more rapid than in 2°C mitigation pathways, particularly in the coming decades
6 and up to mid-century. {2.3.1.2}

7
8 Already by 2030, all end-use sectors, like the building, transport, and industry sector, show significant
9 demand reductions in 1.5°C pathways, beyond the reductions projected for 2°C pathways. Demand
10 reductions from integrated models for 2030 and 2050 are confirmed by detailed assessments of sectorial
11 bottom-up models which also suggest potential further reductions in demand. {2.3.4.2}

12
13 Key technical and behavioural options are sector specific, but generally include a portfolio of efficiency
14 improvements, demand reduction, and switching to lower-carbon fuels. End-use electrification plays a major
15 role in the buildings, industry and transportation sectors. {2.3.4.2, 2.4.3.1}

16
17 CO₂ emissions from energy supply decline to zero between 2030 and 2060, with continued large decreases
18 thereafter in 1.5°C mitigation pathways. The share of primary energy from renewables increases rapidly,
19 becoming the dominant source of energy by 2050 in most pathways. Coal usage is phased out rapidly in
20 mitigation pathways consistent with 1.5°C, with annual reductions rates of 4-5% until mid-century. In case
21 coal use is not yet entirely phased out by 2050, 40-100% of it is combined with carbon capture and storage,
22 which starts to be implemented soon after 2020 with a mean annual 1.1 EJ yr⁻¹ increase in capacity from
23 2020 to 2050. For other fossil fuels, the mid-century picture is more differentiated with scenarios indicating
24 slowly declining use of oil, and a wide range of futures for natural gas. {2.3.4.1}

25
26 Most scenarios include substantial deployment of biomass energy, often combined with carbon capture and
27 storage. On average, it supplies nearly as much energy as wind and solar combined and nearly half as much
28 as total fossil fuel energy by 2050. Greater implementation of this technology is required when phase out of
29 fossil fuels proceeds more slowly. {2.3.4.1}.

30
31 Annual average energy system supply-side investments from 2030 to 2050 tend to be 40% (interquartile
32 range: 20-140%) higher in 1.5°C pathways than when assuming optimal energy-supply investment without
33 climate policies. This increase is accompanied by important shifts in sectoral investment patterns, already in
34 the near term through 2030. Median annual fossil-fuel electricity investments over the 2010-2030 period
35 decline by ~70 billion USD yr⁻¹ (~45%) and median annual fossil-fuel extraction investments decline by a
36 similar magnitude, while median annual renewable electricity investments increase by ~100 billion USD yr⁻¹.
37 {2.3.4.4.2}

38
39 In some cases, the rates of change projected in 1.5°C pathways for specific transitions fall within the high
40 end of what has been observed historically, for example, efficiency improvements in transportation.
41 However, many rates of change are well beyond the historical experience and thus suggest the need for
42 strong and dedicated policies to achieve them, for example, for switching to lower-carbon fuels in the
43 transportation sector. In other cases, the projected trends for 1.5°C pathways are of the opposite sign to
44 recent historical trends, again suggesting the need for a clear policy shift. For example, the rate of forest area
45 change switches from an average 6 Mha yr⁻¹ decline in the 1990-2010 period to an average 6 Mha yr⁻¹
46 increase over the 2010-2050 period. Similarly the strong rate of CO₂ emissions decline in the energy supply
47 and end-use sectors in the period until 2030 shows a clear structural break with trends over the past decades.
48 {2.3.4.2.1, 2.3.4.2.3, 2.3.4.3}.

49
50 Underlying scenario assumptions (including those regarding economic and population growth, per capita
51 food and energy demand, dietary choice and food wastage, and forest management policies) play important
52 roles in determining the degree of mitigation necessary to achieve a 1.5°C pathway. For example, the
53 cumulative mitigation over the 21st century required to move from a no-climate policy baseline to a 1.5°C
54 consistent scenario varies by a factor 2 to 3 between a low consumption sustainability-focused society
55 (SSP1) and an energy intensive and technologically focused society (SSP5). {2.3.3, 2.3.4.3, 2.5.1}

1 **Carbon dioxide removal (CDR) and pathway characteristic after mid-century.** After mid-century,
2 pathways consistent with 1.5°C maintain net zero or net negative CO₂ emissions, neutralizing residual
3 emissions of other long-lived greenhouse gases (predominantly nitrous oxide from agriculture) and reduce
4 emissions of short-lived climate forcers (particularly of methane) as much as possible in order to keep them
5 at constant low levels. {2.4.1}. CDR is used in all 1.5°C pathways to neutralize residual emissions and return
6 the cumulative amount of CO₂ emissions after a peak around mid-century to values consistent with the end-
7 of-century budgets of keeping warming below 1.5°C. The total amount of CDR projected in the pathways is
8 of the order of 710-900 GtCO₂ over the 21st century, with a third to half of this dedicated to draw down the
9 excess in emitted carbon budget after having reached carbon neutrality. Compared to well below 2°C
10 pathways, 1.5°C pathways additionally mitigate about 400 GtCO₂ by direct emissions reductions and about
11 200 GtCO₂ by compensation through CDR. {2.4.2.1}

12
13 Biomass energy with carbon capture and storage (BECCS) is the single CDR option which all 1.5°C
14 pathways consider. Aside from afforestation, other options for CDR are currently not typically included in
15 the scenarios currently available to this assessment. Even with this small portfolio of options, 1.5°C
16 pathways show very diverse configurations and uses of CDR, which entail fundamentally different concerns
17 for the simultaneous achievement of sustainability objectives. {2.4.2.2, 2.4.2.3}

18
19 Both BECCS and afforestation require land, to produce sustainable biomass and to store CO₂ through the
20 growth of trees, respectively. In general, land-use changes do not differ markedly between 1.5°C and less
21 stringent 2°C pathways. When BECCS and afforestation are considered together, scenarios project land
22 demand for afforestation to be several times larger than the land demand for BECCS. Taken together, the
23 combined land demand for both CDR options in 2100 is of the order of 800-1800 Mha, mainly converted
24 from pasture land. These dynamics are heavily influenced by assumptions about future population levels,
25 food crops and livestock demand. {2.4.2.2, 2.4.2.3}

26
27 Strongly limiting energy demand is a key feature of 1.5°C pathways, in which final energy demand in 2100
28 is generally increased by 20-60% relative to 2014 levels (interquartile range across available scenarios).
29 However, scenarios show that through shifts to more sustainable energy, material and food consumption
30 patterns, energy demand levels lower than today can be achieved together with strong growth in economic
31 output until the end of the century. In turn, the largest share of this energy demand is met by electricity,
32 which covers up to about two thirds of final energy by 2100. {2.4.3.1, 2.4.3.2}

33
34 Achievement of a 1.5°C pathway is overall easier in a sustainability-focused world (e.g., SSP1) and aiming
35 at following such pathways facilitates synergies with achieving sustainability objectives, including poverty
36 alleviation, increased energy security and improved public health. In some cases, trade-offs exist, such as
37 competition of biomass production with food crops for land and water. These trade-offs are significantly
38 smaller and hence more easily avoidable in sustainability-focused worlds, which adopt sustainable energy,
39 material, and food consumption patterns. {2.5.3}

40
41 There has been substantial progress in coordination of scenario production and integrated assessment
42 modelling in recent years, providing a better characterization of the influence of various factors affecting the
43 transition to climate stabilisation. Limitations remain in these models, however, as, for example, climate
44 damages, avoided impacts or societal co-benefits of the fundamental transformations that are modelled
45 remain largely unaccounted for in the internal decision making process in models. Further efforts to develop
46 these models and link their insights more closely with sector specific models and with studies of
47 sociotechnical transitions are needed to improve understanding. {2.6}

2.1 Introduction to Mitigation Pathways and the Sustainable Development Context

This chapter assesses the literature on mitigation pathways to limit global mean warming to 1.5°C (relative to the preindustrial base period 1850-1879). 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?

Furthermore, climate protection can be considered as an aspect of sustainable development. “Climate Action” is one of the 17 internationally agreed Sustainable Development Goals (SDGs), and there are many overlaps between policies and actions to address climate change and the other SDGs (see Chapter 5). Mitigation scenarios are typically designed to reach a target defined by climate impacts alone, with economic optimization (least cost) defining the pathways. However, there are co-impacts of mitigation on multiple other sustainable development goals which provide both challenges and opportunities for climate action. Hence there are substantial efforts to evaluate the impact of the various mitigation pathways on sustainable development, focusing in particular on aspects for which 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.

Scenarios have been described previously as “alternative images of how the future might unfold and are an appropriate tool with which to analyse how driving forces may influence future emission outcomes and to assess the associated uncertainties. They assist in climate change analysis, including climate modelling and the assessment of impacts, adaptation, and mitigation. The possibility that any single emissions path will occur as described in scenarios is highly uncertain” (Nakicenovic et al. 2000). The word pathway is often used interchangeably with the word scenario. However, pathways more often describe the clear temporal evolution of specific scenario aspects over time.

2.1.1 Mitigation Pathways compatible with 1.5 °C

Emissions scenarios and the specific pathways included within them are projections of the future development of emissions and their drivers. These need to cover all sectors and regions over the 21st century to be associated with a climate change projection out to 2100. The climate change 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 Section 2.2).

Emission pathways such as those based on current legislation or the pledges incorporated into Nationally Determined Contributions (NDCs) lead to well above 1.5°C warming, hence we examine mitigation pathways consistent with 1.5°C (a class of pathways aiming for a normative end point specified by a climate target). For this chapter we will use the term “pathways” to refer to those developed with detailed modelling. More conceptual or idealised pathways will be referred to as such. Mitigation pathways 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.).

Multiple types of scenarios consistent with 1.5°C were defined in Chapter 1, including stabilisation and overshoot scenarios (see Section 1.2.3). As temperature impact results are probabilistic, a pathway that is consistent with 1.5°C may still miss (in either direction, see Section 1.2.3.4). Additionally, this means consistency with a target must be defined probabilistically, with threshold values selected based on risk avoidance preferences. The mitigation scenarios considered here can be generally characterised as either stabilisation or overshoot scenarios (specific classes are described in Section 2.2.3.1). Stabilisation 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

1 expected degree years, with such a metric of the “overshoot intensity” provided in Chapter 1 and employed
2 in Chapter 3). Timing of initially reaching a warming likely above 1.5°C and of returning to a level likely
3 below 1.5°C can be expressed, e.g., as the time when exceedance probability passes 50% or drops below
4 33%. The date at which these limits are passed can be a way to characterise overshoot scenarios
5 (incorporating duration). As in Chapter 1, continued warming scenarios that exceed 1.5°C are not considered
6 consistent with 1.5°C, but can be usefully characterised by the time at which they exceed 1.5°C with more
7 than 33% probability.

8
9 The global mean temperature response to the various pathways explored here is assessed via use of simple
10 geo-physically-based models that do not incorporate internal variability and typically exclude future changes
11 in the Sun and volcanic activity as these cannot be reliably projected (see Sections 2.2.1 and 2.6).

12 13 *2.1.2 Socio-economics underlying 1.5°C scenarios*

14
15 Assumptions regarding future trends in population, consumption of goods and services (including food),
16 economic growth, behaviour, technology, and institutions are all required to generate scenarios. These
17 societal choices must then be linked to the multiple drivers of climate change, including emissions of well-
18 mixed greenhouse gases and aerosol and ozone precursors, land-use and land-cover changes, and production
19 of aircraft contrails.

20
21 Plausible developments need to be anticipated in many facets of the key sectors of energy and land use.
22 Within energy, these consider energy resources (e.g., biofuels), energy supply and conversion technologies,
23 energy consumption, and supply and end-use efficiency. Within land-use, agricultural productivity, food
24 demand, terrestrial carbon management, and biofuel production are all considered. Developments in regard
25 to climate policies are also considered in scenario generation. These include carbon pricing and technology
26 policies such as research and development funding and subsidies. The scenarios incorporate regional
27 differentiation in sectoral and policy development. Discussion of these assumptions within recently
28 developed 1.5°C scenarios is given in Section 2.1.4.

29 30 31 *2.1.3 The Use of Scenarios to Answer Particular Questions*

32
33 By varying scenario assumptions and scenario design, various types of scenarios can be constructed. This is
34 important because the underlying narratives, assumptions and design of scenarios define to a large degree
35 which questions can be addressed, for example, the exploration of implications of delayed climate mitigation
36 action. In this assessment, we have identified the following classes of scenarios which are of particular
37 interest to the questions addressed in this chapter: (a) scenarios with the same climate forcing target in 2100
38 but varying socio-economic assumptions; (b) pairs of otherwise similar scenarios but with targets of 1.5°C
39 and 2°C; (c) pairs of scenarios with stringent mitigation action after 2020 and with a path that follows the
40 NDC until 2030.

41
42 Mitigation pathways generated with IAMs and related models describe an internally consistent and
43 calibrated (to historical trends) way to get from current developments to meeting long-term climate targets
44 like the 1.5°C limit (Clarke et al. 2014). Characteristics of these pathways such as emissions reduction rates,
45 time of peaking, and low-carbon energy deployment rates can be assessed as being consistent with the 1.5°C
46 limit, if there is at least one or a few 1.5°C pathways that exhibit these characteristics. However, they cannot
47 be assessed to be required for reaching the 1.5°C limit, as there may be other 1.5°C pathways that do not
48 exhibit these characteristics. In order to identify required characteristics, a targeted scenario analysis is
49 needed that specifically asked the question if there could be pathways without the characteristics in question.
50 This was done in AR5 for the question by when pathways have to obtain a peak in emissions to still limit
51 warming below 2°C, or which technologies are important to keep the 2°C target within reach. In this
52 assessment, we will distinguish between consistent and the much stronger concept of required characteristics
53 of 1.5°C pathways in this sense wherever possible.

54
55 Ultimately, it is unrealistic that any pathways developed today will be exactly followed until the end of the
56 century. Society will adjust its response as new information becomes available (O’Neill 2008; Webster et al.

1 2008). These adjustments can go in either direction. Earlier scenario studies have shown, however, that
2 deeper emissions reductions in the near term hedge against the uncertainty of both climate response and
3 technology availability (Clarke et al. 2014; Luderer et al. 2013a; Rogelj et al. 2013). Not knowing what
4 adaptations might be put in place in the future, however, and due to limited studies, in this report we
5 primarily examine prescribed (fixed) rather than adaptive pathways.
6
7

8 **2.1.4 New scenario information since AR5**

9

10 In this Chapter, we focus on an extension of the AR5 mitigation pathway assessment based on new scenario
11 literature. A discussion of updates in understanding of climate sensitivity, transient climate response,
12 radiative forcing, and the cumulative carbon budget consistent with 1.5°C are covered in Section 2.2.
13

14 This report relies on the integrated scenario literature for its pathway assessment, which the AR5 mainly
15 discussed in Chapter 6 of Working Group III (Clarke et al. 2014). Since then, several new integrated multi-
16 model studies have appeared in the literature that explore specific characteristics of scenarios markedly more
17 stringent than the lowest scenario category assessed in AR5 (see Table 2.1). Those scenarios explore 1.5°C
18 pathways from multiple perspectives, examining sensitivity to assumptions regarding:

- 19 • socio-economic drivers and developments including energy and food demand as, e.g., characterised by
20 the shared socio-economic pathways (SSPs, see Box 1.1)
- 21 • near term climate policies until 2020 and 2030 describing different levels of strengthening the NDCs
- 22 • the availability of bioenergy and carbon dioxide removal technologies

23 A large number of these scenarios were collected in a scenario database established for the assessment of this
24 special report. It contains 34 1.5°C scenarios (according to the definitions of Chapter 1 and Section 2.1.1), 27
25 additional well below 2°C scenarios, and 130 scenarios with less stringent climate policies to allow putting
26 1.5°C scenarios into context. Currently, these scenarios draw from two main integrated scenarios exercises
27 with multiple modelling teams – the lowest category of scenarios in the framework of the Shared
28 Socioeconomic Pathways (Rogelj et al. 2017a) and scenarios developed within the framework of the
29 ADVANCE project (Luderer et al. 2016a) – combined with individual scenarios from single model studies,
30 like the IEA Energy Technology Perspectives (IEA 2017).
31

32 *[In future revisions, the scenario set available to this assessment will be further complemented with*
33 *scenarios from forthcoming studies (see Table 2.1), and assessment of scenario ranges in line with 1.5°C*
34 *will be updated accordingly.]*
35

36 The scenario ensemble collected as part of the IPCC SR1.5 process represents an ensemble of opportunity.
37 The submitted scenarios cover a wide range of scenario types and thus allow exploration of a wide range of
38 questions. For this to be possible, however, critical scenario selection based on scenario assumptions and
39 setup is required.
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54

Table 2.1: New IAM studies this chapter draws upon and the key focus of the studies indicating which questions can be explored by the scenarios of each study.

<i>Study name</i>	<i>Key focus</i>	<i>Reference papers</i>
<i>SSPx-1.9</i>	<i>Development of new community scenarios based on the full SSP framework limiting end-of-century radiative forcing to 1.9 W m⁻².</i>	<i>(Rogelj et al. 2017a)</i>
<i>ADVANCE</i>	<i>Aggregate effect of the INDCs, comparison to optimal 2°C/1.5°C scenarios ratcheting up after 2020.</i>	<i>(Luderer et al. 2016a), TBD</i>
	<i>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</i>	<i>TBD</i>
<i>CD-LINKS</i>	<i>Exploring interactions between climate and sustainable development policies with the aim to identify robust integral policy packages to achieve all objectives.</i>	<i>TBD</i>
<i>EMF-30</i>	<i>Study of the contribution of short-lived climate forcers in deep mitigation scenarios</i>	<i>TBD</i>
<i>EMF-33</i>	<i>Study of the bioenergy contribution in deep mitigation scenarios</i>	<i>TBD</i>
<i>CEMICS</i>	<i>Study of CDR requirements and portfolios in 1.5°C pathways</i>	<i>TBD</i>

2.2 Geophysical relationships and constraints

2.2.1 Linking geophysical characteristics to mitigation pathways

Emissions pathways can be characterised by various geophysical relationships and constraints such as carbon budgets (Meinshausen et al. 2009; Friedlingstein et al. 2014; Rogelj et al. 2016), radiative forcing (van Vuuren et al. 2011a; Thomson et al. 2011; Riahi et al. 2011), atmospheric concentrations (Clarke et al. 2014) and associated temperature outcomes (Meinshausen et al. 2009; Rogelj et al. 2011; Luderer et al. 2013b). For mitigation pathways compatible with 1.5°C or 2°C, the temperature change associated with short-lived climate forcers strongly affects the remaining carbon budget (Bowerman et al. 2011; Rogelj et al. 2014a, 2015b, 2016b) and temperature outcomes (Lamarque et al. 2011; Bowerman et al. 2013).

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 assessment, 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.

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 rely on the approximate linear relationship between peak temperature and cumulative emissions of carbon (the so-called transient climate response to cumulative emission, or TCRE, see Chapter 1) (Collins et al. 2013a; Friedlingstein et al. 2014; Rogelj et al. 2016b), whereas others based

1 their estimates on equilibrium climate sensitivity (e.g., Schneider et al. 2017a).

2
3 Two approaches were employed in AR5 to determine carbon budgets. In both cases the geophysical science
4 uncertainty (Section 2.2.1) was used to determine probability estimates for the assessed carbon budgets.
5 Working Group I (WGI) reported Threshold Exceedance Budgets (TEB) that correspond to the amount of
6 cumulative CO₂ emissions at the time a specific temperature threshold is exceeded with a given probability
7 in a particular multi-gas and aerosols emission scenario. WGI computed TEBs from 2011 for 2°C relative to
8 the 1880-1861 period. With a 66% likelihood, the TEB is 2900 GtCO₂ when accounting for non-CO₂ GHG
9 and aerosols as in RCP2.6 (Stocker et al. 2013). In contrast to WGI, WGIII evaluated Threshold Avoidance
10 Budgets (TAB) that correspond to the cumulative CO₂ emissions over a given time period of a multi-forcer
11 emission scenario that limits global-mean temperature increase to below a specific threshold with a given
12 probability. WGIII computed TABs for the periods 2011–2050 and 2011–2100 for scenario categories based
13 on the projected radiative forcing in 2100. For mitigation pathways holding warming below 2°C by 2100
14 with >66% likelihood, the WGIII assessment reports that TAB are 150–1300 GtCO₂ between 2011 and 2050
15 and 630–1180 GtCO₂ between 2011 and 2100. WGIII estimated that those pathways have a >50%
16 probability to exceed 1.5°C between 2011 and 2100. Based on a limited number of studies, WGIII also
17 reported TAB for pathways with >50% probability of returning to 1.5°C in 2100 as 90–310 GtCO₂ between
18 2011 and 2100 (Clarke et al. 2014).

19
20 Some published estimates of carbon budgets compatible with 1.5°C or 2°C refer to budgets for CO₂-induced
21 warming only, and hence do not take into account the contribution of non-CO₂ climate forcers (Allen et al.
22 2009; IPCC et al. 2013, MacDougall et al. 2015). Because non-CO₂ climate forcing is projected to be more
23 positive in the future, CO₂-only carbon budgets overestimate the total net cumulative anthropogenic carbon
24 emissions compatible with 1.5°C or 2°C (IPCC 2013; Friedlingstein et al. 2014; Rogelj et al. 2016b). For a
25 66% likelihood to stay below 2°C relative to the 1861-1880 period, AR5 WGI estimates a CO₂-only carbon
26 budget of 3700 GtCO₂. Over a similar period, the carbon budget compatible with 2°C is reduced by 800
27 GtCO₂ when accounting for all CO₂, non-CO₂ GHG and aerosols as in RCP2.6. Both CO₂-only and multi-
28 forcer estimates of carbon budgets are informative to understand the amounts of total net cumulative
29 anthropogenic carbon emissions compatible with a given temperature limit over a given a time period.

30
31 In order to hold warming below 1.5°C or 2°C between 2016 and 2100 with a 66% likelihood, TEBs are 600
32 (540-650; 25-75% range) GtCO₂ for 1.5°C or 1300 (1220-1380) GtCO₂ for 2°C (Table 2.2). TABs for 2°C
33 are 810 (690-1030) GtCO₂. Note that the 25-75% percentile range for TABs for 2°C is narrower when based
34 on the ensemble of opportunity available in the scenario database to this report than previous estimates using
35 the AR5 scenario database, that is 590-1240 GtCO₂ (Rogelj et al. 2016b). Approximated TABs for 1.5°C
36 result in 370-520 and 120-200 GtCO₂ for 50% and 66% likelihoods, respectively (25%-75% percentile
37 ranges). These values are larger than the initial estimates in AR5. Other budget calculations that are available
38 in the literature are also analysed (Table 2.2). These include the threshold peak budget (TPB, carbon budget
39 until peak warming) or the threshold return budget (TRB, carbon budget after an overshoot, here most often
40 until 2100). TPBs are close to TEBs, while TRBs display different features, especially for 1.5°C limits, due
41 to the presence of net carbon dioxide removal, the pathway-dependence of the climate system (Zickfeld et al.
42 2016) as well as the response of the carbon cycle to declining emissions (Jones et al. 2016) (see Section 2.6).

Table 2.2: Median Threshold Exceedance Budget (TEB), Threshold Avoidance Budget (TAB), Threshold Return Budget (TRB) and Threshold Peak Budget (TPB) compatible with different temperature thresholds and probabilities. The 25%-75% range is indicated in brackets for each carbon budget. *:TABs for 1.5°C are approximated from the TABs of scenarios with slightly higher warming (yet, below 2°C) at 50% or 66% temperature outcomes from MAGICC, respectively. NA: not available.

Budget type	Threshold Exceedance Budgets	Threshold Avoidance Budget	Threshold Return Budgets	Threshold Peak Budgets
Abbreviation	TEB	TAB	TRB	TPB
Units	[GtCO ₂ rel. to 2016]			
<i>Compatible with 2°C</i>				
50% likelihood	1500 (1470 — 1640)	970 (740 — 1120)	1450 (1420 — 1500)	1510 (1490 — 1550)
66% likelihood	1300 (1220 — 1380)	810 (690 — 1030)	1130 (1070 — 1260)	1300 (1220 — 1380)
<i>Compatible with 1.5°C</i>				
50% likelihood	700 (640 — 760)	460 (370 — 520)*	790 (650 — 810)	NA
66% likelihood	600 (540 — 650)	170 (120 — 200)*	340 (270 — 360)	NA

Precise comparison of the various budgets is complicated due to their varying definitions. For example, TEBs, TABs and TPBs are not determined at the same time period. For a 2°C warming threshold, TEB, TAB and TPB estimates are determined at time points that range between 2026 and 2084 because the various scenarios show different geophysical characteristics and timing of either exceeding 2°C or avoiding 2°C. TRBs, on the contrary, has a fixed definition in time and as such provide a cleaner delineated estimate of carbon budget compatible with 1.5°C or 2°C across the various mitigation pathways. For the 50% likelihood levels, TRB compatible with 1.5°C is 45% lower than TRB compatible with 2°C.

2.2.2.2 Remaining carbon budget and related uncertainties

Defining the remaining carbon budget compatible with 1.5°C or 2°C requires an accurate estimate of cumulative carbon emissions to date (Chapter 1). Several estimates have been proposed in the literature (Houghton 2007; Ciais et al. 2013; Regnier et al. 2013; Le Quéré et al. 2016) which essentially differ in terms of period of reference, and sources of data (observations, models or both). In this assessment, we use estimates of the total net cumulative anthropogenic emissions for 2016 reported by the Global Carbon Project (Le Quéré et al. 2016) which include contributions from land-use/land-cover changes, fossil fuel combustion and cement production. The contributions of fossil fuel emissions plus cement production and land-use/land cover change are estimated as 36 and 5 GtCO₂, respectively, with a 66% uncertainty range of ±2 GtCO₂.

There are several key uncertainties that determine the remaining carbon budget. A first uncertainty lies in the estimates of the TCRE (Figure 2.1). AR5 WGI provides an indicative range of the TCRE of 0.8 to 2.5°C per 1000 GtC (or 3660 GtCO₂) for 66% likelihood assuming a Gaussian distribution (Collins et al. 2013a). Recent research using different approaches provides further constraints on TCRE. TCRE uncertainties vary depending on the approach followed (model-based, model-data fusion, observation-based), but importantly several independent studies agreed on a Gaussian distribution of the TCRE (IPCC et al. 2013; MacDougall et al. 2017; Tachiiri et al. 2015). The median estimate of TCRE used in our modelling with MAGICC (Figure 2.1), which is based on CMIP5 models, is 1.6°C per 3660 GtCO₂ which lies in the centre of the AR5 WGI assessment's 0.8 to 2.5°C range (Collins et al. 2013a). Clearly a lower or a higher value of the TCRE would increase or reduce allowable budgets, respectively. This uncertainty is reflected in part by the probabilistic model setup of the MAGICC model used here. Several estimates of the TCRE in the literature constrain the

1 range of the TCRE between 1.1 and 1.7°C per 3660 GtCO₂ (Tachiiri et al. 2015).

2
3 Another source of uncertainty, also related to the TCRE, stems from the concept of the TCRE-based
4 calculation itself (Collins et al. 2013a; Gillett et al. 2013). While many estimates of the TCRE are derived
5 from idealised runs with atmospheric CO₂ concentrations rising at 1% per year (Joshi 2016; Tachiiri et al.
6 2015; Gillett et al. 2013), several other estimates of TCRE rely on the fact that the linear relationship
7 approximately holds when using the ratio of total anthropogenic warming to cumulative carbon emissions in
8 a multi-forcer context, and hence assumes a proportionality between the total anthropogenic warming and
9 the non-CO₂ warming (IPCC 2013; Friedlingstein et al. 2014). This proportionality can break down in
10 stringent emissions mitigation pathways, making the TCRE less directly relevant (see Sections 2.2.2.3 and
11 Section 2.6 for further details). The impacts of inhomogeneously distributed forcers on global mean
12 temperature may also depend on their spatial distribution and thus may not be fully captured in reduced-form
13 models (Myhre et al. 2013; Shindell 2014; Rotstayn et al. 2015; Marvel et al. 2016).

14
15 TCRE is defined until peak warming, i.e., until global CO₂ emissions reach approximately net zero levels. In
16 a situation where net CDR (see Section 2.4) from the atmosphere is achieved, the linear relationship between
17 the carbon budget and temperature can be altered. In such cases CDR reduces atmospheric CO₂
18 concentrations more quickly than would naturally be the case. TCRE is slightly weaker with decreasing CO₂
19 than with rising CO₂, which is referred to as the path-dependence of the TCRE (Zickfeld et al. 2012;
20 Herrington and Zickfeld 2014; Krasting et al. 2014; Zickfeld et al. 2016). Zickfeld and MacDougall (2016)
21 estimate that the asymmetry of TCRE to rising versus decreasing CO₂ is about 7%, implying a slightly
22 higher temperature outcome for a given carbon budget when it is achieved by net CDR after a carbon budget
23 overshoot. A part of this non-linearity has been attributed to the lagged response of slow components of the
24 Earth system to past CO₂ emissions. This is the case for the deep ocean which results in continued warming
25 after the start of CDR, also referred to as the recalcitrant warming (Held et al. 2010). Asymmetry of the
26 TCRE implies deviation in carbon budgets for a given temperature threshold after the overshoot. Such a
27 carbon budget can be characterised as the threshold return budget (Figure 2.1). With a 66% likelihood, they
28 range between 215 and 358 GtCO₂ for 1.5°C and 1060 and 1416 GtCO₂ for 2°C. For the same threshold of
29 warming and the same probability, the threshold return budgets are smaller than TEBs (which have been
30 identified as slight overestimates (Rogelj et al. 2016b) due to the small lag in temperature response to CO₂
31 emissions (Joos et al. 2013)) but greater than TABs, complicating the analysis of allowable carbon emissions
32 compatible with 1.5°C or 2°C.

33
34 Finally, large uncertainties remain in some Earth system feedback processes that can impact remaining
35 carbon budgets compatible with 1.5°C or 2°C, for example, permafrost feedbacks. Permafrost thawing is
36 expected to release carbon and methane to the atmosphere. This release reduces the remaining carbon budget
37 for 1.5°C or 2°C. Using an EMIC, MacDougall et al. (2015) estimate that this feedback reduces the CO₂-
38 only carbon budget for 2°C (4650 GtCO₂) by 440 GtCO₂ under RCP45. Under RCP2.6 and 1.5°C pathways,
39 this reduction is expected to be smaller due to lower warming-induced permafrost thawing (Schneider von
40 Deimling et al. 2012). However, the amplitude of this feedback remains highly uncertain because the
41 response of permafrost to climate change is not well constrained. Several feedbacks between carbon cycle
42 and non-CO₂ greenhouse gases and aerosols might also impact the future dynamics of the natural carbon
43 sink. For example, nutrient limitation due to change in reactive nitrogen or phosphorus deposition over land
44 and ocean (Duce et al. 2008; Mahowald et al. 2017). Finally, multiple geophysical climate targets beyond
45 global mean temperature rise (like global mean temperature rise, ocean acidification, and net primary
46 production on land) can be simultaneously taken into account. For any given likelihood of meeting such
47 combined targets, carbon budgets would be greatly reduced due to counteracting mechanism and processes
48 in the geophysical system (Steinacher et al. 2013).

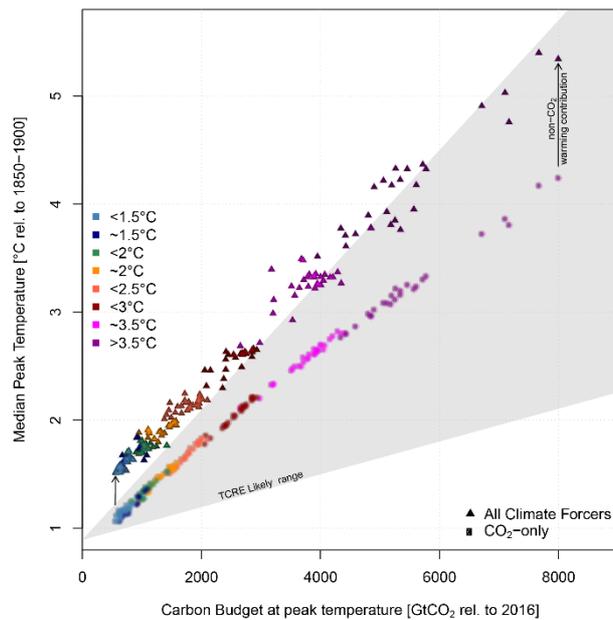


Figure 2.1: Median peak temperature (relative to 1850-1900) as a function of threshold peak carbon budgets (TPB, relative to 2016). Filled circles and triangles are indicative of the median warming due to CO₂ and all climate forcings, respectively, as computed by the MAGICC setup used in this assessment. The grey shaded area represents the range of values derived from the assessed TCRE range as reported in (Collins et al. 2013). Types of pathways are represented with the same colour code as used in Section 2.2.3.

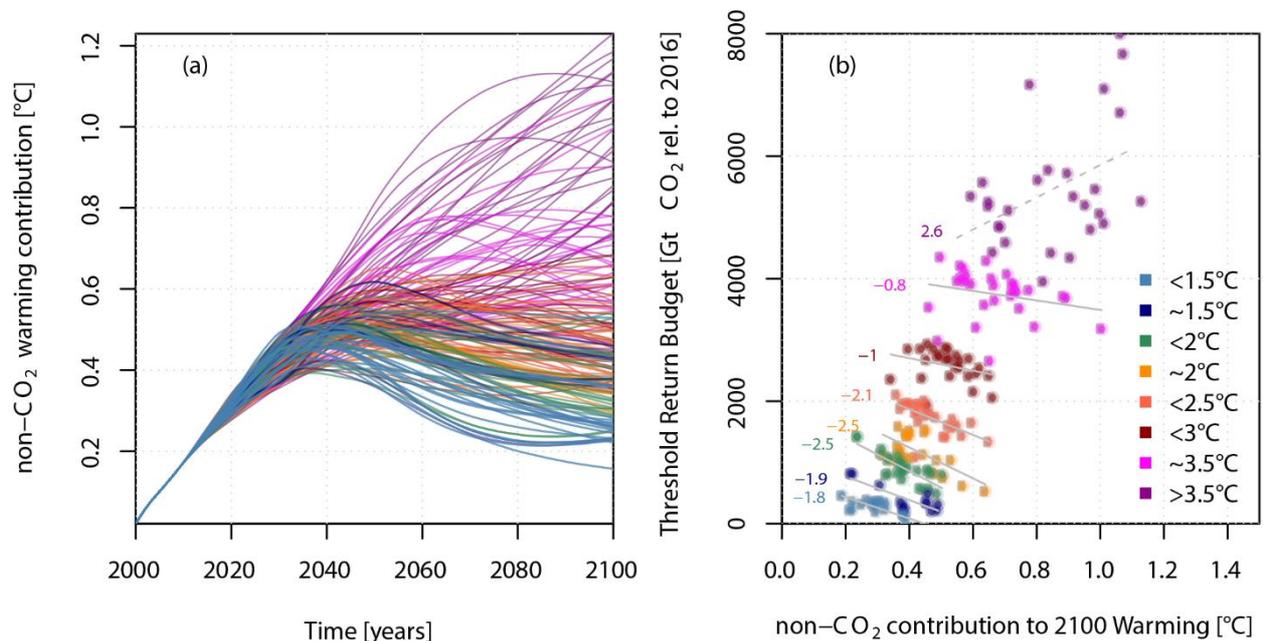
2.2.2.3 Role of non-CO₂ GHGs and aerosols

Most studies including non-CO₂ greenhouse gases and aerosols partition climate forcings into two groups by their lifetime: methane, ozone precursors and aerosols are defined as short-lived climate forcings (SLCF) due to their shorter lifetime in the atmosphere, while CO₂ and other non-CO₂ long-lived climate forcings such as nitrous oxide, sulphur hexafluoride and other halogenated carbon gases contribute to forcing over decades. Non-CO₂ greenhouse gases and aerosols are emitted by natural sources (wetland, marshes, inland waters) (Saunio et al. 2016; Tsigaridis et al. 2006; Borges et al. 2015) and anthropogenic sources (industry, agriculture) (Rigby et al. 2010; Bodirsky et al. 2012; Lioussé et al. 2010; Bond et al. 2013). Mitigation pathways assessed in this report rely on near-present estimates of non-CO₂ emissions as their starting point. For example, they use 2010 levels of emissions for methane (CH₄) and nitrous oxide (N₂O) ranging between 320-400 MtCH₄ y⁻¹ and 7-11 MtN₂O y⁻¹, respectively. Compared to CO₂, emissions of non-CO₂ greenhouse gases and aerosols are still poorly constrained (Ciais et al. 2013; Boucher et al. 2013).

Temperature impacts of non-CO₂ forcings are particularly important when evaluating stringent mitigation pathways (Weyant et al. 2006; Rogelj et al. 2015a, 2011, 2014b). SLCFs are often co-emitted with CO₂ so in mitigation scenarios many CO₂-targeted mitigation measures also reduce SLCF forcing magnitude (Rogelj et al. 2014a; Shindell et al. 2012). Reduction in SO₂ emissions largely associated with fossil fuel burning are expected to reduce the cooling effects of both aerosol radiative interactions and aerosol cloud interactions, leading to warming (Myhre et al. 2013). In contrast, targeted mitigation measures for methane, nitrous oxide, black carbon and hydrofluorocarbon emission reduction could help to limit warming to 1.5°C or 2°C by 2100 (Bowerman et al. 2011; Rogelj et al. 2014a, 2015b, 2016b; Shindell et al. 2012; Ramanathan and Xu 2010). Emissions and radiative forcing for the SLCFs are typically more uncertain and have greater geographical variation than CO₂ (Myhre et al. 2013). This uncertainty increases the relative uncertainty of the temperature pathways associated with low emission scenarios compared to high emission scenarios (Clarke et al. 2014). It is also important to note that geographical patterns of temperature change and other climate impacts, especially those related to precipitation, depend significantly on forcing mechanism (Samset et al. 2016; Myhre et al. 2013; Shindell et al. 2015) (see Chapter 3).

The assessment of the available mitigation pathways indicates that the influence of non-CO₂ climate forcings reduces the threshold return carbon budgets by about 2000 GtCO₂ per degree of additional warming

1 attributed to non-CO₂ forcers (the 1.5°C compatible pathways on Figure 2.2b). This relationship is robust in
 2 most of the mitigation pathways limiting warming below 3°C. Above this temperature threshold, this
 3 relationship between carbon budget and temperature contribution from non-CO₂ forcing does not hold.
 4
 5



6
 7 **Figure 2.2:** Role of non-CO₂ climate forcers in assessed pathways. (a) temporal evolution of the temperature
 8 contribution from non-CO₂ climate forcers and (b) variation in threshold return budgets (TRBs) as a
 9 function of the temperature contribution from non-CO₂ forcing. In (b) numbers indicate the slope of the
 10 TRBs as function of temperature contribution from non-CO₂ forcing in 1000 GtCO₂ per °C of non-CO₂
 11 warming. The non-CO₂ temperature contribution has been estimated with equation 8.SM.13 from (Myhre
 12 et al. 2013).
 13
 14

15 2.2.3 Geophysical characteristics of mitigation pathways

16 2.2.3.1 Pathway classification

17 Mitigation pathways assessed in this chapter contain fundamental structural differences that complicate their
 18 direct comparison. Those differences can be categorised by three key features. The first one relates to the
 19 nature of the goal to achieve. Emission pathways assessed here were initially developed to reach a long-term
 20 temperature goal, such as 1.5°C or 2°C, a specific cumulative carbon budget by 2100, or a long-term
 21 radiative forcing target. Some pathways also focus on near- or mid-term goals which relate to policy
 22 formulations such as the Nationally Determined Contributions (UNFCCC 2015) or deep decarbonisation
 23 transitions (Bataille et al. 2016a). A second difference between pathways is that although most of the
 24 mitigation pathways used in this assessment allow the long-term climate goal to be temporarily exceeded, the
 25 timing, the amplitude, and duration of the overshoot (as defined in Chapter 1) differs between them. A last
 26 difference relates to the complexity of the emissions mix that composes the framing of mitigation pathways.
 27 Several emissions pathways include all relevant forcing agents such as the non-CO₂ GHG, ozone precursors
 28 and aerosols, while others only account for a subset of GHG or focus only on CO₂.
 29
 30

31 These differences between mitigation pathways complicate the mapping of pathways. It is however possible
 32 to classify mitigation pathways into eight groups using their temperature outcomes, i.e., their likelihood to
 33 exceed a given level of warming over the 21st century (Table 2.3). Similar approaches to defining types of
 34 mitigation pathways have been used earlier (Rogelj et al. 2011; UNEP 2016), and facilitate assessment of
 35 their associated mitigation measures (see Section 2.3 and Section 2.4).
 36

37 *[Note to Reviewers: This level of warming is determined using the working definition for a historical*
 38 *reference period (1850-1900 – to be updated to 1850-1879 in the SOD, this would only result in a minimal*

1 *difference, see Chapter 1).]*

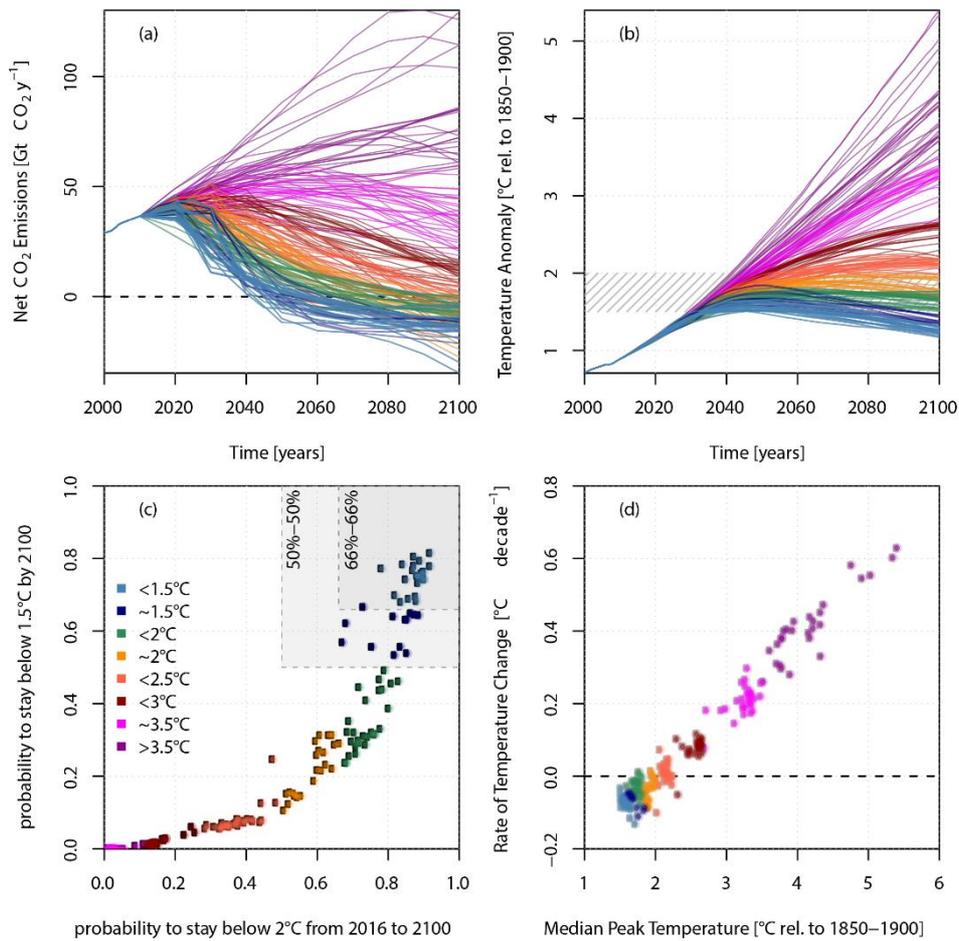
2
3 **Table 2.3:** Description of classification or typology of emissions pathways available in the scenario database to this
4 assessment in terms of probability of exceed a given temperature threshold (P_T).
5

Types of Mitigation pathways	Probability to exceed a given warming threshold	Symbol	Acronym	Count in database
Well below 1.5°C	$P_{1.5^\circ\text{C}}(2100) < 0.331$ and $P_{2^\circ\text{C}}(2016-2100) < 0.331$	<1.5°C	WB1.5C	21
Medium 1.5°C	$0.331 \leq P_{1.5^\circ\text{C}}(2100) < 0.501$ and $P_{2^\circ\text{C}}(2016-2100) < 0.331$	~1.5°C	Med1.5C	13
Well below 2°C	$P_{2^\circ\text{C}}(2016-2100) < 0.331$ excluding above-mentioned pathways	<2°C	WB2C	27
Medium 2°C	$P_{2^\circ\text{C}}(2016-2100) < 0.501$ excluding above-mentioned pathways	~2°C	Med2C	22
Well below 2.5°C	$P_{2.5^\circ\text{C}}(2016-2100) < 0.331$ excluding above-mentioned pathways	<2.5°C	WB2.5C	26
Well below 3°C	$P_{3^\circ\text{C}}(2016-2100) < 0.331$ excluding above-mentioned pathways	<3°C	WB3C	26
Medium 3.5°C	$P_{3.5^\circ\text{C}}(2016-2100) < 0.501$ excluding above-mentioned pathways	~3.5°C	Med3.5C	29
Above 3.5°C	When $P_{3.5^\circ\text{C}} \geq 0.501$ during at least 1 year	>3.5°C	Above3.5C	27

6
7
8 **2.2.3.2 Near-term to 2050**

9 Even within the scenario typology (Table 2.3), there is a large degree of variance between emissions
10 pathways. Still, mitigation pathways can be examined based on two key geophysical characteristics: the
11 presence of overshoots and the timing of reaching net-zero CO₂ emissions. Those characteristics have been
12 highlighted in several studies focusing on stringent mitigation pathways (Wigley et al. 2007; Huntingford
13 and Lowe 2007; Zickfeld and Herrington 2015; Nohara et al. 2015; Schleussner et al. 2016; Rogelj et al.
14 2015d). In the ensemble of scenarios collected in the database for this report, pathways holding warming
15 below or close to 1.5°C in 2100 (<1.5°C and ~1.5°C) are all projected to overshoot median temperature rise
16 around mid-century before returning below that level in 2100. Also net CO₂ emissions and radiative forcing
17 are higher at the time of peak warming (at mid-century) than at the end of the century (Table 2.4). Both
18 1.5°C pathway classes (<1.5°C and ~1.5°C) reach carbon neutrality (or net-zero CO₂ emissions) before 2050
19 in most of those scenarios (Figure 2.4), and have the strongest rate of temperature decline after their peak
20 (Figure 2.3). Both classes are also characterised by a strong reduction of the non-CO₂ warming contribution,
21 which peaks around 2040 and then declines virtually all available scenarios in the two 1.5°C classes (Figure
22 2.2).

23
24 In contrast, scenarios in the <2°C through >3.5°C classes (see Table 2.3 for definitions) do not display such
25 features between 2016 and 2050. Although most of the <2°C pathways have overshoots and reach carbon
26 neutrality at some point during the 21st century, most of those characteristics occur after 2050. The same
27 goes for the types of mitigation pathways leading to higher warming threshold. In many ways, the first group
28 of pathways (<1.5°C and about 1.5°C) can thus be understood as early stringent mitigation action pathways,
29 while the latter types of pathways include delayed mitigation actions pathways (see Section 2.3).
30



1
2
3
4
5
6
7
8

Figure 2.3: Pathways classification (typology) overview. (a) Net CO₂ emissions from 2000 to 2100, (b) 50th percentile global mean temperature increase relative to 1850-1900, (c) probability of holding warming below 2°C during the entire twenty-first century and below 1.5°C by 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.

1 **Table 2.4:** Geophysical characteristics of mitigation pathways derived at median peak temperature and at the end of the century (2100). Geophysical characteristics of overshoot
 2 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.
 3 NA indicates that no mitigation pathways exhibits the given geophysical characteristics. Radiative forcing metrics are: total anthropogenic radiative forcing (RFall),
 4 CO₂ radiative forcing (RFCO₂), and non-CO₂ radiative forcing (RFnonCO₂).
 5

Classes	Geophysical characteristics at median peak temperature										Geophysical characteristics in 2100									Overshoot Properties		
	Temperature [°C]	Year	CO ₂ [ppm]	RFall [W m ⁻²]	RFCO ₂ [W m ⁻²]	RFnonCO ₂ [W m ⁻²]	TPB [GtCO ₂ rel. to 2016]	Probability to Exceed 1.5°C	Probability to Exceed 2.0°C	Probability to Exceed 2.5°C	Temperature [°C]	CO ₂ [ppm]	RFall [W m ⁻²]	RFCO ₂ [W m ⁻²]	RFnonCO ₂ [W m ⁻²]	Cum. CO ₂ until 2100 [GtCO ₂ rel. to 2016]	Probability to Exceed 1.5°C	Probability to Exceed 2.0°C	Probability to Exceed 2.5°C	counts	Severity [°C year]	Exceedance year
<1.5°C	1.57 (1.53-1.63)	2047 (2045-2049)	440 (430-440)	3.0 (2.9-3.1)	2.4 (2.4-2.5)	0.6 (0.5-0.6)	670 (620-750)	0.6 (0.55-0.7)	0.11 (0.09-0.14)	0.02 (0.01-0.02)	1.25 (1.23-1.28)	380 (370-390)	2.0 (2.0-2.1)	1.7 (1.6-1.8)	0.3 (0.3-0.4)	280 (150-360)	0.25 (0.22-0.27)	0.06 (0.06-0.08)	0.01 (0.01-0.01)	21	1 (0-3)	2036 (2034-2037)
~1.5°C	1.66 (1.63-1.73)	2049 (2047-2052)	440 (440-460)	3.2 (3.2-3.3)	2.5 (2.5-2.7)	0.7 (0.6-0.8)	780 (690-950)	0.74 (0.68-0.78)	0.15 (0.14-0.24)	0.02 (0.02-0.05)	1.38 (1.36-1.43)	390 (380-400)	2.3 (2.2-2.3)	1.8 (1.7-1.9)	0.5 (0.4-0.5)	330 (250-490)	0.37 (0.36-0.44)	0.09 (0.08-0.12)	0.02 (0.02-0.02)	13	5 (3-8)	2033 (2032-2035)
<2°C	1.74 (1.7-1.77)	2062 (2058-2072)	450 (450-460)	3.2 (3.1-3.3)	2.6 (2.6-2.7)	0.6 (0.5-0.6)	1010 (920-1090)	0.77 (0.76-0.8)	0.26 (0.22-0.29)	0.06 (0.05-0.07)	1.65 (1.56-1.69)	430 (420-440)	2.8 (2.6-2.9)	2.3 (2.2-2.4)	0.4 (0.4-0.5)	870 (810-1030)	0.68 (0.58-0.71)	0.22 (0.17-0.26)	0.07 (0.05-0.09)	25	12 (9-14)	2034 (2032-2036)
~2°C	1.9 (1.88-1.95)	2074 (2068-2079)	470 (470-480)	3.4 (3.4-3.5)	2.9 (2.8-3.0)	0.5 (0.5-0.7)	1300 (1120-1480)	0.86 (0.85-0.88)	0.4 (0.37-0.46)	0.12 (0.1-0.15)	1.79 (1.7-1.92)	450 (440-470)	3.0 (2.8-3.3)	2.6 (2.4-2.8)	0.5 (0.4-0.6)	1150 (1030-1460)	0.78 (0.72-0.85)	0.34 (0.27-0.44)	0.11 (0.10-0.15)	21	21 (20-24)	2033 (2032-2034)
<2.5°C	2.14 (2.1-2.18)	2094 (2088-2100)	500 (490-510)	3.7 (3.7-3.8)	3.1 (3.1-3.3)	0.5 (0.5-0.7)	1770 (1620-1950)	0.94 (0.93-0.94)	0.63 (0.59-0.66)	0.26 (0.23-0.29)	2.12 (2.09-2.18)	500 (480-510)	3.6 (3.6-3.7)	3.1 (3.0-3.2)	0.5 (0.4-0.6)	1770 (1600-1940)	0.93 (0.92-0.94)	0.61 (0.58-0.65)	0.25 (0.24-0.29)	18	32 (31-34)	2032 (2032-2034)
<3°C	2.61 (2.51-2.63)	2100 (2100-2100)	570 (550-580)	4.5 (4.4-4.6)	3.9 (3.7-3.9)	0.6 (0.6-0.7)	2660 (2410-2750)	0.99 (0.98-0.99)	0.86 (0.84-0.87)	0.57 (0.51-0.59)	2.61 (2.51-2.63)	570 (550-580)	4.5 (4.4-4.6)	3.9 (3.7-3.9)	0.6 (0.6-0.7)	2660 (2410-2750)	0.99 (0.98-0.99)	0.86 (0.84-0.87)	0.57 (0.51-0.59)	1	42 (42-42)	2031 (2031-2031)
~3.5°C	3.29 (3.22-3.34)	2100 (2100-2100)	680 (660-700)	5.8 (5.6-5.8)	4.8 (4.6-4.9)	0.9 (0.7-1)	3810 (3570-4000)	1 (1-1)	0.98 (0.97-0.98)	0.88 (0.86-0.89)	3.29 (3.22-3.34)	680 (660-700)	5.8 (5.6-5.8)	4.8 (4.6-4.9)	0.9 (0.7-1.0)	3810 (3570-4000)	1 (1-1)	0.98 (0.97-0.98)	0.88 (0.86-0.89)	0	NA	NA
>3.5°C	4.16 (3.78-4.33)	2100 (2100-2100)	820 (790-870)	7.2 (6.7-7.5)	5.8 (5.5-6.1)	1.4 (1.2-1.5)	5250 (4850-5660)	1 (1-1)	1 (1-1)	0.98 (0.97-0.99)	4.16 (3.78-4.33)	820 (790-870)	7.2 (6.7-7.5)	5.8 (5.5-6.1)	1.4 (1.2-1.5)	5250 (4850-5660)	1 (1-1)	1 (1-1)	0.98 (0.97-0.99)	0	NA	NA

6

2.2.3.3 Post-2050

After 2050, mitigation pathways lead to a very large range of geophysical characteristics (Table 2.4). Thirty-four of the available pathways out of 191 limit median temperature below or close to 1.5°C, 49 to below or close to 2°C, while 108 lead to higher temperature outcomes by 2100. This section again uses the pathway classes defined in Table 2.3.

Pathways in line with 1.5°C (<1.5°C and about 1.5°C) all reach net-zero CO₂ emissions in the period 2040-2065, compared to the larger class of 2°C pathways (<2°C and about 2°C), some of which only reach net-zero CO₂ emissions by the end of the century (Figure 2.4). 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, due to an interplay of strongly reduced annual CO₂ emissions and declining short-lived forcers (see Section 2.3.3). 1.5°C pathways lead to peak atmospheric CO₂ concentrations between 430 and 460 ppm; that is about 5 to 15% higher than the 2015 concentration (Le Quéré et al. 2016). 2°C pathways peak CO₂ concentrations at about 10 to 30 ppm CO₂ higher levels. By the end of the century, 1.5°C pathways all have CO₂ concentrations below today's levels, in contrast to 2°C pathways, which continue to see CO₂ concentrations that are about 5-15% higher than today. Within the group of 1.5°C pathways, the ratio of the end-of-century carbon budget to the maximal cumulative carbon emissions (reached at the year of carbon neutrality), is non-linearly related to the year of net-zero CO₂ emissions (Figure 2.4). This already provides an indication of the level of negative CO₂ emissions deployed in the various mitigation pathways (see also Section 2.4). A part of these negative CO₂ emissions is used to compensate for the residual warming due to non-CO₂ GHG and aerosols by the end of the century (Figure 2.2) as suggested in the literature (Fuss et al. 2013, 2014b; Peters et al. 2017; Kriegler et al. 2013; 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 2.3). This is not the case for mitigation pathways limiting warming to 2°C or higher levels. In 2°C pathways (<2°C and about 2°C) temperatures at the end of the century can be stabilised, be declining or still increasing. In higher pathways classes, median warming more often than not continues to increase over this period.

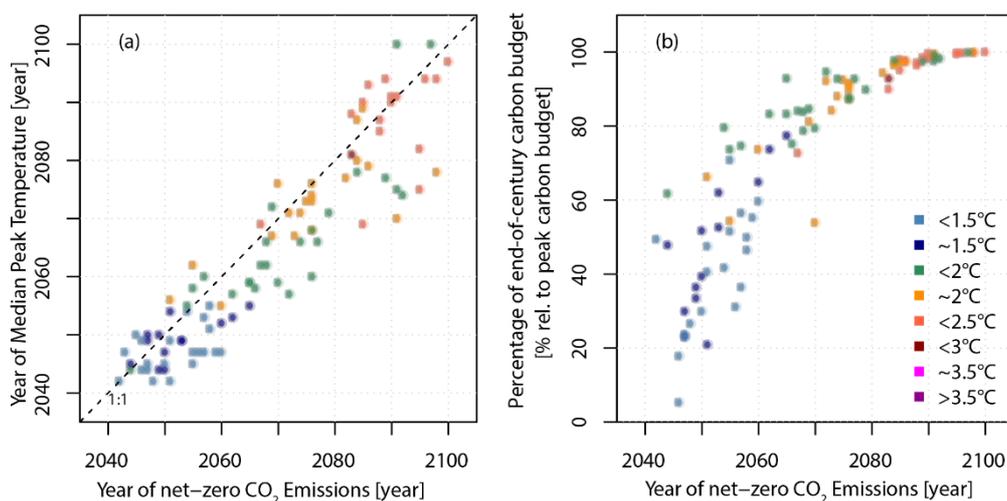


Figure 2.4: Characteristics of pathways reaching net-zero CO₂ emissions between 2016 and 2100. (a) Timing of median peak warming as function of the year of net-zero CO₂ emissions and (b) the percentage ratio of end-of-century budget to the carbon budget until year of net-zero CO₂ emissions (i.e., the maximum carbon budget, derived at the year of net zero CO₂ emissions). Both budgets have been computed starting from 2016. In (a), the dashed line represents the first diagonal of the scatterplot.

2.3 General characteristics of 1.5°C pathways and transitions in the near-to-medium term

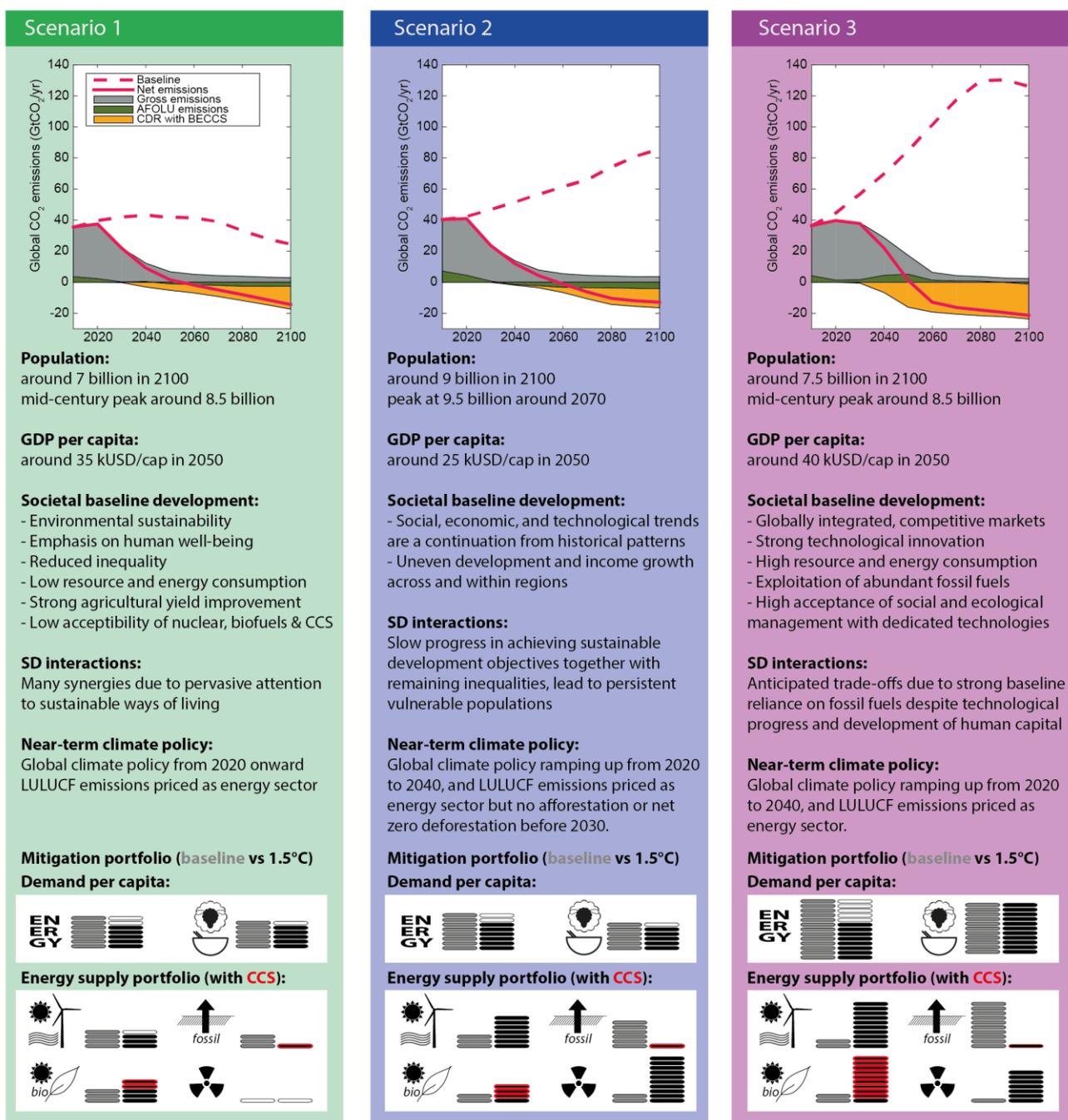
2.3.1 Overview of mitigation pathways

Limiting global mean temperature to any level requires global CO₂ emissions to become net zero at some point in the future (Collins et al. 2013a). At the same time, current (year: 2015) global annual CO₂ emissions are of the order of 41 billion metric tons of CO₂ per annum (GtCO₂ yr⁻¹) (Le Quéré et al. 2016). Reducing these emissions from their current levels to net zero 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. The question here is how do such transformations look in pathways compatible with limiting global mean temperature to 1.5°C relative to pre-industrial levels? Are there key characteristics that can be robustly identified? Which factors enable or hamper this transition? How do actions and choices in the near term impact the achievability of such pathways in the more distant future? In this section we assess the transformation until mid-century in pathways compatible with limiting global mean temperature rise to 1.5°C.

[Note to Reviewers: for the SOD this section will be made fully consistent with the pathways classification introduced in Section 2.2, and updated information available in the database supporting this assessment.]

2.3.1.1 General scenario concepts

Earlier assessments already highlighted two important, related concepts in the framing and understanding of answers provided to the questions posed above (Clarke et al. 2014). First, there is no single pathway to achieve a specific climate objective. A variety of pathways exist that can be compatible with limiting warming to 1.5°C, which depend on underlying societal choices and preferences. These choices and preferences 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 or regionally fragmented (see Figure 2.5). The second concept related to the framing of transformation pathways 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 (Figure 2.5 and Sections 2.4 and 2.5). 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 large variety in 1.5°C pathways suggests that policy decisions and societal choices are essential in shaping pathways.



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19

Figure 2.5: Overview of scenario characteristics of three different 1.5°C pathway types which differ in their assumptions about socio-economic trends, societal baseline development on which climate policies are imposed and enabling and hindering factors for near-term climate policy. Illustrative pathway types correspond to 1.9 Wm⁻² scenarios of three marker implementations of the Shared Socioeconomic Pathways (Riahi et al. 2017; Rogelj et al. 2017a) representing a green-growth (Scenarios 1, SSP1, van Vuuren et al. 2017), middle-of-the-road (Scenario 2, SSP2, Fricko et al. 2017), and an energy intensive development with strong focus on fossil fuel exploitation in the baseline (Scenario 3, SSP5, Kriegler et al. 2017). Symbols at the bottom of each pathway type illustrate characteristics averaged over the second half of the century: final energy demand per capita, and agricultural food and livestock demand; primary energy contributions of non-biomass renewables, fossil fuels, bio-energy, and nuclear. Grey bars illustrate baseline demand, black bars demand in a scenario consistent with 1.5°C (1.9 Wm⁻² in 2100). Red outlined bars illustrate contributions combined with CCS.

The diversity of pathways available to achieve stringent climate change mitigation futures 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 preferences, the evolution of per capita energy demand and of per capita food demand, choices related to preferences in technologies for the

1 energy sector, and choices related to agricultural productivity and land use. These dimensions have been
2 recently explored in the context of the Shared Socioeconomic Pathways (SSP) (O'Neill et al. 2014) which
3 provide narratives (O'Neill et al. 2017) and quantifications (Leimbach et al. 2017; Crespo Cuaresma 2017;
4 Dellink et al. 2017; KC and Lutz 2017; Riahi et al. 2017) of different future worlds in which scenario
5 dimensions are varied to explore differential challenges to adaptation and mitigation (see Box 1.1 on
6 scenarios and pathways).

7
8 Population and economic growth projections can vary strongly across scenarios (Leimbach et al. 2017;
9 Crespo Cuaresma 2017; Dellink et al. 2017; KC and Lutz 2017). For example, based on alternative future
10 fertility, mortality, migration and educational assumptions, population projections vary between 8.5 and 10.0
11 billion people by 2050, and 6.9 to 12.6 billion people by 2100. These ranges to a large extent depend on
12 future female educational attainment, with higher attainment leading to lower fertility rates and therewith
13 decreased population growth up to a level of 1 billion people by 2050 (KC and Lutz 2017; Lutz and KC
14 2011). Consistent with populations development, GDP per capita also varies strongly in future scenarios,
15 with 2050 GDP in baseline scenarios varying between 18 and more than 40 thousand USD per capita
16 (2005USD), in part driven by assumptions on development convergence between and within regions
17 (Leimbach et al. 2017; Crespo Cuaresma 2017; Dellink et al. 2017). SSP-based studies have identified very
18 high challenges to mitigation (and hence very few to no scenarios compatible with 1.5°C) for worlds in
19 which global population growth proceeds along the high-end of current emissions projections (around 10 and
20 12.6 billion people in 2050 and 2100, respectively) combined with low educational achievements and low
21 per capita income growth (global mean around 10.7 and 11.5 thousand USD per capita in 2050 and 2100,
22 respectively).

23
24 Besides assumptions related to the drivers, scenarios are also subject to assumptions about the mitigation
25 policies that can be put in place. Mitigation policies can either be applied immediately in scenarios, or follow
26 staged or delayed approaches. Policies can span many sectors (e.g., carbon pricing), or policies can be
27 applicable to specific sectors only (like the energy sector) with other sectors (e.g., the agricultural or the
28 land-use sector) treated differently (Kriegler et al. 2014b). These variations can have an important impact on
29 the ability of models to generate scenarios compatible with stringent climate targets like 1.5°C. In the
30 scenario ensemble available to this assessment, several variations of near-term mitigation policy
31 implementation can be found: immediate global cooperation from 2020 onward towards a global climate
32 objective, including all sectors (Riahi et al. 2017; Luderer et al. 2016a), a phase in of globally coordinated
33 mitigation policy from 2020 to 2040 (Riahi et al. 2017), and a delay of global mitigation policy, following
34 NDCs until 2030 (Luderer et al. 2016a). Each of these implementation allows exploration of different
35 aspects of 1.5°C pathways.

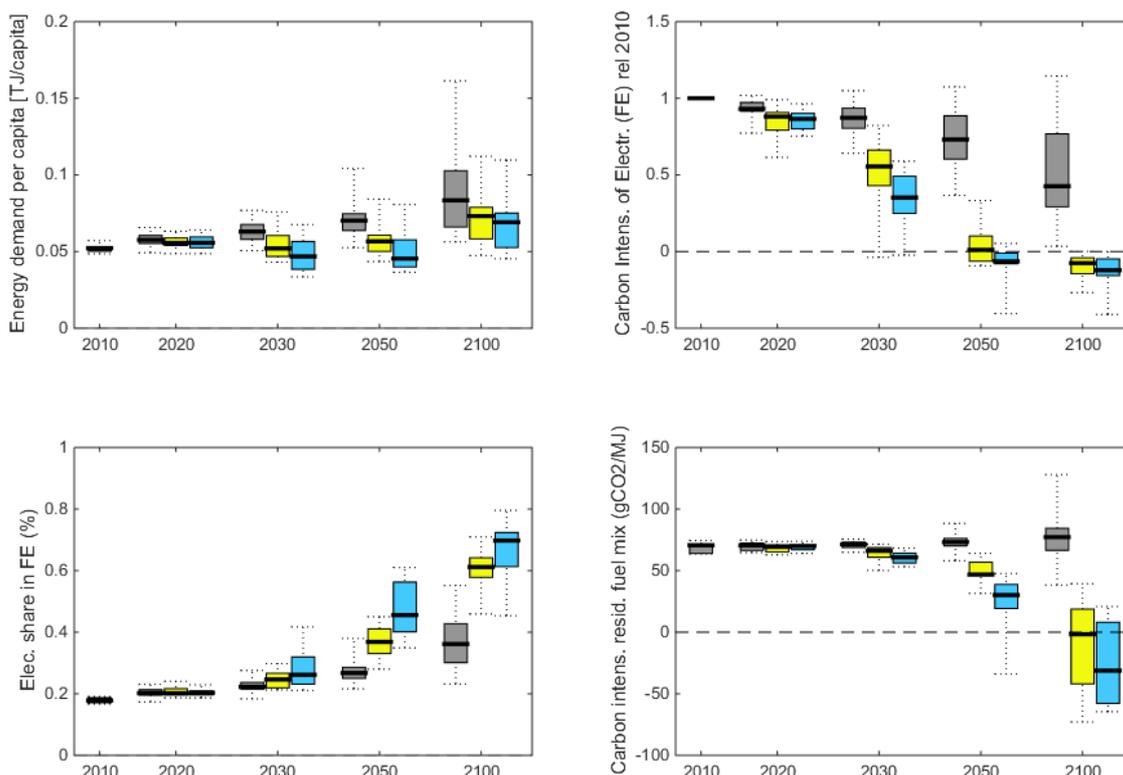
36
37 The wide range of possibilities in terms of technological and societal assumptions thus leads to a wide
38 variety of potential pathways in line with 1.5°C. Figure 2.5 illustrates three potential pathway types based on
39 the green-growth (SSP1), middle-of-the-road (SSP2), and energy intensive fossil-fuelled (SSP5) narratives
40 of the SSPs (Riahi et al. 2017; O'Neill et al. 2017). Baseline per capita energy and food demand between the
41 scenarios varies by a factor of two in the second half of the century, a difference which remains in the
42 accompanying 1.5°C scenarios. The differences in societal drivers also lead to significantly different
43 evolutions of emissions over time, as well as configurations of the energy supply system. Wherever possible,
44 this chapter will highlight key pathway types that illustrate the various societal choices and their
45 consequences.

46 47 48 *2.3.1.2 General characteristics of 1.5°C pathways*

49 1.5°C and well below 2°C transition pathways are characterised by large-scale transformations of the energy,
50 industry, and land sector (Popp et al. 2017; Bauer et al. 2017; Riahi et al. 2017). Four contributing factors or
51 macro decarbonisation indicators can help to understand the structure of the energy (including transportation
52 and buildings) and industry transformations: reductions in per capita energy demand, reductions in the
53 carbon intensity of electricity, an increasing share of final energy being provided by electricity, and
54 reductions in the carbon intensity of the residual fuel mix, each of which are affected by scenario
55 assumptions. Figure 2.6 illustrates how these general trends shift between baseline scenarios and 1.5°C and
56 2°C scenarios. 1.5°C pathways show a general fast transition until mid-century and a slower, more sustained
57 evolution thereafter. In this section we focus on the first fast near-term transition phase of 1.5°C pathways,

1 while Section 2.4 assesses the implications for the second half of the century.

2
3 In general, 1.5°C and 2°C pathways are similar in their evolution of macro indicators for decarbonisation,
4 both having to comply with a stringent carbon budget. However, the largest differences between 1.5°C and
5 2°C pathways are particularly seen in the first half of the century, where 1.5°C pathways show a stronger
6 reduction of per capita energy demand, a faster in electrification of energy end use, and a faster
7 decarbonisation of the carbon intensity of electricity and of the residual fuel mix (that is, the fuel mix which
8 does not contribute to the production of electricity in the energy system).
9
10



11
12 **Figure 2.6:** Decomposition of transformation pathways in energy demand per capita reductions (top left: TJ of final
13 energy per capita), carbon intensity of electricity (top right: Electricity CO₂ over Electricity in Final
14 Energy), the electricity share in final energy (bottom left), and the carbon intensity of the residual (non-
15 electricity) fuel mix (bottom right). Scenarios from the SSP scenario ensemble. This figure will be
16 updated as more studies become available.
17

18 Energy demand reduction are a key characteristic of 1.5°C pathways. Limiting energy demand results in an
19 overall smaller energy system and therewith facilitates the transition to a low-carbon society (Clarke et al.
20 2014). Energy demand reductions are particularly important because end-use efficiency improvements are
21 able to leverage upstream energy reductions which can be several times to an order of magnitude larger than
22 the initial end-use demand reduction. This is immediately clear when comparing useful energy output for a
23 particular service category to the associated primary energy input (see data in De Stercke 2014). The more
24 demand can be limited, the more flexible supply side mitigation measures can be combined to decarbonise
25 the overall system. Across the wide range of scenarios available to this assessments, reductions relative to
26 baseline energy demand are remarkably similar. In general 1.5°C scenarios see a reduction in final energy
27 demand in the order of 20% (median, interquartile range 13-30%) and 30% (23-42%) relative to a no-climate
28 policy baseline in 2030 and 2050, respectively, compared to 10% (6-19%) and 20% (15-25%) in 2°C
29 pathways. This results in absolute final energy demand levels of 376 EJ yr⁻¹ (314-456 EJ yr⁻¹) and 417 EJ yr⁻¹
30 (348-492 EJ yr⁻¹) in 2030 and 2050, respectively, compared to 356 EJ yr⁻¹ in 2010 (see Figure 2.7).
31

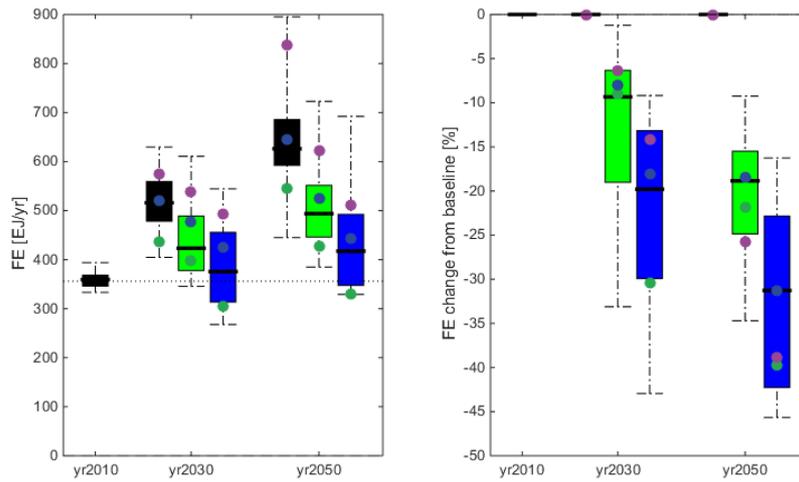
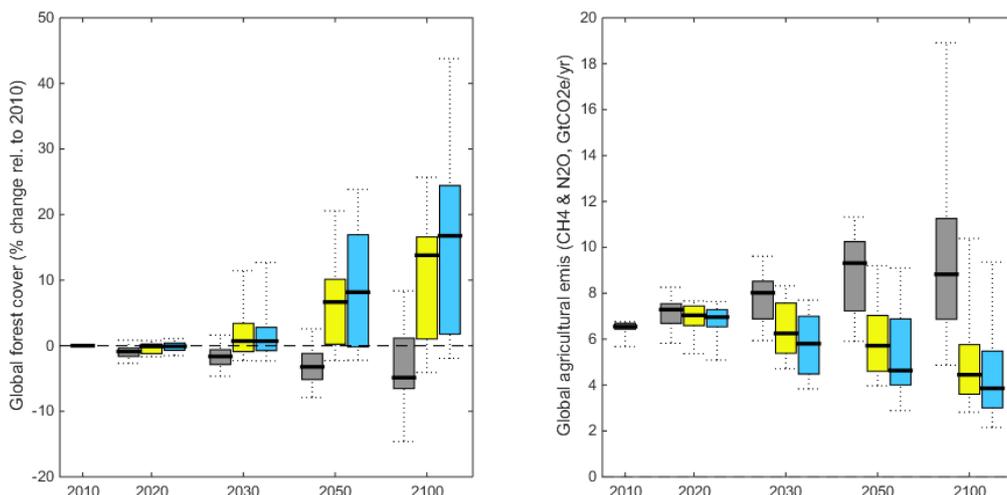


Figure 2.7: Overview of final energy (FE) demand evolution in baselines (black), 2°C scenarios (2.6 Wm⁻² scenarios, green), 1.5°C scenarios (1.9 Wm⁻² scenarios, blue). Ranges show the minimum-maximum range. Dots indicate single scenarios. Data from (Riahi et al. 2017; Rogelj et al. 2017a). (Note: these ranges will be updated as more studies and scenarios are submitted and become available for assessment. In further iterations, this figure will use the pathway typologies introduced in Section 2.2.) (left) absolute final energy demand; (right) final energy demand reductions relative to a no-climate policy baseline. Dots represent key pathway types which are chosen to represent varying challenges to mitigation in Figure 2.5. Green: SSP1 (IMAGE model), blue: SSP2 (MESSAGE-GLOBIOM model), purple: SSP5 (REMIND-MAGPIE model).

An important further aspect of global transformation pathways is the role of the agricultural and land system (Popp et al. 2017). This system is responsible both for food and feed production and for the production of biomass for energy or other uses. The demand level 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 future evolutions with 1.5°C pathways showing options in which global forest cover is approximately kept constant and options in which it is increased by 20% or more due to afforestation and reforestation measures (Figure 2.8). 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 greenhouse gas emissions from agriculture or, under alternative societal choices, while keeping forest cover approximately constant and higher, yet still decreasing agricultural greenhouse gas emissions until 2100. Furthermore, the agricultural system is also characterised by sizeable amounts of very hard to eliminate residual non-CO₂ emissions (Figure 2.8) (Gernaat et al. 2015). These increase in their relative importance in very stringent mitigation pathways. Limiting demand for greenhouse gas-intensive foods is thus a key through shifts to healthier and more sustainable diets and lifestyles that limit food waste (Popp et al. 2017).



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30

31

1 **Figure 2.8:** Overview of land-use related transitions in transformation pathways. Change in global forest cover
2 relative to 2010 (left panel) and global agricultural GHG emissions of CH₄ and N₂O (right panel,
3 aggregated with the AR4 GWP-100 metric). Scenarios from the SSP scenario ensemble. Highlighted
4 archetypes are colour-coded in the same way as in Figure 2.17.
5
6

7 2.3.1.3 *Mitigation options in 1.5°C pathways*

8 Transformation pathways assessed in this section have been developed by global integrated assessment
9 models that represent key societal systems and their interactions, like the energy system, the land system,
10 and the economy (see Section 6.2 in Clarke et al. 2014). Very often these models also include interactions
11 with a representation of the geophysical system, for example, by including spatially explicit land models or
12 carbon-cycle and climate models. The complex features of these subsystems are approximated and simplified
13 in these models. IPCC AR5 provided an overview of how differences in model structure can influence the
14 outcome of transformation pathways (see Section 6.2 in Clarke et al. 2014). These insights also apply here.
15 Furthermore, in the context of ambitious 1.5°C transformation pathways, the portfolio of mitigation options
16 available to the model also becomes increasingly important. Integrated assessment models include a wide
17 variety of supply- and demand-side mitigation options, as well as measures that achieve CDR from the
18 atmosphere (see also Chapter 4 for a bottom-up discussion of these mitigation technology option). Integrated
19 assessment models cover most of the supply-side mitigation options and demand-side options are either
20 integrated in the model or part of the underlying assumptions, which can be varied (Table 2.5). CDR options
21 are much more speculative and are therefore typically only partially included in integrated assessment model
22 analyses.

1 **Table 2.5:** Taxonomy of mitigation options for 1.5°C transformation pathways. Options available in the scenarios assessed in this section are colour-coded blue; options available
 2 in some models, but not necessarily in the scenarios assessed here are colour-coded yellow; potential mitigation options currently not typically included in integrated
 3 assessment model analyses are colour-coded white.
 4

SUPPLY SIDE MEASURES	DEMAND SIDE MEASURES	Greenhouse gas removal
<i>Decarbonisation of Electricity</i>	<i>Energy demand reductions</i>	
Bio-electricity, including biomass co-firing	Energy efficiency improvements in energy end uses (appliances in buildings, engines in transport, industrial processes)	Afforestation / Reforestation
CCS at coal and gas-fired power plants	Higher share of useful energy in final energy (e.g., insulation of buildings, lighter weight vehicles, coupled heat and power, ...)	Changing agricultural practices enhancing soil carbon
Nuclear energy	Reduced energy and mobility service demand (via behavioural change, reduced material and floor space demand, infrastructure and buildings configuration, modal shift in individual transportation) Models mostly represent price and income elasticity of energy (service) demand	Biochar and soil carbon enhancement
High-temperature geothermal heat		Restoration of peat- and wetlands
Solar PV	Other demand reductions	Biomass use for energy production with carbon capture and storage (BECCS) (either combustion or fermentation)
Solar CSP	Reduced material demand via higher resource efficiency, structural change, behavioural change and material substitution (e.g., steel and cement)	Direct air capture (DAC) of CO ₂ using chemical solvents
Wind (on-shore and off-shore)		Mineralization of atmospheric CO ₂ through enhanced weathering of rocks
Hydro power		Ocean iron fertilization
Tidal energy		Ocean alkalisation
<i>Decarbonisation of non-electric fuels</i>	<i>Electrification of Demand</i>	Carbon Capture and Usage – CCU; bioplastics, carbon fibre
Biofuels	Transport: Electric vehicles, electric rail ...	Removing CH ₄ , N ₂ O and halocarbons via photocatalysis from the atmosphere

Hydrogen	Buildings: Heat pumps, electric stoves ...	
Power-to-gas, methanisation, synthetic hydrocarbons	Buildings: Heat pumps, electric stoves ...	
Artificial photosynthesis to hydrogen and other chemical bonds	Industry: Electric arc furnace ...	
CCS in industrial process applications (cement, pulp and paper, iron steel, oil and gas refining, chemicals)		
solar and geothermal heating		
Substitution of F-gases		
reduced gas flaring and leakage in extractive industries, reduced gas leakage from pipelines		
Replacing fossil fuels by electricity in end-use sectors		
<i>Land use supply options</i>	<i>Land use demand options</i>	
Methane reductions in ruminants, rice paddies etc.	Dietary changes, reduction of food waste	
Livestock and grazing management, protein feed, synthetic meat, Increasing agricultural productivity, substitution of nitrogen with mineral fertilizer	Reduced deforestation	
	Fertilizer reduction / increasing nitrogen fertilizer efficiency, reduced land degradation	

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

A wide variety of pathways can be consistent with limiting global mean temperature increase to 1.5°C relative to preindustrial levels. However, despite their diversity, these pathways also share key characteristics. Table 2.6 provides a list of characteristics that are based on the assessment in the remainder of this chapter.

Table 2.6: Overview of key characteristics of 1.5°C pathways and differences compared to 2°C pathways. Reported values give the median and the interquartile range between brackets, or the interquartile range only (if only a range is given).

Characteristic in 1.5°C pathways	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 2.3.4.1
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 2.3.4.2
Energy efficiency improvements are a crucial enabling factor for 1.5°C	Particularly until 2050 per capita energy demand is strongly tempered in 1.5°C pathways, leading to final energy demand reductions in the order of 20% (13-30%) and 30% (23-42%) relative to a no-climate policy baseline in 2030 and 2050, respectively, compared to 10% (6-19%) and 20% (15-25%) in 2°C pathways.	Section 2.3.1
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 2.3.4
Comprehensive emission reductions are implemented in the coming decade	Net annual CO ₂ emissions are reduced to 18-30 GtCO ₂ yr ⁻¹ by 2030 and 0-4 GtCO ₂ yr ⁻¹ in 2050, reaching carbon neutrality shortly thereafter, from 2015 levels of about 41 GtCO ₂ yr ⁻¹ (Le Quéré et al. 2016). GHG emissions are reduced to 25-41 and 5-11 GtCO ₂ -eq yr ⁻¹ in 2030 and 2050, respectively. Studies that have attempted to reach 1.5°C scenarios from higher level indicate many failed attempts.	Section 2.3.3
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 a very large proportion of the non-CO ₂ mitigation potential is already fully deployed for reaching a 2°C pathway.	Section 2.3.3
Considerable shifts in investment patterns	1.5°C pathways indicate annual average low-carbon energy investments in wind and solar from 2010 to 2030 of the order of 60-150 and 30-120 billion USD yr ⁻¹ (interquartile range) while investments in fossil fuel electricity and extraction decline steadily until 2050. Energy demand investments are an additional critical factor for which total estimates are difficult to define.	Section 2.3.4.4
SDG interactions	Highlighting major synergies in the area of and risks of trade-offs depending on the chosen mitigation portfolio	Section 2.5
CDR at scale before mid-century	By 2050, 1.5°C pathways project deployment of BECCS at a scale of 4-11 GtCO ₂ yr ⁻¹ (interquartile range), depending on the level of energy demand reductions and mitigation in other sectors. Some scenarios are available with lower deployment levels in the order of 1 GtCO ₂ yr ⁻¹ in 2050.	Section 2.3.3 Section 2.3.4.1

12

2.3.3 Emissions evolution

Anthropogenic greenhouse gas emissions are the main driver of global warming (IPCC 2013), and to limit global-mean temperature rise to 1.5°C during this century (see Section 2.2) they are strongly reduced. Scenarios show reductions in both CO₂ and non-CO₂ greenhouse gases until 2050, with CO₂ contributing most to the overall reduction. Global greenhouse gas emissions peak and start declining by 2030 in typical scenarios available in the literature (Sanderson et al. 2016; Su et al. 2017; Walsh et al. 2017; Rogelj et al. 2015a). Here we assess the salient temporal evolutions of the various climate altering emissions in 1.5°C scenarios until mid-century.

Global CO₂ emissions embark on a steady decline reaching net zero by 2050 or shortly thereafter. This overall evolution of net CO₂ emissions is achieved in scenarios through a combination of various both compensating and reinforcing anthropogenic contributions: (a) CO₂ generation by fossil fuel combustion and industrial processes, (b) CO₂ emissions or removals from land-use, land-use change, and forestry, (c) engineering sinks where CO₂ from fossil fuels or industrial activities is captured and permanently stored in geological formations before it can be released to the atmosphere (i.e., fossil CCS), (d) CO₂ removal by capturing CO₂ (absorbed from the atmosphere during the growth of biomass) at the time it is combusted or processed in a centralised plant and storing it permanently (BECCS), amongst others. Despite all reaching net CO₂ emissions levels in 2050 that are close to zero, scenarios apply these four contributions in very 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. 2017a). Figure 2.9 shows an overview of the varying evolutions of each of these contributors in 1.5°C scenarios and in comparison to 2°C and no-climate policy baseline scenarios, with key statistics reported in Table 2.7.

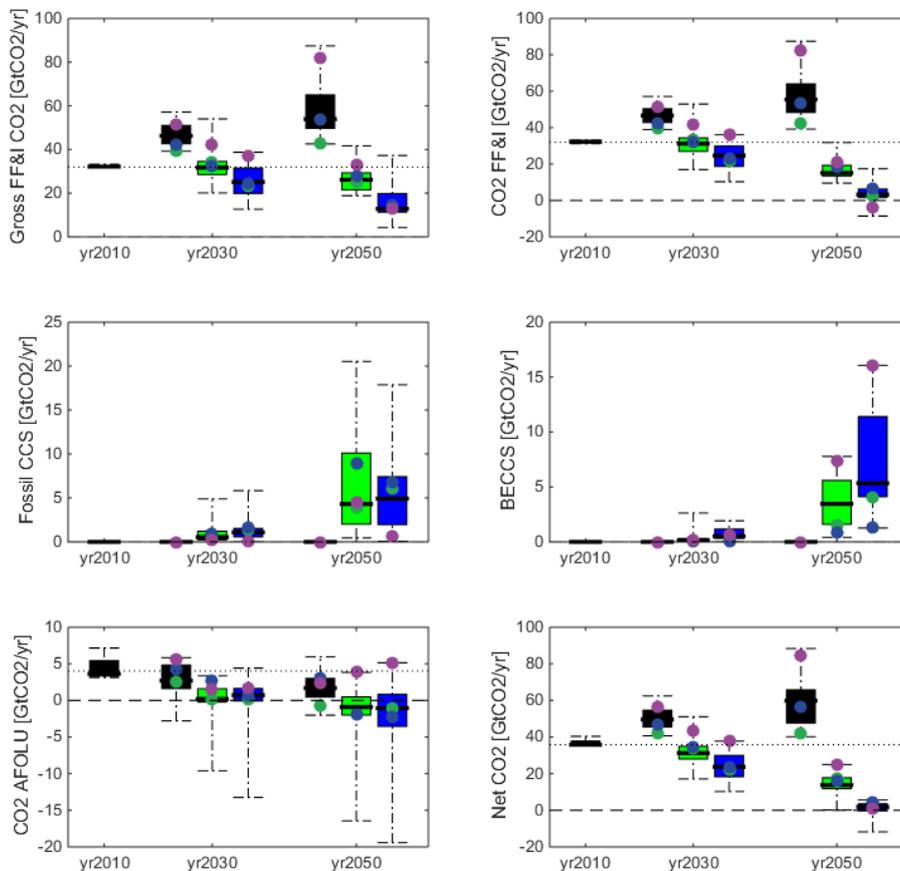


Figure 2.9: Evolution and break down of global CO₂ emissions until mid-century in no-climate policy baselines (grey), 2°C scenarios (2.6 Wm⁻² scenarios, green), 1.5°C scenarios (1.9 Wm⁻² scenarios, blue). Ranges show the minimum-maximum range. Dots indicate single scenarios. Data

1 from (Riahi et al. 2017; Rogelj et al. 2017a). (Note: these ranges will be updated as more studies
 2 and scenarios are submitted and become available for assessment). The various panels show: (top-
 3 left) gross CO₂ emissions from fossil fuel and industrial activities (computed by adding the annual
 4 amounts of total CCS, i.e., BECCS and FossilCCS, to the total net reported CO₂ emissions and
 5 subtracting CO₂ emissions from land use, land-use change, and forestry), (top-right) net CO₂
 6 emissions from fossil fuel and industrial activities, (middle-left) CO₂ captured and stored from
 7 fossil fuels and industrial activity by CCS, (middle-right) CO₂ removal by BECCS, (bottom-left)
 8 CO₂ emissions from land use, land-use change, and forestry, and (bottom-right) net global CO₂
 9 emissions. In further iterations, this figure will use the pathway typologies introduced in Section
 10 2.2. Dots represent key pathway types which are chosen to represent varying challenges to
 11 mitigation. Green: SSP1 (IMAGE model), blue: SSP2 (MESSAGE-GLOBIOM model), purple:
 12 SSP5 (REMIND-MAGPIE model).

13
 14 Studies regularly use emission reduction rates to compare the anticipated emissions reductions of
 15 mitigation scenarios with abatement achieved in the past (van Vuuren and Stehfest 2013; Riahi et al.
 16 2015; van Sluisveld et al. 2015). Compound annual growth rates (the annual percentage change
 17 compared to the previous year) have been used in most of the cases. This functional form, however, is
 18 not appropriate to describe emissions evolutions in which emissions reach net zero levels or become
 19 negative, which is the case, for example, for net CO₂ emissions or AFOLU CO₂ emissions. Therefore,
 20 we here report annual absolute emissions reductions instead, see Table 2.7.

21
 22 The three pathway types highlighted in Figure 2.9 illustrate different configurations by means of the
 23 SSP markers. In a scenarios that models an inclusive world developing along a low demand trajectory
 24 (SSP1, illustrative green dot in Figure 2.9) baseline CO₂ emissions from fossil fuel and industry are
 25 the lowest, compared to the two other pathways which model a middle-of-the-road (SSP2: blue dot
 26 Figure 2.9) and an energy intensive and technologically focused society with extensive exploitation of
 27 fossil fuels in the baseline (cf. SSP5, purple dot in Figure 2.9. Also baseline AFOLU CO₂ emissions
 28 differ strongly by 2050, being positive in the SSP2 and SSP5 marker but negative in SSP1. These
 29 variations between emission pathways imply important differences in the challenge of achieving a
 30 1.5°C mitigation pathway (Rogelj et al. 2017a). For example, the cumulative mitigation over the 21st
 31 century required to move from a no-climate policy baseline to a 1.5°C consistent scenario varies by a
 32 factor 2 to 3 between SSP1 and SSP5. Moreover, these very diverse baseline emissions are in turn
 33 mitigated by very diverse strategies: by focusing on demand reductions and sustainable lifestyles
 34 (SSP1), by supply-side technology driven solutions (SSP5), or by taking a middle-of-the-road
 35 perspective in line with historical societal dynamics (SSP2). Consequentially, particularly the
 36 projected deployment of BECCS until mid-century varies drastically across the three pathway types
 37 highlighted here, with 2050 levels of about 4, 1, and 16 GtCO₂ yr⁻¹ in the SSP1, SSP2, and SSP5
 38 marker, respectively.

39
 40 **Table 2.7:** Emissions levels in 2010, 2030, and 2050 for no-climate policy baselines, 2°C scenarios (2.6 Wm⁻²
 41 scenarios), and 1.5°C scenarios (1.9 Wm⁻² scenarios), and annual rate of change between 2010 and
 42 2030, and 2030 and 2050, respectively. Data from (Riahi et al. 2017; Rogelj et al. 2017a). [Note:
 43 these ranges will be updated as more studies and scenarios are submitted and become available for
 44 assessment].] Values show: 25th percentile, median, 75th percentile, across all available scenarios.
 45 This scenario set will be expanded for the Second Order Draft with forthcoming scenarios. Note
 46 that expressing emissions reductions as compound annual growth rates as in IPCC AR5 WG3
 47 Chapter 6 cannot be applied here due to the presence of negative emissions values. Net GHG
 48 emissions are expressed in units of CO₂-equivalence computed with 100-year Global Warming
 49 Potentials reported in IPCC AR4.

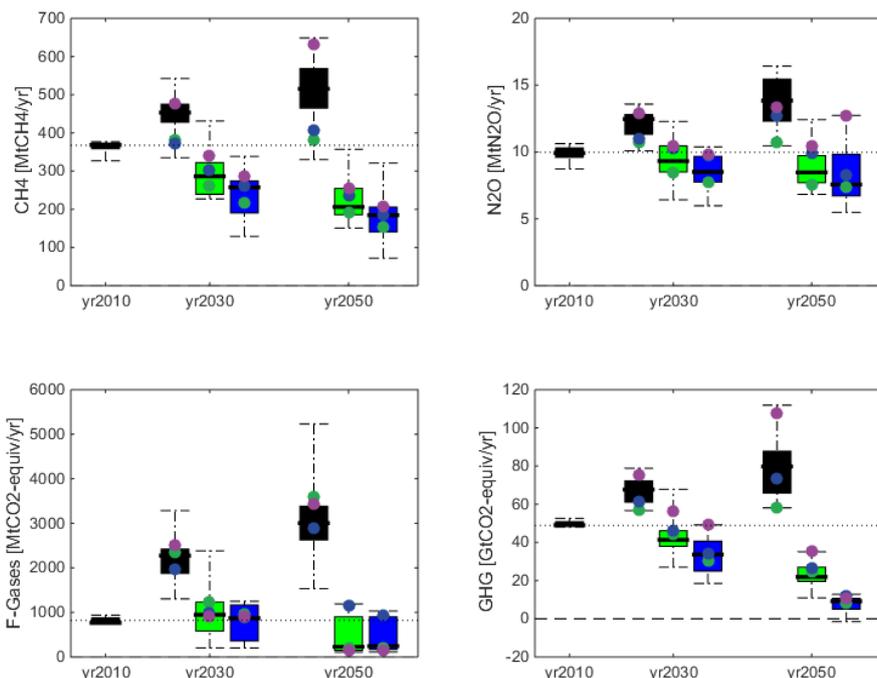
Emissions	Scenario set	2010	2030	2050	Annual rate of change 2010-2030	Annual rate of change 2030-2050

		[Gt CO ₂ yr ⁻¹]	[Gt CO ₂ yr ⁻¹]	[Gt CO ₂ yr ⁻¹]	[Gt CO ₂ yr ⁻²]	[Gt CO ₂ yr ⁻²]
Gross CO ₂ FF&I	Baseline	32/32.2/32.6	42.7/46.3/51	49.7/53.9/65	0.5/0.7/0.9	0.3/0.5/0.6
	2.6 Wm ⁻²	32/32.2/32.6	28.5/31.7/34.6	21.5/26.2/29.3	-0.2/0/0.3	-1.1/-1/-0.7
	1.9 Wm ⁻²	32/32.2/32.6	19.9/25.1/31.5	11.3/12.9/19.8	-0.5/-0.3/0	-1.7/-1.5/-1.3
Net CO ₂ FF&I	Baseline	32/32.3/32.6	42.8/46.6/50.4	48.3/55.4/64.1	0.5/0.7/0.9	0.3/0.5/0.6
	2.6 Wm ⁻²	32/32.2/32.6	27/31.2/34.4	13.4/15.1/19.3	-0.3/-0.1/0.1	-1.8/-1.5/-1.2
	1.9 Wm ⁻²	32/32.2/32.6	18.7/24.7/29.9	1.6/3.2/6.3	-0.7/-0.4/-0.1	-2.4/-2/-1.8
CO ₂ LULUCF	Baseline	3.3/3.6/5.4	1.6/2.7/4.8	0.5/1.7/3	-0.1/-0.1/-0.1	-0.1/-0.1/0
	2.6 Wm ⁻²	3.3/3.6/5	-0.2/0.2/1.6	-2/-0.9/0.5	-0.2/-0.2/-0.2	-0.3/-0.2/-0.1
	1.9 Wm ⁻²	3.3/3.6/4.8	-0.1/0.7/1.6	-3.5/-1.1/0.9	-0.2/-0.2/-0.1	-0.4/-0.2/-0.1
Fossil CCS	Baseline	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
	2.6 Wm ⁻²	0/0/0	0.2/0.5/1.2	2/4.3/10.1	0/0/0.1	0.1/0.2/0.4
	1.9 Wm ⁻²	0/0/0	0.6/1.1/1.5	2/4.9/7.4	0/0.1/0.1	0.1/0.1/0.3
BECCS	Baseline	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
	2.6 Wm ⁻²	0/0/0	0/0.2/0.3	1.6/3.5/5.6	0/0/0.1	0.1/0.2/0.3
	1.9 Wm ⁻²	0/0/0	0.3/0.5/1.2	4.1/5.3/11.4	0/0/0.1	0.2/0.3/0.6
Net CO ₂	Baseline	35.6/35.8/37.8	45.5/49.6/54.6	47.7/59.8/65.8	0.4/0.7/0.9	0.2/0.4/0.6
	2.6 Wm ⁻²	35.6/35.8/37.2	28/31.2/35	11.8/13.8/17.8	-0.5/-0.3/-0.1	-1.9/-1.6/-1.4
	1.9 Wm ⁻²	35.6/35.8/36.8	18.4/23.7/29.9	-0.4/1.8/3.6	-0.9/-0.8/-0.3	-2.7/-2.2/-2
Net GHG	Baseline	48.4/49.1/50.9	61.1/67.7/72.3	65.9/79.8/87.8	0.6/0.9/1.1	0.3/0.6/0.8
	2.6 Wm ⁻²	48.4/49.1/50.5	38/41.4/46.1	19.6/21.9/27	-0.6/-0.4/-0.2	-2.4/-2.1/-1.7
	1.9 Wm ⁻²	48.4/49.1/50.4	25/33.6/40.6	5/9.2/10.7	-1.2/-0.9/-0.5	-3.2/-2.7/-2.5

1
2 Stringent mitigation pathways are characterised by emissions reductions of all GHGs (Clarke et al.
3 2014). Despite the limited mitigation options for some non-CO₂ GHG emissions (particularly the case
4 for N₂O, see Figure 2.10) (Gernaat et al. 2015), global GHG emissions are reduced strongly by about
5 80% relative to their 2010 levels in 2050. Net CO₂ emissions in 2030 and 2050 are markedly lower in
6 1.5°C scenarios than in 2°C scenarios. This is much less the case for methane (CH₄) and nitrous-oxide
7 (N₂O) emissions. AR5 identified two primary factors that influence the depth and timing of reductions
8 in emissions of non-CO₂ Kyoto gases: (1) the abatement potential and costs of reducing the emissions
9 of these gases and (2) the strategies that allow making trade-offs between them (Clarke et al. 2014).
10 Many studies indicate many low-cost mitigation options for non-CO₂ gases in the near term compared
11 to supply side measures for CO₂ mitigation (Clarke et al. 2014). A large share of this potential is hence
12 already exploited in weaker mitigation scenarios in line with 2°C. At the same time, by mid-century
13 and beyond, the emissions reductions of non-CO₂ Kyoto gases, in particular CH₄ and N₂O, are
14 hampered by the residual emissions of several hard-to-mitigate emissions sources linked to livestock
15 production and fertilizer use (Clarke et al. 2014; Gernaat et al. 2015). This results in reductions of CO₂
16 taking up the largest share of emissions reductions when moving between a 1.5°C and a 2°C pathway.
17
18 Besides CO₂ and other well-mixed GHGs, radiatively active particles (aerosols) and their precursors as
19 well as ozone precursors are strongly mitigated in 1.5°C scenarios. The particles include both types
20 that cause warming and cooling, whereas ozone (in the troposphere) causes warming (Myhre et al.
21 2013). Reductions in aerosols can have substantial benefits for decreasing regional climate disruptions
22 and reductions in both surface aerosols and ozone also provide health co-benefits as air pollution is
23 reduced (Shindell et al. 2012; Anenberg et al. 2012). In some cases, important sources of these air

1 pollutants such as traditional biomass burning stoves or kerosene lamps would be unaffected by
 2 climate policies. The overall reduction in emissions of these short-lived climate forcers can have
 3 effects of either sign on temperature depending on the balance between cooling and warming agents,
 4 prompting suggestions to target the warming agents (referred to as short-lived climate pollutants or
 5 SLCPs; e.g., (Shindell et al. 2012). In terms of their global climate effects, however, reductions are
 6 already so strong in stringent mitigation scenarios in line with 1.5°C that estimated additional climate
 7 cooling from measures that aim at reducing warming aerosols would be very limited (Rogelj et al.
 8 2014a). Because the dominant sources of warming aerosol mixtures are emitted during the combustion
 9 of fossil fuels (Bond et al. 2013), the rapid phase-out of unabated fossil-fuels would also result in
 10 removal of these short-lived climate forcers. Some caveats apply, e.g., if residential biomass use
 11 would be encouraged in industrialised countries in stringent mitigation pathways without appropriate
 12 pollution control measures, aerosol concentrations could also increase. Similarly, many proposed
 13 measure to target the shorter-lived GHG methane are included in 1.5°C scenarios (Figure 2.10; though
 14 some, such as intermittent irrigation of rice paddies, not always). Hence as pointed out previously,
 15 both 2°C and 1.5°C scenarios require large reductions in short-lived climate forcers. In such cases, the
 16 large reduction in mainly cooling aerosol precursors (sulphur dioxide and nitrogen dioxide) can results
 17 in additional warming, making reduction of all SLCF components all the more imperative to keep
 18 near-term global mean temperature rise limited. Action on SLCPs has also been suggested to facilitate
 19 achievement of the sustainable development goals (Shindell et al. 2017a). Public health benefits of
 20 stringent mitigation pathways in line with 1.5°C can be sizeable and potentially larger than the initial
 21 mitigation costs (West et al. 2013).

22
23



24
 25 **Figure 2.10:** Evolution global GHG emissions until mid-century in no-climate policy baselines (grey), 2°C
 26 scenarios (2.6 Wm⁻² scenarios, green), 1.5°C scenarios (1.9 Wm⁻² scenarios, blue). Ranges show
 27 the minimum-maximum range. Dots indicate single scenarios. Data from (Riahi et al. 2017; Rogelj
 28 et al. 2017a). [Note: these ranges will be updated as more studies and scenarios are submitted and
 29 become available for assessment.] The various panels show: (top-left) CH₄ emissions, (top-right)
 30 N₂O emissions, (bottom-left) F-gas emissions, (bottom-right) net global total GHG emissions. Net
 31 GHG emissions are expressed in units of CO₂-equivalence computed with 100-year Global
 32 Warming Potentials reported in IPCC AR4. In further iterations, this figure will use the pathway
 33 typologies introduced in Section 2.2.

34
35
36

2.3.4 *Disentangling the whole-system transformation*

2.3.4.1 *Energy*

Energy transitions play a key role in low CO₂ emission pathways (Clarke et al. 2014; Bruckner et al. 2014). In mitigation pathways consistent with the 1.5°C target, a rapid transition towards a zero or negative CO₂ emission energy system is crucial (Rogelj et al. 2015a). Compared with the 2°C threshold, both the pace and magnitude of the energy transition are more rapid under the 1.5°C target. Two aspects are typically emphasised in 1.5°C pathways: one is rapid growth in the share of energy derived from low carbon sources including renewables, nuclear, and fossil fuel with CCS, the other is BECCS which can provide carbon dioxide removal. For both aspects, the rate of change and the required spending are important potential hurdles.

2.3.4.1.1 *Evolution of primary energy contributions over time*

Based on the mitigation pathways consistent with the 1.5°C target from the scenario database, CO₂ 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 2.8). By 2050, renewable energy provides more than half of total primary energy (Figure 2.11), with the largest portion from biomass fuels. 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.

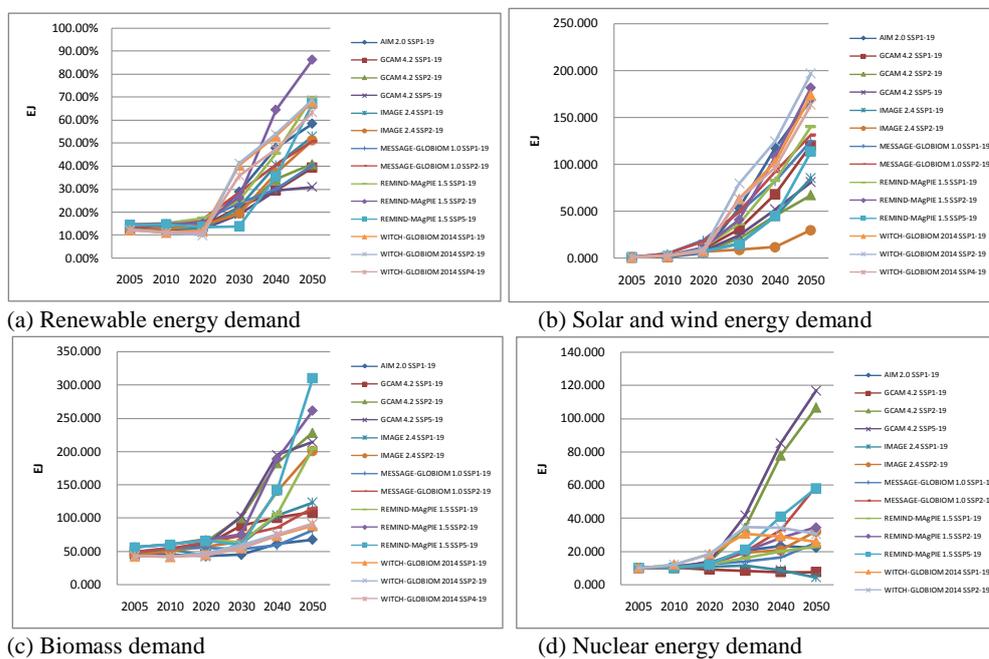
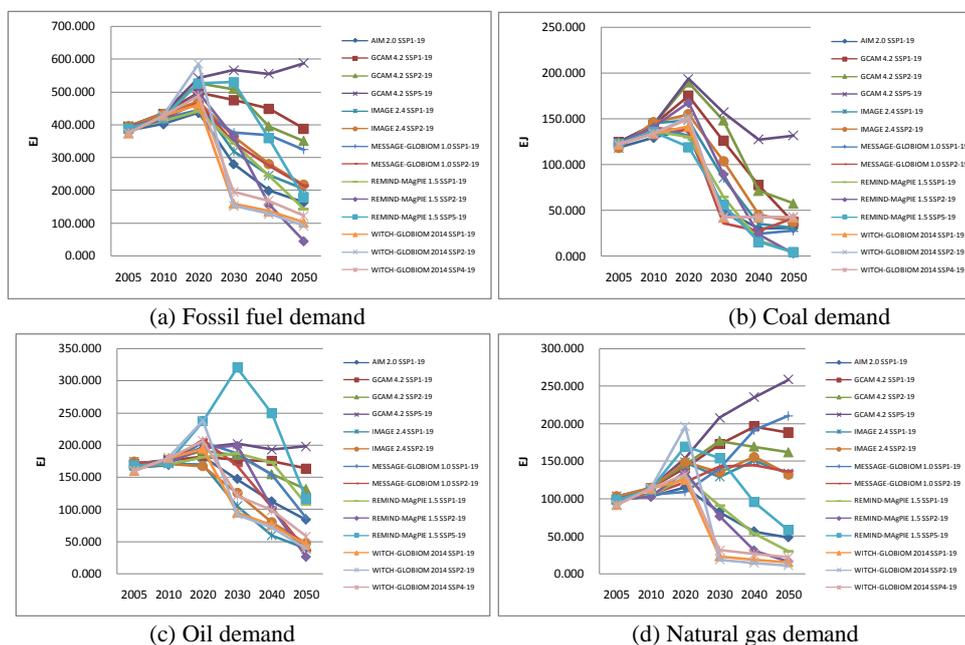


Figure 2.11: Low carbon energy penetration in 1.5°C scenarios. Data from (Riahi et al. 2017; Rogelj et al. 2017a). 1.9 W m-2 scenarios are taken as a proxy for 1.5°C scenarios.

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. Before 2050, Natural gas is more complex, with demand through 2050 highly diverse across scenarios. Some show rapid decreases after 2020, whereas in others demand continues

1 increasing through 2050 (see Figure 2.12). Scenarios with higher demand for natural gas adopt CCS
 2 for natural gas use. Like coal, oil demand decreases in these scenarios and its share of global primary
 3 energy drops by more than half.
 4



7
 8
 9 **Figure 2.12:** Fossil fuel energy demand transition in 1.5°C scenarios. Data from (Riahi et al. 2017; Rogelj et al.
 10 2017a). 1.9 W m-2 scenarios are taken as a proxy for 1.5°C scenarios.

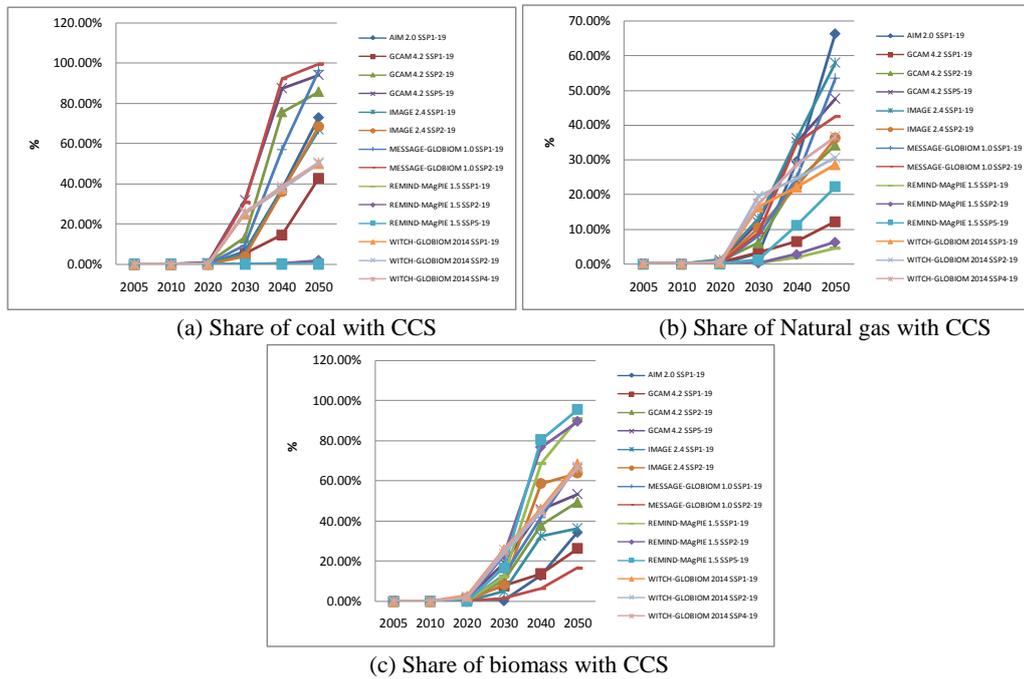
11
 12
 13 **Table 2.8:** Overview of energy supply system transformation characteristic. Data from (Riahi et al. 2017;
 14 Rogelj et al. 2017a). (Note: these ranges will be updated as more studies and scenarios are
 15 submitted and become available). Values indicate means, bracketed values the minimum maximum
 16 range.

	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 (1.0 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%

17
 18
 19 **2.3.4.1.2 Deployment of CCS**

20 Deployment of CCS plays a very important role in CO₂ emission reductions in mitigation pathways
 21 consistent with 1.5°C. The carbon budget limitation requires a rapid implementation of CCS, soon
 22 after 2020. In scenarios with substantial remaining use of coal for energy, the bulk of that usage needs
 23 to be equipped with CCS (Figure 2.13(a)). Specifically, more than 70% (42.7% to 99.6%) of coal will
 24 be equipped with CCS, with an annual 1.1EJ yr⁻¹ increase from 2020 to 2050. Some models consider
 25 the residual emissions that are not captured when using coal with CCS to be too high for 1.5°C
 26 scenarios. These scenarios show very small CCS for coal (for example, the 1.5°C REMIND-MAGPIE
 27 scenarios) and a have very fast phase out of coal use over the next few decades. Similarly to coal,
 28 when natural gas consumption is substantial in these scenarios much of it will be equipped with CCS
 29 after 2020 (see Figure 2.13(c)). By 2050, natural gas with CCS would be 39%, though with a larger

1 spread than for coal. As for coal, scenarios with higher natural gas demand require higher penetration
 2 of CCS, while lower demand scenarios are able to achieve 1.5°C with lower rates of CCS utilisation.
 3
 4



5
6

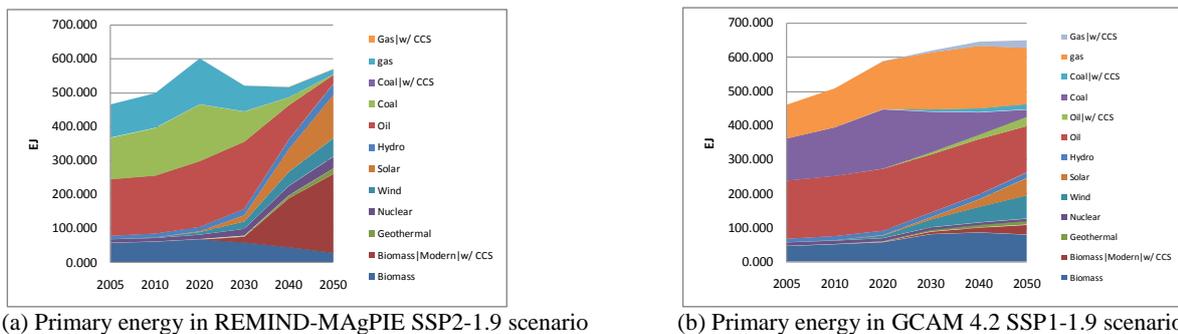
7
8

9 **Figure 2.13:** CCS deployment in 1.5°C scenarios. Data from (Riahi et al. 2017; Rogelj et al. 2017a). 1.9 W m-2
 10 scenarios are taken as a proxy for 1.5°C scenarios.

11

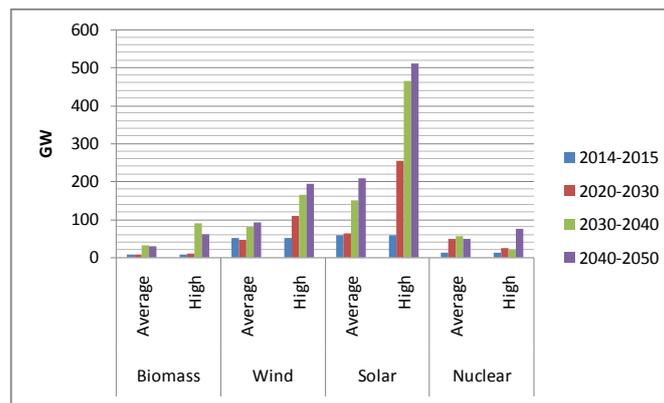
12 In most scenarios, BECCS is a crucial technology in achieving the deep cuts of CO₂ emissions
 13 required for the 1.5°C target. By 2050 BECCS is projected to take up 59% (17% to 95%) of total
 14 biomass demand (see Figure 2.13(c)). Demand for BECCS would be 102 EJ yr⁻¹ (19 EJ yr⁻¹ to 296 EJ
 15 yr⁻¹) by 2050, on average nearly as much as wind and solar combined and nearly half as much as total
 16 fossil fuel energy (and more than worldwide use of oil). Higher reliance on BECCS is associated with
 17 higher fossil fuel demand, which requires much greater CO₂ emissions reductions from BECCS to
 18 compensate for the fossil fuel-related emission. Higher BECCS scenarios hence have less pressure to
 19 rapidly phase out fossil fuel use, but must deploy BECCS at very rapid speeds. Conversely, lower
 20 BECCS scenarios have to phase out fossil fuels more rapidly, and focus on strongly limiting energy
 21 demand. These trade-offs are illustrated in Figure 2.14, showing scenarios with similar carbon budgets
 22 but in one case rapidly increasing the penetration of low carbon power generation such as renewables
 23 and nuclear, and then relying less on BECCS and fossil fuel+CCS, whereas in the other there is a
 24 slower phasing out of fossil fuels accompanied by much more BECCS and fossil fuel+CCS.
 25
 26

27
28



(a) Primary energy in REMIND-MAGPIE SSP2-1.9 scenario

(b) Primary energy in GCAM 4.2 SSP1-1.9 scenario



(c) newly installed capacity per year

Figure 2.14: Variation in primary energy mixes between scenarios (a,b) and newly installed capacity per year (c). 1.9 W m⁻² scenarios are taken as a proxy for 1.5°C scenarios. Newly installed capacity per year for selected sources in 1.5°C scenarios. Data from (Riahi et al. 2017; Rogelj et al. 2017a).

2.3.4.1.3 Pace of change

The power generation sector is the most important sector in the transition, and needs to transform at a rapid rate. Figure 2.14 presents the newly installed capacity per year for each decade until mid-century. Scenarios show a pace of newly installed capacity that goes much beyond today's development pace for all low-carbon power generation sources. Scenarios that rely on a full technology portfolio show that there is not a big increase in annual newly installed capacity for wind, solar and biomass between today and the 2020-2030 period. For nuclear power, however, these full portfolio scenarios assume a departure in near future. After 2030, all new capacity for low carbon power is installed a pace well beyond today's.

2.3.4.2 End-use sectors

2.3.4.2.1 Industry

The industry sector is the largest end-use sector both in terms of final energy demand and greenhouse gas emissions. Its direct CO₂ emissions currently account for about 25% of total man-caused fossil fuel and process CO₂ emissions, and have increased with an average rate of 3.4% between 2000 and 2014, significantly faster than total CO₂ 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 CO₂ emissions inventory. Industry-related emissions come from a large variety of activities. Material industries are particularly energy and emissions intensive: steel, non-ferrous metals, chemicals, non-metallic minerals and chemicals alone account for close to 50% of energy demand (IEA 2014a, 2015a), and 60% of direct industry sector emissions in 2010 (Fischedick et al. 2014). 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; IEA 2017).

Only few studies analysed incremental mitigation efforts in the industry sector for 1.5°C consistent stabilisation compared to those in 2°C pathways (Luderer et al. 2016b; Rogelj et al. 2015a). They suggest that a major share of the additional emission reductions required for 1.5°C stabilisation beyond those in 2°C consistent pathways will have to come from industry. Like other demand sectors, industry contributes a relatively higher share to the additional CO₂ emission reductions for strengthening ambition to 1.5°C, as supply side emissions reductions are almost fully exploited already in 2°C-consistent stabilisation pathways (Rogelj et al. 2017a; Luderer et al. 2016b; Rogelj et al. 2015a).

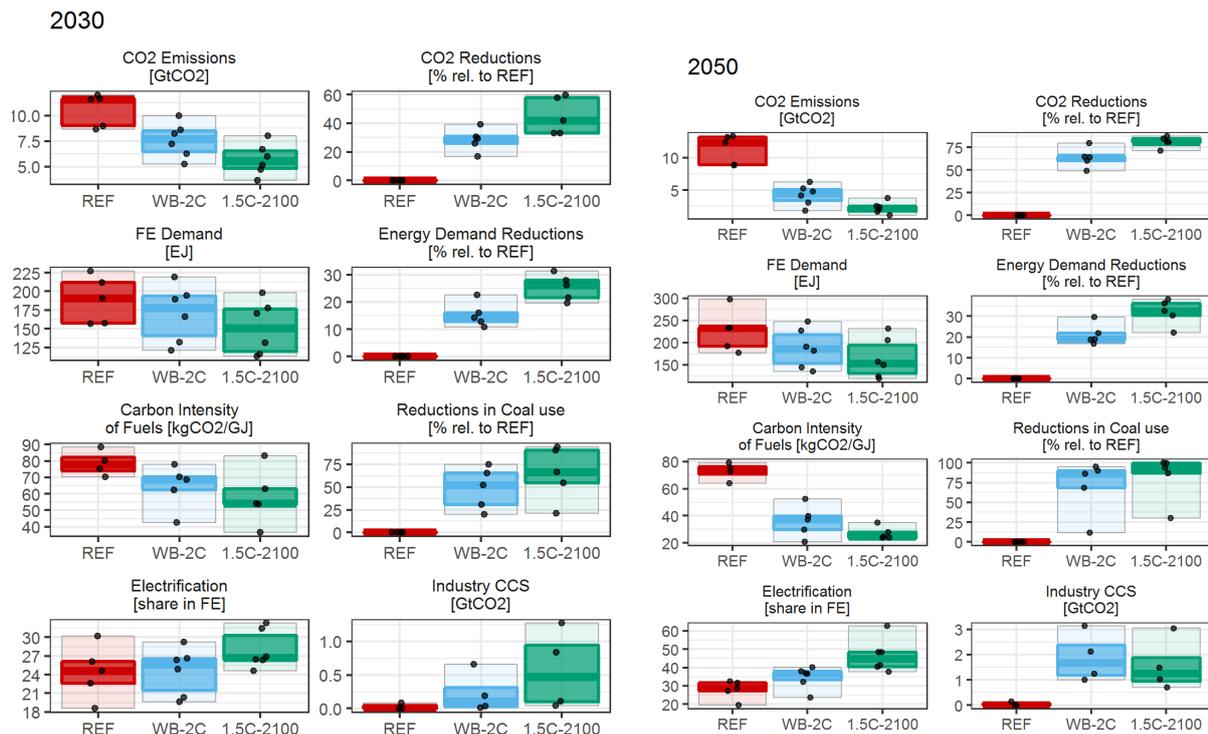


Figure 2.15: Indicators of industry sector mitigation efforts in 2030 (left) and 2050 (right) for reference policy (REF), well below 2°C (WB-2C), and returning to below 1.5°C by the end of the century (1.5C-2100) scenarios assessed in the ADVANCE project (Luderer et al. 2016b).

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 of the fossil carbon content of non-electric fuels, and (v) application of carbon capture and storage. The potential mitigation contributions of these strategies as well as their limitations will be discussed in the following.

[For the current draft, the scenario analysis is based on results from the ADVANCE project as well as IEA Energy Technology Perspectives 2017, and will be expanded to a wider scenario set for SOD.]

(i) 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 (Riahi et al. 2017; Bauer et al. 2017). Beyond consumer demand reductions, material efficiency, i.e., providing material services with less overall material production, can contribute to moderating the industrial metabolism (Allwood et al. 2013). Material efficiency improvements can be brought about by design of longer-lasting and less material intensive products, as well as increased recycling (Allwood et al. 2011, 2013). Further research is required to quantify the potential contribution of material efficiency and material service demand reduction to climate change mitigation.

(ii) Energy efficiency improvements in industrial production

Bottom-up studies estimate an aggregate energy efficiency potentials for industry of about 25% (27% (Saygin et al. 2011) and 24% (Kermeli et al. 2014), respectively). Energy efficiency improvements are particularly important as short-term mitigation measures. IEA ETP estimates that energy efficiency measures account for 47% of the emissions reductions achieved unit 2030 in their beyond 2°C scenario.

1 Reaping energy efficiency potentials hinges critically on advanced management practices in industrial
2 facilities such as energy management systems, as well as targeted policies to accelerate adoption of
3 best available technology (IEA 2017).
4

5 Similarly, energy demand reductions relative to reference policy trends amount to 26% (median, 22-
6 28% interquartile range) in the ADVANCE 1.5°C scenarios by 2030, accounting for more than half of
7 the CO₂ abatement achieved. By 2050, final energy demand reductions reach 32 (30-36) % in 1.5°C
8 scenarios relative to a reference policies scenario, considerably higher than the 20 (20-22) % in the
9 well-below 2°C scenarios (Figure 2.15). It is important to note that these energy demand reductions
10 encompass both efficiency improvements in production as well as reductions in material demand as
11 discussed above, as most models do not discern these two factors.
12

13 *(iii) Electrification of industry energy demand*

14 It is well understood that more rapid and deeper emission reductions can be achieved for electricity
15 supply than for non-electric energy (Clarke et al. 2014; Krey et al. 2014b; Kriegler et al. 2014a). By
16 mid-century, fossil CO₂ emissions per unit electricity have decreased by 80-90% in well-below 2°C
17 pathways, and around 95% in 1.5°C-consistent scenarios (Luderer et al. 2016b). An accelerated
18 electrification of industrial end uses thus becomes an increasingly powerful mitigation option. In the
19 ADVANCE scenarios (Luderer et al. 2016b), the share of electricity reaches 45 (41-50) % by 2050 in
20 1.5°C-consistent scenarios, compared to 37 (34-38) % in well-below 2°C scenarios and 29 (28-32) %
21 under reference policies (Figure 2.15).
22

23 *(iv) Reducing the fossil carbon content of non-electric fuels*

24 In 1.5°C consistent scenarios, fossil carbon intensity of non-electric fuels consumed in industry
25 decreases to ~30 kgCO₂ GJ⁻¹ by 2050, compared to 75 (66-80) kgCO₂ GJ⁻¹ under reference policies,
26 and 40 (32-42) kgCO₂ GJ⁻¹ in the ADVANCE well-below 2°C scenarios. Considerable carbon
27 intensity reductions are already achieved by 2030. This are largely reached by a rapid phase out of
28 coal. In 2030, 1.5°C-scenarios have a 52 (30-63) % reduction in industrial coal consumption relative to
29 reference policies. On the other hand, biomass becomes an increasingly important energy carrier in the
30 industry sector in deep-decarbonisation scenarios, in particular in the longer term. In addition, in some
31 scenarios also hydrogen plays a considerable role as a substitute for fossil-based non-electric energy
32 demands.
33

34 *(v) Application of carbon capture and storage*

35 Many industrial processes, in particular in the steel, cement and chemical subsectors, can be combined
36 with carbon capture and storage to limit the release of CO₂ to the atmosphere (UNIDO 2010).
37 Integrated modelling studies that account for CCS in industry project a contribution of 0.9-3 GtCO₂ yr⁻¹
38 by 2050.
39

40 Given project long-lead times and the need for technological innovation, early scale up of industry
41 CCS is essential. In stark contrast to the potential importance of CCS for abating emissions for
42 industrial activities, the development and demonstration of such projects has been slow. As of now,
43 only two large-scale industrial CCS projects outside of oil and gas processing are in operation (Global
44 CCS Institute 2016). Once mature, the bulk of industrial CCS applications is projected to have CO₂
45 avoidance costs of 30 \$ tCO₂⁻¹ or higher (Kuramochi et al. 2012). Carbon pricing is therefore a key
46 prerequisite for mobilising its mitigation potential.
47

48 All mitigation strategies discussed above have limitations. The scope for decreasing material inputs to
49 the economy, and the willingness of consumers to pursue a less material-intensive lifestyle might be
50 limited. Similarly, there are economic and thermodynamic limits to efficiency improvements (Saygin
51 et al. 2011). Electrifying some energy services, most importantly high temperature heating, has a
52 substantial exergy penalty as it converts a high-quality into a low-quality energy carrier, and thus
53 reduces the overall efficiency of the system (Banerjee et al. 2012). Similarly, hydrogen is an imperfect
54 substitute for non-electric fuels, and is also a relative expensive energy carrier if produced from
55 renewable primary energy sources. The decarbonisation of final energy is also limited by the fact that

1 hydrocarbons often not only serve as energy sources, but also as material feedstocks to chemical
2 processes. The industry sector competes with other demand sectors for a limited amount of sustainable
3 biomass (Rose et al. 2013; Creutzig et al. 2015). Finally, there are practical limits to the deployment of
4 carbon capture and storage in smaller industrial facilities, and even many of those installations
5 equipped with CCS are likely to have significant residual emissions due to imperfect capture (UNIDO
6 2010).

7
8 Furthermore, the industrial sector is also one of the most important sources of HFCs (Velders et al.
9 2015), which consequentially are also strongly reduced in stringent mitigation scenarios (Gernaat et al.
10 2015), and recent studies have confirmed significant potentials for their reduction (Velders et al. 2015;
11 Purohit and Höglund-Isaksson 2017). HFCs are being controlled under the Kigali Amendment to the
12 Montreal Protocol, which mandates the phase-out of the consumption of these gases over the coming
13 decades. Recent research estimates that compliance with the measures described in the amendment
14 would lead to a reduction of HFC emissions of about 60% relative to a global pre-Kigali baseline
15 (Höglund-Isaksson et al. 2017).

16
17 As a consequence, integrated modelling studies that feature sectoral detail as well as sectoral studies
18 suggest that no single mitigation option can serve as a silver bullet for reducing industry's emissions in
19 line with 1.5-2°C stabilisation, but that rather most or even all of the above listed options will have to
20 contribute. The available studies show that energy demand savings and the reduction of industrial coal
21 use are near-term priorities for putting the industry sector on track for 1.5°C consistent
22 decarbonisation. In the longer term also electrification, bioenergy as well as CCS play an increasingly
23 important role.

24 25 2.3.4.2.2 *Buildings*

26 In 2010 buildings accounted for 32% of total global final energy use, 19% of energy-related GHG
27 emissions (including electricity-related), approximately one-third of black carbon emissions, and an
28 eighth to a third of F-gases (Lucon et al. 2014). Greenhouse gas (GHG) emissions from the building
29 sector have more than doubled since 1970 to reach 9.18 GtCO₂eq yr⁻¹ in 2010, representing 25% of
30 total emissions without the Agriculture, Forestry, and Land Use (AFOLU) sector; and 19% of all
31 global 2010 GHG emissions (Lucon et al. 2014). When upstream electricity generation is taken into
32 account, buildings are responsible for 26% of global energy-related CO₂ emissions in 2014. One-third
33 of those total buildings-related emissions, or roughly 8% are from direct fossil fuel consumption (IEA
34 2017).

35
36 Past growth of energy consumption is mainly driven by population and economic growth, with
37 improved access to electricity, and higher use of electrical appliances and space cooling resulting from
38 increasing living standards, especially in developing countries (Lucon et al. 2014). These trends will
39 continue in the future and in 2050, energy consumption is projected to increase by 40-125% compared
40 to 2010 in baseline scenarios in absence of climate policy. In middle-of-the-road baseline scenarios, an
41 increase of 45-75% is projected. The IEA's 6DS scenario (IEA 2016) falls within this range with an
42 increase of 60% compared to 2010. Energy consumption slows down, however, in 2°C and 1.5°C
43 compatible scenarios, with a levels of 5 to 95% and -10 to 90%, respectively, compared to 2010 in
44 2050. More detailed sectorial studies show similar trends (IEA 2014b, 2015b, 2016, 2017). This
45 lowering in energy consumption in 1.5°C scenarios represents reductions of 10% (5-30% full range)
46 compared to a no-climate policy baseline in 2050. Mitigation option are often more fully represented
47 in sectorial models (Lucon et al. 2014), leading to estimated relative potential energy consumption
48 reductions of 24% and more in 2050 (see Figure 2.16). This results in bottom-up sectorial studies
49 estimating energy consumption in the building sector in 2030 and 2050 to be close to 2010 levels,
50 already in 2°C consistent scenarios.

51
52 In contrast to energy demand, CO₂ emissions from buildings clearly decrease in 1.5°C scenarios from
53 their current levels due to a shift from fossil fuels to electricity. IAM scenarios see direct emissions in
54 2030 and 2050 being reduced to roughly 2.8 GtCO₂ yr⁻¹ (median, 1.7-3.9 full range) and 1.5 GtCO₂ yr⁻¹
55 (median 0.3-3.1, full range) compared to their estimated 2010 levels of roughly 3.3 GtCO₂ yr⁻¹.

1 Bottom-up studies from the IEA (IEA 2014b, 2015b, 2016, 2017) are situated at the bottom half of this
2 range with their projections for 2°C consistent scenarios. These emissions reductions are driven by a
3 clear tempering of energy demand and a strong electrification of the building sector (Figure 2.16).
4 Globally integrated scenarios project an increase in the share of electricity in the final energy supply of
5 the building sector from about 28% today to 43% (median, 35-49% full range) and 64% (median, 48-
6 75% full range) by 2030 and 2050, respectively. Scenarios consistent with 1.5°C mainly distinguish
7 themselves from 2°C consistent scenarios by means of a much stronger electrification of the building
8 sector (Figure 2.16). This electrification contributes to the reduction of direct CO₂ emissions in the
9 building sector by replacing carbon intensive alternatives, like oil and coal. Furthermore, when
10 combined with a rapid decarbonisation of the power system (see Section 2.3.4.1) it also enables further
11 reduction of indirect CO₂ emissions. In contrast to other dimensions, sectorial bottom-up models in
12 general estimate lower electrification potentials for the building sector in comparison to global IAMs.
13 Besides CO₂ emissions, air conditioning in buildings also leads to emissions of HFCs. These gases
14 have high global warming potential yet contribute currently only a small amount to the overall
15 warming. However, their projected future impact can be significantly mitigated through efficiency
16 measures and switching of cooling gases (Shah et al. 2015; Purohit and Höglund-Isaksson 2017).
17

18 The building sector is characterised by very long-living infrastructure and immediate steps are hence
19 important to avoid lock-in of inefficient carbon and energy-intensive buildings. This applies both to
20 new buildings in developing countries where the substantial new construction is expected in the near
21 future and retrofit of existing building stock in developed regions. This represents both a significant
22 risk and opportunity for mitigation (Lucon et al. 2014). These measures are included in the mitigation
23 scenarios. A recent study highlights the benefits of deploying the most advanced renovation
24 technologies. These might only become available on the market five years from now, but would avoid
25 lock-in into less efficient measures (Güneralp et al. 2017). Aside from the effect of building envelope
26 measures, adoption of energy-efficient technologies such as condensing boilers, heat pumps and more
27 recently light-emitting diodes (LED) is also important for the reduction of energy and CO₂ emissions (IEA 2017).
28
29

30 Behavioural literature indicates that reasonable CO₂ emission savings can be achieved in the near-term
31 by relatively small changes. By the tenth year of national implementation, 3.39% of US emissions
32 from residential buildings could be saved as compared to today by insulating buildings, sealing drafts,
33 and installing efficient buildings in the US, another 1.72% could be saved by replacing inefficient
34 HVAC (Heating, Ventilation, and Air Conditioning) equipment, 0.81% – improving HVAC
35 maintenance, and 0.71% by setting back the thermostats (Dietz et al. 2009). Other studies have also
36 indicated that CO₂ emission savings can be achieved by effective use of air conditioning and
37 ventilation (Pellegrino et al. 2016; Jaboyedoff et al. 2004), intelligent (automated) thermostats for
38 heating (Nägele et al. 2017), and potentially smart homes (Wilson et al. 2015).
39
40

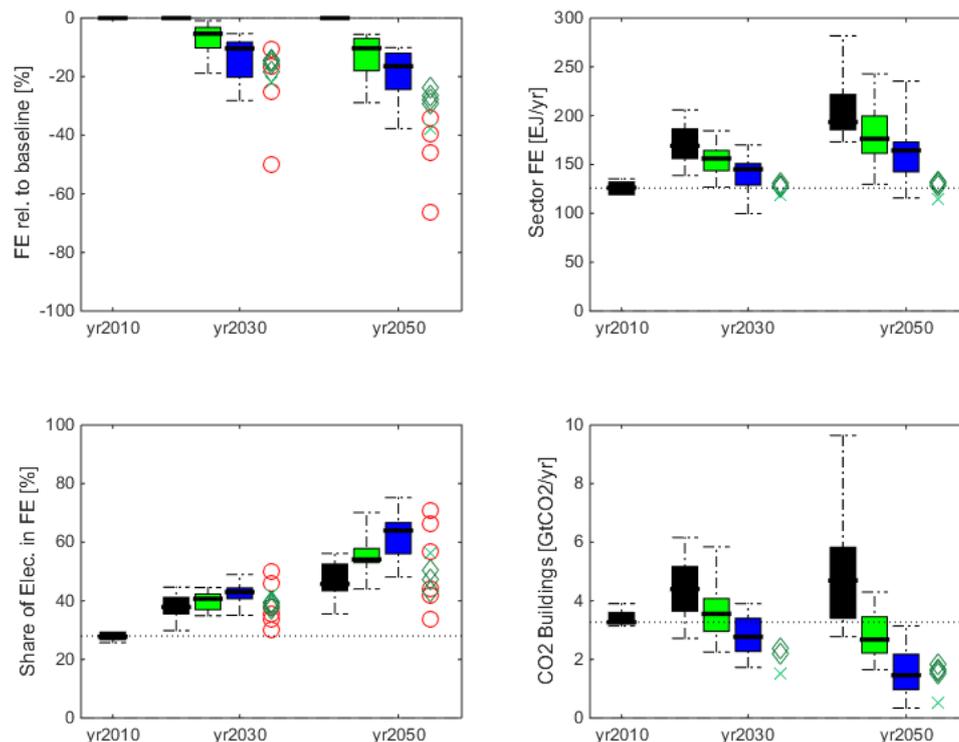


Figure 2.16: Characteristics of the buildings sector in 1.5°C and related scenarios until mid-century. Data is shown for no-climate policy baselines (black), 2°C scenarios (2.6 Wm⁻² scenarios, green), and 1.5°C scenarios (1.9 Wm⁻² scenarios, blue). Whiskers show the minimum-maximum range, boxes the interquartile range, and horizontal black lines the median. Data from (Riahi et al. 2017; Rogelj et al. 2017a). [Note: these ranges will be updated as more studies and scenarios are submitted and become available for assessment.] Red circles are from single model studies as reported in Figures 6.37 and 6.38 of (Clarke et al. 2014). Green diamonds show results for ‘2DS’ scenarios (50% probability of staying below 2°C) from (IEA 2014, 2015, 2016, 2017). Green crosses show results for the ‘WB2DS’ (50% probability of staying below 1.75°C) from (IEA 2017). The various panels show: (top-left) final energy in the building sector compared to a no-climate policy baseline, (top-right) absolute final energy demand in the building sector, (bottom-left) share of electricity in final energy in the building sector (rate of electrification), and (bottom-right) global direct CO₂ emissions from the building sector.

2.3.4.2.3 Transport

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; Lucon et al. 2014; Smith and Bustamante 2014). Yet, few of these studies investigate in a detailed way the transport sector’s role in such an effort. What is more, while these studies may give a perspective on what “well below 2°C” (with at least 66% likelihood) means for the sector, no in-depth transport study has yet been published examining the more stringent target of 1.5°C. This section assesses these studies to draw out robust insights for how global transport could slow the growth of and eventually reduce its emissions in a manner consistent with stringent global climate targets such as 2 or 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 GtCO₂ yr⁻¹ in 2010 – direct emissions; approximately 23 % of total energy-related CO₂ emissions (Clarke et al. 2014).

Edelenbosch et al. 2016 carried out a multi-model inter-comparison study to understand the transport sector’s role in global mitigation efforts. Results from eleven whole-systems (integrated assessment and energy-economy) models indicate that in a mitigation scenario that aims to be compatible with

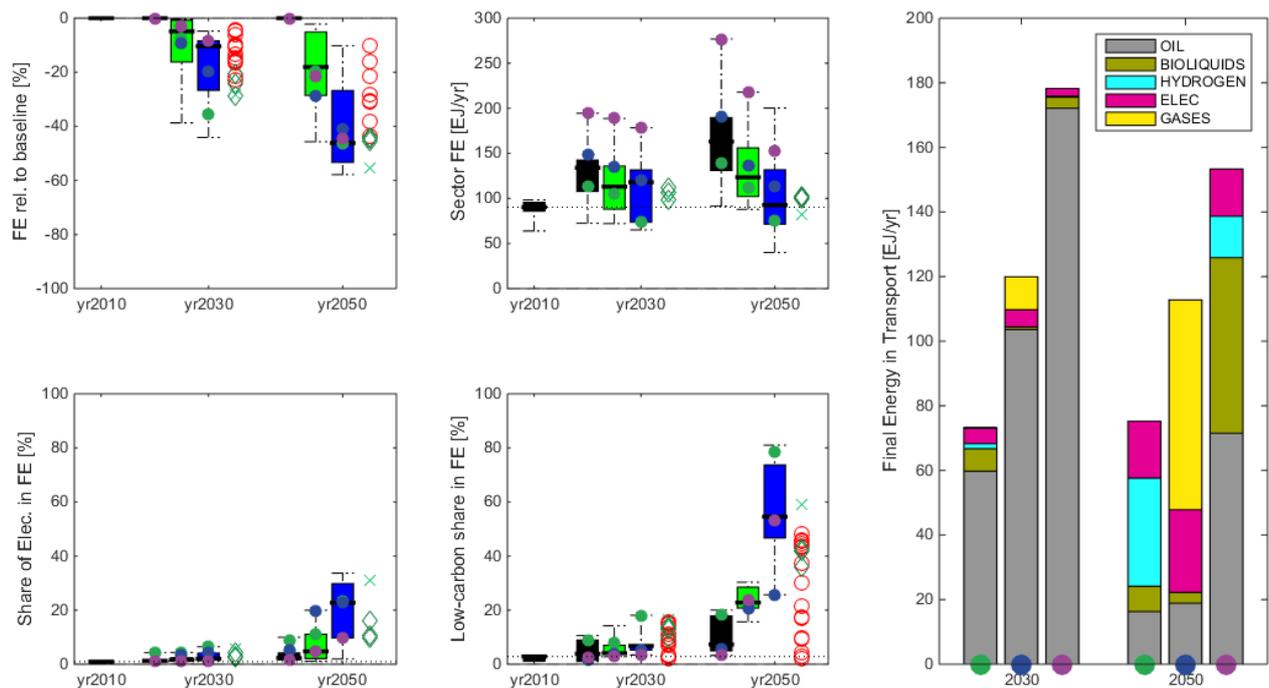
1 ‘well below 2°C’ (there assumed to be stabilisation of atmospheric concentrations of GHGs at 450
2 ppm CO₂-eq in 2100), passenger-related CO₂ emissions (thus excluding freight) range from 3.6 to 6.2
3 GtCO₂ yr⁻¹ in 2030 and from 1.6 to 6.7 GtCO₂ yr⁻¹ in 2050 (compared to ~3.6 GtCO₂ yr⁻¹ in 2010). The
4 International Energy Agency’s recently developed ‘B2DS’ pathway envisions a similar level of
5 economy-wide mitigation stringency (IEA 2017). For the entire transport sector, it estimates total
6 emissions of 6.1 GtCO₂ yr⁻¹ in 2030 and 2.5 GtCO₂ yr⁻¹ in 2050, while for passenger transport the
7 estimate is 1.5 GtCO₂ yr⁻¹ in 2050. Earlier, the IEA’s ‘2DS’ scenario estimated 3.8 and 2.8 GtCO₂ yr⁻¹
8 in 2030 and 2050, respectively, for passenger transport IEA 2014b). The mid-century projection from
9 the IEA analysis is on the low end of the range of the IAM literature because the scenario, by design,
10 looks at how far known clean energy technologies could go if pushed to their practical limits. Thus,
11 according to these results from multiple models, there exists a fair amount of uncertainty regarding
12 whether transport sector CO₂ emissions by mid-century need actually be lower than in 2010, even if in
13 the period beyond 2050 models clearly show that they do (in some cases approaching zero). This
14 uncertainty results from the systemic nature of the models/scenarios: each puts a different emphasis on
15 sector-specific mitigation burdens, typically due to considerations of cost-effectiveness.

16
17 Deep emissions reductions in the transport sector can be achieved by several means. Technology-
18 focused measures such as energy efficiency and fuel-switching are two of these. Also important are
19 behavioural measures such as mode-shifting and travel demand management. While the former
20 solutions (technologies) tend always to figure into deep decarbonisation pathways in a major way, this
21 is not always the case with the latter. Comparing different types of global transport models, (Yeh et al.
22 2016) find that transport-only frameworks generally envision greater mitigation potential from
23 behavioural solutions. Though, even there, it is primarily the switching of passengers and freight from
24 less- to more-efficient travel modes (e.g., cars, trucks and airplanes to buses and trains) that is the
25 main strategy; other actions, such as increasing vehicle load factors (occupancy rates) and outright
26 reductions in travel demand (e.g., as a result of tele-commuting or integrated transport, land-use and
27 urban planning), figure much less prominently. Whether these dynamics accurately reflect the actual
28 mitigation potential of behavioural-related mitigation options is a point of debate. (Creutzig 2016), for
29 instance, notes the diverse perspectives on transport mitigation solutions that are foreseen by different
30 scientific communities.

31
32 To give a better sense for how the different drivers of emissions compare in model-derived scenarios,
33 Edelenbosch et al. 2016 carry out detailed decomposition analyses. The authors reveal that in well
34 below 2°C scenarios the annual rate of change in CO₂ emissions due to activity growth is likely to be
35 positive through mid-century (generally between +0.3 and +0.7% yr⁻¹). In other words, even in
36 stringent mitigation scenarios, demand for transport services may very well continue to grow
37 considerably going forward, particularly in developing countries, albeit at rates slightly lower than
38 what would otherwise be witnessed in scenarios with much weaker climate policy regimes. To
39 counteract these CO₂-increasing drivers, the global IAMs assessed by Edelenbosch et al. 2016 tend to
40 rely heavily on energy intensity improvements (efficiency; CO₂ rate of change of -0.3 to -1.2% yr⁻¹,
41 thus at the high end of OECD countries’ historical experience) as well as switching to lower-carbon
42 fuels (-0.2 to -1.2% yr⁻¹, thus in sharp contrast to the historical experience). Meanwhile, structural
43 changes in transport demand (mode-shifting) make a very minor contribution in the models (0 to
44 +0.1% yr⁻¹ in most cases).

45
46 Edelenbosch et al. 2016 show that in well below 2°C scenarios the share of fossil fuels in the total
47 transport fuel mix could decrease to 84-94% by 2030 and to 46-87% by 2050 (down from about 95%
48 at present). At the same time, the shares of hydrogen and electricity could rise to 0-6% (1-19%) in
49 2030 (2050); and for biofuels 2-10% (7-46%). The IEA’s well below 2°C pathway is on the more
50 ambitious side with respect to alternative fuels: it foresees a combined share of electricity, hydrogen
51 and biofuels reaching 16% in 2030 and 59% in 2050. Hence, there is wide variation among scenarios
52 regarding changes in the transport fuel mix over the first half of the century. Post-2050, however,
53 more drastic changes are commonly seen. A critical uncertainty is how rapidly countries can overhaul
54 their existing vehicle stocks and establish wholly new refuelling and recharging infrastructures.
55 One study that has conducted a systematic analysis of the 1.5°C target is Rogelj et al. 2017a. And

1 while a detailed treatment of transport sector outcomes is not presented there, comparison of the
 2 results is nevertheless insightful, particularly with respect to the different conditions under which the
 3 1.5°C target can be reached (Figure 2.17). More specifically, as indicated in the figure below, transport
 4 service, and thus fuel, demands could be considerably lower in an SSP1 world where policies to
 5 promote efficient mobility are more successful. This stands in stark contrast to an SSP5 future, where
 6 demands for people and goods movement grow much more quickly. In the latter case, oil-based fuels
 7 continue to contribute a significant share of the fuel mix by mid-century simply because advanced
 8 vehicles powered by low-carbon fuels are only able to scale up so quickly. In a world of lower
 9 demand, deployment of these new technologies can make a relatively larger contribution to the fuel
 10 mix.
 11



12
 13
 14 **Figure 2.17:** Characteristics of the transport sector in 1.5°C and related scenarios until mid-century. Small
 15 panels on the left hand side and in the middle show data for no-climate policy baselines (black),
 16 2°C scenarios (2.6 Wm⁻² scenarios, green), 1.5°C scenarios (1.9 Wm⁻² scenarios, blue). Whiskers
 17 show the minimum-maximum range, boxes the interquartile range, and horizontal black lines the
 18 median. Dots indicate single scenarios highlighted in the panel on the right. Data from (Riahi et al.
 19 2017; Rogelj et al. 2017a). [Note: these ranges will be updated as more studies and scenarios are
 20 submitted and become available for assessment.] Red circles are from single model studies as
 21 reported in Figures 6.37 and 6.38 of (Clarke et al. 2014). Green diamonds show results for ‘2DS’
 22 scenarios (50% probability of staying below 2°C) from (IEA 2014, 2015, 2016, 2017). Green
 23 crosses show results for the ‘B2DS’ (50% probability of staying below 1.75°C) from (IEA 2017).
 24 The various panels show: (top-left) final energy in the transport sector compared to a no-climate
 25 policy baseline, (top-middle) absolute final energy demand in the transport sector, (bottom-left)
 26 share of electricity in final energy in the transport sector (rate of electrification), (bottom-middle)
 27 share of low-carbon fuels in final energy in the transport sector (includes electricity, hydrogen and
 28 biofuels), and (right) portfolios of final energy in 1.5°C consistent scenarios for three pathway
 29 types (here: IMAGE SSP1-19 – green dot, MESSAGE-GLOBIOM SSP2-19 – blue dot, REMIND-
 30 MAgPIE SSP5-19 – purple dot). “Gases” also include biogas.

31
 32
 33 In addition to the system perspective (either at a sector or economy-wide level) provided by the
 34 modelling studies assessed above, the sociotechnical literature provides insights into potential
 35 measures and reductions. This literature focuses at local scales with only a limited number of insights
 36 that can be generalised outside of their original context. Nevertheless, sociotechnical studies allow one
 37 to understand the potential at the local scale of aspects of behavioural change. Measures at the

1 household level, like switching to fuel-efficient vehicles and low resistance tires, changing driving
2 behaviour, and improving motor vehicle maintenance are reported to have the potential to lead to
3 6.1%, 1.2%, and 0.7% savings in US household direct emissions (Dietz et al. 2009). Switching from
4 car and motorcycles to either walking or cycling would lead to 62% and 52% savings in transportation
5 emissions in London and Delhi respectively (Woodcock et al. 2009). Finally, the sociotechnical
6 literature found that employer-based commuting and telecommuting to work could save 4-6% and 48-
7 77% of vehicle kilometres travelled in the US (Salon et al. 2012).

8
9 Going beyond ‘well below 2°C’ in the direction of 1.5°C will require an acceleration of the mitigation
10 solutions already featured in the deep decarbonisation pathways discussed above (e.g., more efficient
11 vehicle technologies operating on lower-carbon fuels), as well as those having received lesser attention
12 in most global transport decarbonisation pathways up to now (e.g., mode-shifting and travel demand
13 management) (Kauppila et al.). Low-emitting automated vehicles combined with a high degree of on-
14 demand ride-sharing could also be critical to bridging the gap between 2 and 1.5°C while still allowing
15 individuals’ travel needs to be adequately served (Kauppila et al.). Current-generation, global scenario
16 pathways generally do not include these newer transport sector developments, which in a sense
17 leverage technological solutions to induce shifts in traveller behaviour. Complementing these
18 mitigation solutions, Kauppila et al. note that a suite of policies and measures would need to be
19 applied aggressively throughout the world in order to drive transport emissions down to levels
20 consistent with a 1.5°C scenario, including, among others, strong and consistent pricing instruments
21 (making parking and certain roads/zones more expensive, while lowering the cost of public transport);
22 strict zone- or time-base vehicle restriction schemes in urban areas; integrated transport, land-use and
23 urban planning; enhanced infrastructure for cycling/walking, electric vehicles, and public transit (e.g.,
24 bus rapid transit); and information campaigns that promote cycling/walking and public transit.

25
26 *[Note for SOD: No literature was found that explicitly speaks to mitigation of international bunkers in*
27 *line with 1.5°C. If available this literature will be assessed here.]*

28 29 2.3.4.3 Land-use transitions and changes in the agricultural sector

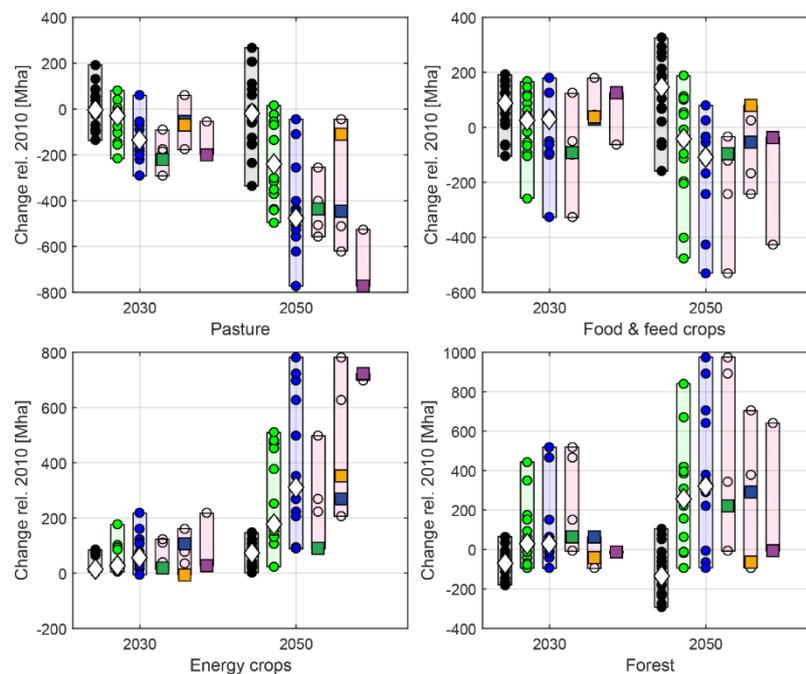
30 The agricultural and other land-use sector (AFOLU) plays an important and possibly essential role in
31 stringent mitigation futures (Clarke et al. 2014; Smith and Bustamante 2014). On the one hand, its
32 emissions need to be limited over the course of this century (see Section 2.3.3). On the other hand, the
33 AFOLU sector has to meet the demands for food and feed of a growing global population, as well as
34 supply biomass products for energy and other uses in a low-carbon society. Meeting both demands
35 together - and this in combination with limits to overall emissions - will require changes in land use
36 and agricultural as well as forestry practices. A multitude of options are available to achieve this
37 (Smith and Bustamante 2014; Popp et al. 2017) (see also Chapter 4, Section 4.3). Here we make use of
38 scenarios from integrated assessment models based on the quantifications of the Shared
39 Socioeconomic Pathways (SSPs) that produce distinct land-use evolutions in line with limiting
40 warming to 1.5°C (Riahi et al. 2017; Popp et al. 2017; Rogelj et al. 2017a; Fujimori 2017; Calvin et al.
41 2017; van Vuuren et al. 2017; Fricko et al. 2017; Kriegler et al. 2017).

42
43 *[This assessment may be extended with insights from other modelling exercises, as they are submitted*
44 *and become available for assessment during the writing of the SOD.]*

45
46 Transitions and changes in land use until mid-century are a feature of the large majority of SSP
47 scenarios, both in stringent mitigation scenarios and baseline scenarios in absence of climate action
48 (Figure 2.18). In the latter case, changes are mainly due to socio-economic drivers like growing
49 demands for food, feed and wood products. Moreover, transitions in scenarios consistent with a global
50 mean temperature increase of 1.5°C differ from the baseline scenarios in their land-use change
51 fingerprint, depending on the underlying socioeconomic factors and the interplay with mitigation in
52 other sectors (Figure 2.18) (Popp et al. 2017; Riahi et al. 2017; Rogelj et al. 2017a).

53
54 General transition trends can be identified for many land types in 1.5°C scenarios. Due to schemes that
55 avoid deforestation, mitigation that demands land (such as biomass production for BECCS and

1 afforestation) is mainly taking place at the cost of agricultural land for food and feed production. Land
 2 for 2nd generation energy crops expands by 2030 and 2050 in all available scenarios that assume a
 3 cost-effective achievement of a 1.5°C temperature goal (Figure 2.18), but the scale depends strongly
 4 on underlying socioeconomic assumptions (see later discussion of land pathway types). Avoided
 5 deforestation restricts agricultural expansion and forest cover can expand strongly in 1.5°C and 2°C
 6 scenarios alike compared to its extend in no-climate policy baselines due to the use of afforestation
 7 and reforestation measures. However, the extent to which forest cover expands varies highly across
 8 models. In some cases, forest cover is projected to stay virtually constant. This is due to whether
 9 afforestation is included in these scenarios as a mitigation technology. As a consequence, pasture land
 10 is generally reduced compared to both baselines in which no climate mitigation action is undertaken
 11 and 2°C consistent scenarios. Furthermore, cropland for food and feed production decreases in most
 12 1.5°C scenarios, both compared to a no-climate baseline and relative to 2010.
 13



14
 15 **Figure 2.18:** Overview of Land-Use Change transitions in 2030 and 2050, relative to 2010. Black: baseline;
 16 green: 2.6 Wm-2 scenarios; blue: 1.9 Wm-2 scenarios. Pink: 1.9 Wm-2 scenarios grouped per
 17 underlying socioeconomic assumption (from left to right: SSP1 (sustainability), SSP2 (middle-of-
 18 the-road), SSP5 (fossil-fuelled development)). Ranges show the minimum-maximum range. Dots
 19 indicate single scenarios. White diamonds the median across scenarios. Coloured squares in the
 20 pink ranges indicate the position of the four land pathway types presented in Figure 2.19. Each
 21 panel shows the changes for a different land type. 1.9 and 2.6 Wm-2 are taken as proxies for 1.5°C
 22 and 2°C scenarios, respectively. Data from (Riahi et al. 2017; Rogelj et al. 2017a).
 23

24 An important aspect of these land transitions is the pace at which they are projected to take place over
 25 the coming decades in 1.5°C scenarios, especially in comparison to baseline scenarios without climate
 26 change mitigation and historical transitions (Table 2.9). For instance, in 1.5°C scenarios between 2010
 27 and 2030, pasture land is transformed at a pace of -15 to +3 Mha yr⁻¹ (full range across scenarios,
 28 median: -7 Mha yr⁻¹), cropland for food and feed production is expanding or contracting at a pace of
 29 +9 to -16 Mha yr⁻¹ (median: 1.4 Mha yr⁻¹), energy crops at 11 to 0 Mha yr⁻¹ (median: 3 Mha yr⁻¹),
 30 while forest cover changes at a pace of -5 to +26 Mha yr⁻¹. In most cases, rates further increase for the
 31 2030-2050 period. Decreasing pasture areas in 1.5°C scenarios are amplified prolongations of
 32 historical (8.7 Mha yr⁻¹ for 1970-1990 and 0.9 Mha yr⁻¹ for 1990-2010) and baseline trends (median:
 33 0.1 Mha yr⁻¹ for 2010-2030). Median total cropland increases in 1.5°C scenarios of 2.9 Mha yr⁻¹ (2010-
 34 2030) and 5.1 Mha yr⁻¹ (2030-2050) are significantly higher than reported changes of 0.5 Mha yr⁻¹ for
 35 the time span of 1990-2010 but similar to 1970-1990 (4.6 Mha yr⁻¹). Forest cover increases due to

1 REDD+ measures in stringent mitigation scenarios is a reversed dynamic compared to historical and
2 baseline forest losses, and thus suggest that distinct policy and government measures would be needed
3 to achieve this.

4
5 Changes of the AFOLU sector are driven by three main factors: demand changes, efficiency of
6 production, and policy assumptions (Smith et al. 2013). Demand for agricultural products and other
7 land-based commodities is influenced by societal consumption patterns (including dietary preferences
8 and food waste affecting demand for food and feed), demand for forest products for pulp and
9 construction, and demand for biomass for energy production (Smith and Bustamante 2014; Lambin
10 and Meyfroidt 2011). Efficiency of agricultural production relates to improvements in agricultural
11 practices, agricultural yield increases as well as intensification of livestock production systems leading
12 to higher feed efficiency and changes in feed composition. Policy assumptions relate to the level of
13 land protection, the treatment of food waste, policy choices about the timing of mitigation action
14 (early vs late), the choice and preference of land-based mitigation options (for example, the inclusion
15 of afforestation and reforestation as mitigation options), and trade.

16
17
18 **Table 2.9:** Annual pace of land-use change in 1.5°C scenarios in Mha yr⁻¹. Values: median [full range]. Based
19 on land use developments projected by integrated assessment models under the assumptions of the
20 Shared Socioeconomic Pathways (Popp et al. 2017; Riahi et al. 2017; Rogelj et al. 2017a). 1.9 and
21 2.6 Wm⁻² are taken as proxies for 1.5°C and 2°C scenarios, respectively. FAO data are from
22 (FAOSTAT 2017).
23

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 Wm ⁻²	-6.7 [-14.6/3.0]	-15.0 [-28.7/-1.9]	8.7	0.9
	2.6 Wm ⁻²	-1.5 [-10.9/4.1]	-7.0 [-21.6/-0.7]	Permanent meadows and pastures (FAO)	Permanent meadows and pastures (FAO)
	Baseline	-0.1 [-6.9/9.7]	-1.5 [-9.9/9.0]		
Cropland for food and feed	1.9 Wm ⁻²	1.4 [-16.4/9.0]	-7.8 [-18.2/2.1]		
	2.6 Wm ⁻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 Wm ⁻²	2.9 [-0.3/10.8]	13.2 [3.5/34.8]		
	2.6 Wm ⁻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 Wm ⁻²	5.4 [-10.2/12.8]	5.1 [-5.1/26.7]	4.6	0.9
	2.6 Wm ⁻²	5.2 [-8.4/9.3]	4.4 [-7.1/17.8]	Arable land and Permanent crops (FAO)	Arable land and Permanent crops (FAO)
	Baseline	5.7 [-2.7/9.9]	4.8 [0.6/9.6]		
Forest	1.9 Wm ⁻²	1.3 [-4.8/26.0]	10.6 [-1.2/32.9]	N.A.	-5.6
	2.6 Wm ⁻²	1.4 [-4.7/22.2]	7.2 [-2.4/31.7]	Forest (FAO)	Forest (FAO)
	Baseline	-3.4 [-9.0/3.3]	-2.7 [-6.5/4.1]		

24
25 A recent study (Stevanović et al. 2017) finds that production (agricultural production measures in
26 combination with avoided deforestation) and consumption side (diet change in combination with lower
27 shares of food waste) measures have a similar reduction potential of 43–44% in 2100. For livestock
28 production, Weindl et al. demonstrate that lower consumption of livestock products can substantially
29 reduce deforestation (47-55%) and cumulative carbon losses (34-57%). On the supply side, already
30 minor productivity growth in extensive livestock production systems leads to substantial CO₂ emission
31 abatement, but the emission saving potential of productivity gains in intensive systems is limited,
32 mainly due to trade-offs with soil carbon stocks. In addition to that, Havlík et al. 2014 show that even

1 within existing livestock production systems, a transition from extensive to more productive systems
2 bears substantial GHG abatement potential, while improving food availability. Wise et al. 2014 and
3 Popp et al. 2014a highlight the need and capability of crop yield improvements for reducing land
4 competition and resulting cropland expansion, resulting in significant decreases in terrestrial carbon
5 dynamics. Ultimately, there are also interactions between these three factors and the wider society and
6 economy. For instance, the availability of affordable carbon-dioxide removal technologies that are not
7 land based (like direct air capture – DAC, see also Chapter 4, Section 4.3.6) or either the ability of
8 other sectors to achieve their projected mitigation contributions (Clarke et al. 2014). Variations in
9 these drivers can lead to drastically different land-use implications (Popp et al. 2014b) (Figure 2.19). It
10 is worth reiterating that the IAMs do not include spatially resolved climate damages to agriculture, nor
11 damages due to ozone exposure or the effects of varying indirect fertilization due to N deposition from
12 the atmosphere (e.g., Shindell et al. 2012; Mahowald et al. 2017). These models may thus have
13 difficulty adequately capturing the differences in crop productivity between scenarios and in particular
14 may underestimate the benefits of emissions reductions, especially for non-CO₂ warming agents that
15 do not cause carbon fertilization (Shindell 2016).

16
17 Scenarios that are consistent with 1.5°C rely on one or more of the three strategies highlighted in the
18 previous paragraph (demand changes, efficiency gains, and policy assumptions) when limiting
19 emissions while meeting food, feed, wood products and energy needs.

20 For example, scenario 1 is based on assumptions of generally low resource and energy consumption
21 (including healthy diets with low animal-calorie shares and low food waste) as well as significant
22 agricultural intensification in combination with high levels of nature protection. In this land pathway
23 type, also due to relatively low overall emissions in the baseline, comparably small amounts are
24 needed for land demanding mitigation activities such as BECCS and afforestation. In scenario 2, by
25 contrast, higher baseline emissions require more land based CDR, whereas land based biomass supply
26 is provided by dedicated bioenergy crops and forest biomass supply (by 2050, about 15% of the
27 required biomass comes from managed forests, which leads to a higher expansion of managed forests
28 than in the other land pathway types). In contrast to scenario 1 (and also scenario 3) mitigation also
29 works through the demand side in scenario 2 (not shown in Figure 2.19). By 2050, global food
30 production is reduced to 10% compared to a no-climate policy baseline – for livestock products this
31 number is almost doubled (18%). In contrast, scenario 3 is based on a resource- and energy-intensive
32 future (including unhealthy diets with high animal shares and high shares of food waste) but also on a
33 technology oriented future with high reliance on fossil fuel resources and associated high levels of
34 GHG emissions in the baseline. In this land pathway type, climate change mitigation strategies are
35 strongly based on the highly efficient CDR option BECCS (Humpenöder et al. 2014). As a
36 consequence, significant amounts of biomass are provided by bioenergy crop expansion in
37 combination with agricultural intensification. Scenario 4 relies on policy assumptions and options in
38 its effort to reach 1.5°C. In particular, this scenario strongly relies, besides BECCS, on a policy to
39 incentivise afforestation for CDR, and thus results in an expansion of natural forest area and a
40 corresponding increase in terrestrial carbon stock.

41

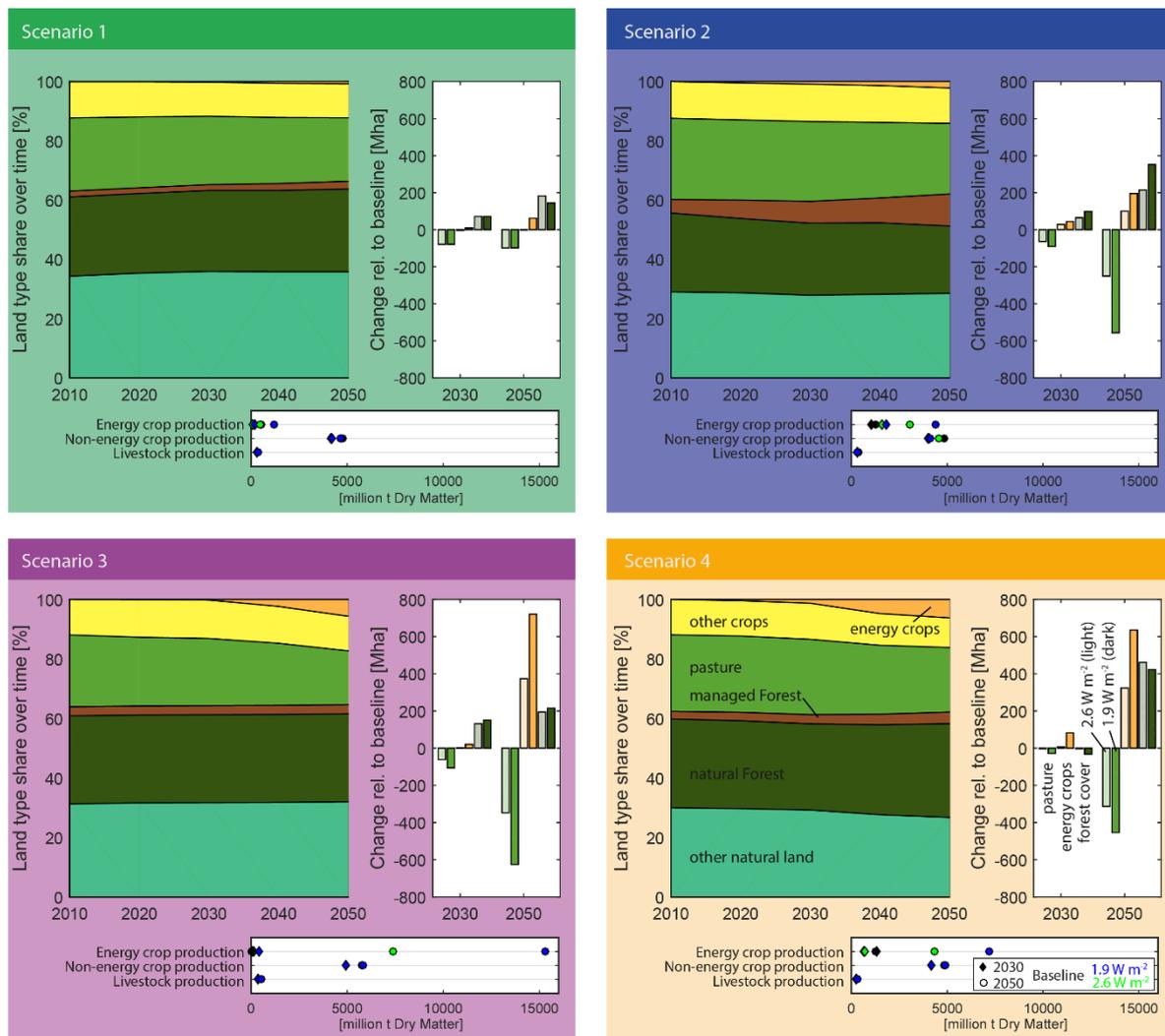


Figure 2.19: Four land pathway types for land transitions consistent with 1.5°C. 1.9 and 2.6 Wm⁻² are taken as a proxy for 1.5°C and 2°C scenarios, respectively. Each square illustrates the characteristics of one particular land pathway type and shows: (a) a temporal evolution until 2050 of the share of various land types in 1.9 Wm⁻² scenarios; (b) change of land surface for three land types (pasture, energy crops, and forest cover) relative to a no-climate mitigation baseline for 2.6 Wm⁻² (lighter bars) and 1.9 Wm⁻² (darker bars) scenarios, respectively, in 2030 and 2050; (c) production indicators in 2030 (diamonds) and 2050 (circles) for the baseline, 2.6 Wm⁻² and, 1.9 Wm⁻² scenarios. Data from (Riahi et al. 2017; Rogelj et al. 2017a).

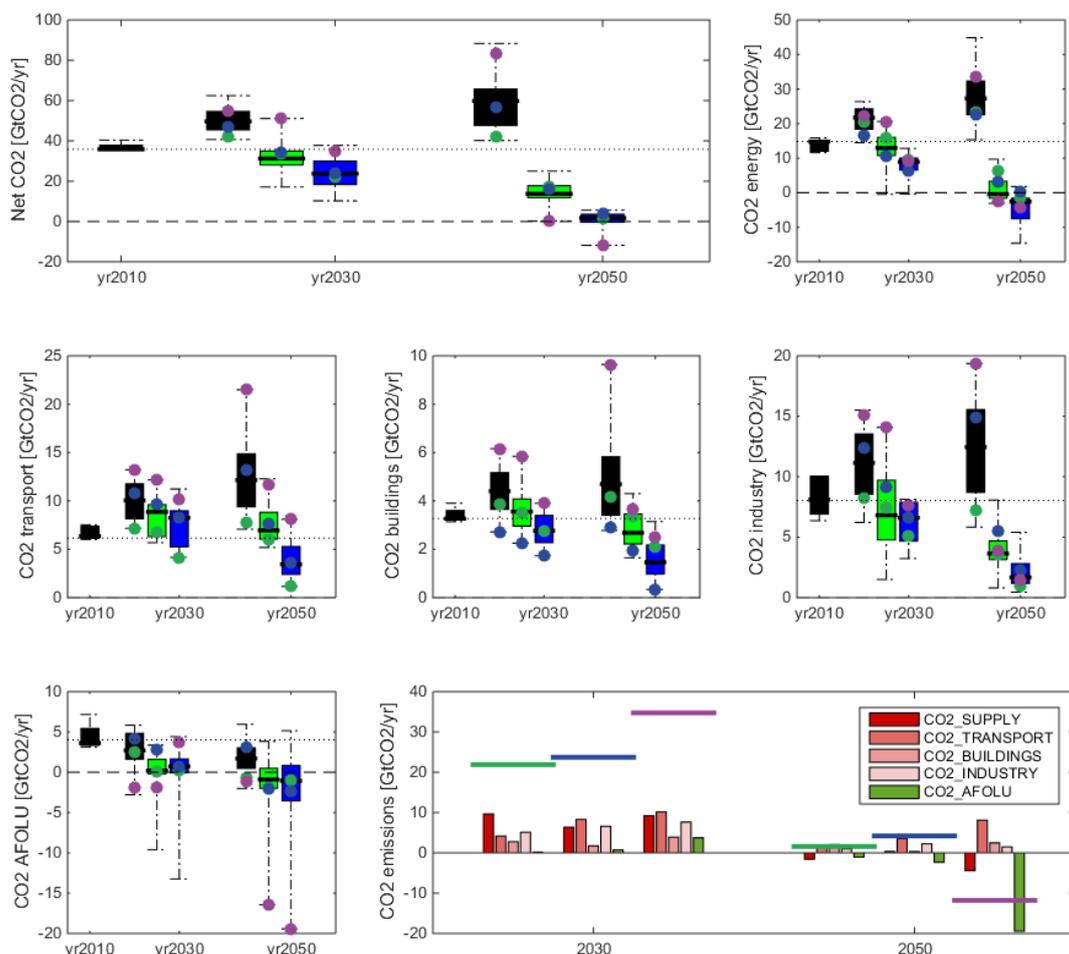
2.3.4.4 Mitigation portfolios and investments

2.3.4.4.1 Mitigation portfolios

Be it for the energy, transport, buildings, industrial, or AFOLU sector, the assessment in this section shows that multiple options and choices are available in each of these sectors to pursue a 1.5°C pathway. Because the overall emissions total under a pathway is limited by a geophysical carbon budget, choices in one sector affect the efforts that are required from others (Clarke et al. 2014). The impact of reduced (or improved) availability of key technologies on costs and achievability of stringent mitigation pathways has been explored with dedicated multi-model model studies for questions related to 2°C (Krey et al. 2014b; Kriegler et al. 2014a; Riahi et al. 2015). Similar studies are not available for questions related to 1.5°C, despite the availability of some single-model studies that explore this question tangentially (Luderer et al. 2013a; Rogelj et al. 2013). However, from the

1 scenarios available to this assessment, a set of possible 1.5°C consistent mitigation portfolios can be
 2 identified (Figure 2.20), which differ between them in underlying socioeconomic assumptions and
 3 models by which they are generated.

4
 5 The choice of mitigation portfolio can have wide-ranging implications for the achievement of other
 6 societal objectives. Only recently integrated studies have started to explore multiple societal objectives
 7 (Clarke et al. 2014). This literature already suggest that decarbonisation and energy efficiency provide
 8 near-term synergies with multiple other societal objectives, like energy security and air quality co-
 9 benefits. However, it also highlights that these co-benefits are neither automatic nor assured but result
 10 from conscious and carefully coordinated policies and implementation strategies (Clarke et al. 2014;
 11 Shukla and Chaturvedi 2012). This highlights the importance of mitigation portfolio choices,
 12 particular when also considering the achievement of sustainability objectives. Examples of mitigation
 13 portfolios are illustrated in Figure 2.20 One scenario achieves the near-term transition until mid-
 14 century through a strong emphasis on demand reductions through measures and policies that
 15 incentivise behavioural change, sustainable consumption patterns, and healthy diets (green dots). This
 16 results in emissions reductions in all sectors, limited amounts of residual emissions, and relatively low
 17 use for carbon dioxide removal. This contrasts with an alternative scenario where energy and food
 18 demand is high and emphasis is put on policies that attempt to reduce supply-side emissions through
 19 technological means (purple dots). In this scenario, energy demand and associated emissions from
 20 some end-use sectors, like the transport and the buildings sectors, are difficult to mitigation, requiring
 21 large-scale deployment of carbon dioxide removal in the land-use sector. Each of these portfolios has
 22 very different implications for the achievement of sustainable development objectives, as further
 23 discussed in Section 2.5.



25 **Figure 2.20:** Overview of portfolios of contributions to achieve net CO2 emissions reductions in 1.5°C and
 26 related scenarios until mid-century. Panels with box plots show data for no-climate policy
 27 baselines (black), 2°C scenarios (2.6 Wm-2 scenarios, green), 1.5°C scenarios (1.9 Wm-2
 28

scenarios, blue). Whiskers show the minimum-maximum range, boxes the interquartile range, and horizontal black lines the median. Dots indicate single scenarios highlighted in the panel on the bottom right. Data from (Riahi et al. 2017; Rogelj et al. 2017a). [Note: these ranges will be updated as more studies and scenarios are submitted and become available for assessment. This figure could also contain a BECCS panel]. The various panels show: (top-left) not global CO₂ emissions, (top-right) energy supply CO₂ emission, (middle row) CO₂ emissions of the transport, buildings and industry sector, respectively, (bottom-left) CO₂ emissions from AFOLU, and (bottom-right) portfolios of CO₂ emissions in 1.5°C consistent scenarios for three pathway types (here: IMAGE SSP1-19 – green line, MESSAGE-GLOBIOM SSP2-19 – blue line, GCAM SSP5-19 – purple line). Coloured horizontal lines show net global CO₂ emissions for the respective scenarios. Coloured bars show sector contributions per scenario.

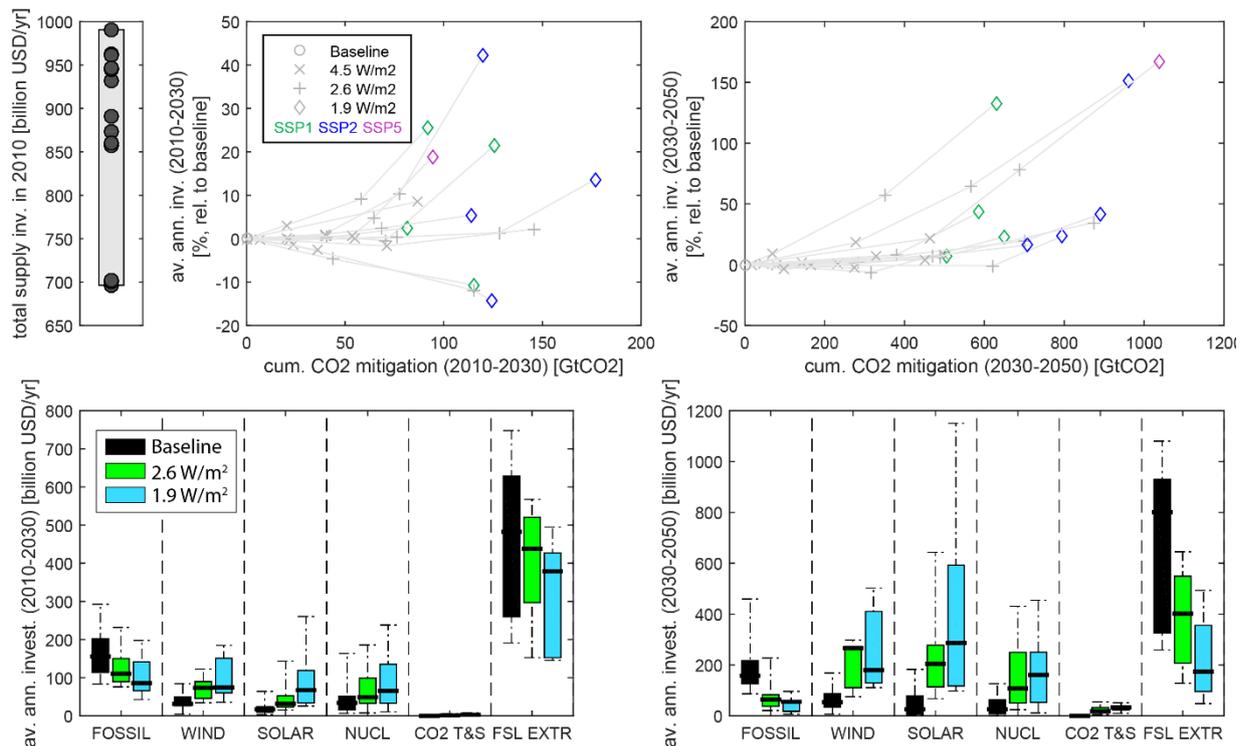
2.3.4.4.2 Investments

Realising the transformations towards a 1.5°C world requires a significant shift in investment patterns. Literature on climate change mitigation investments is sparse, with most detailed literature still focusing on 2°C pathways (Clarke et al. 2014; McCollum et al. 2013; Bowen et al. 2014; Marangoni and Tavoni 2014). Estimates for historical supply-side energy system investment in the year 2010 vary from 0.7 to 1 trillion USD (in 2005 US dollar using market exchange rates, or roughly 1.5-2% of global GDP) in IAMs, with independent estimates from the Global Energy Assessment (Riahi et al. 2012) or approximated from the IEA (see McCollum et al. 2013) being situated at the higher end of this range. 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 broad and a narrow one, to provide a first order estimate of historical end-use technology investments. The broad definition defines end-use technologies as the technological systems purchasable by final consumers in order to provide a useful service, for example, heating and air conditioning systems, cars, freezers, or aircraft. The narrow definition sets the boundary at the specific energy-using components or subsystems of the larger end-use technologies, for example, a compressor, a car engine, a fan, or heating element. 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) for the broad definition and 0.1 to 0.6 trillion USD (central estimate 0.3 trillion USD) for the narrow estimate. Due to these definitional issues, demand-side investment projections are uncertain, often underreported, and difficult to compare in an appropriate way.

Research carried out by six IAM teams in the framework of the LIMITS project found that climate policies in line with limiting warming to 2°C with >70% likelihood would require a significant upscaling of energy system supply-side investments reaching about 1.1 trillion USD annually between 2010 and 2050 (McCollum et al. 2013). The same literature also points towards the uncertainties in the exact size of current energy system investments. These uncertainties reappear in 1.5°C investment portfolios. Yet, some trends are discernible, based on the scenario set available in the database to this assessment. First, depending on the extent of energy demand reductions, average total supply-side investments over the next couple of decades can be either higher or lower than those in no-climate policy baselines (Figure 2.21). By mid-century average investments tend to increase in all available 1.5°C scenarios yet to very varying degrees (median: 40%, interquartile range: 20-140%). Model differences play a larger role in determining this uncertainty range than structured variations of socioeconomic assumptions in the available scenarios. Second, when looking at how investment flows are redirected when moving from a no climate policy baseline to a 1.5°C world, a clear shift away from investments in fossil fuel electricity (which includes fossil fuel electricity with CCS in its total) and fossil fuel extraction can be found. In 1.5°C pathways, median annual fossil fuel electricity investments over the 2010-2030 period are of the order of 85 billion USD yr⁻¹, while in absence of climate policy they are projected to amount to 155 billion USD yr⁻¹. This decreasing trend continues for the 2030-2050 period, yet the investments in both fossil fuel electricity and fossil fuel extraction remain sizeable until mid-century in 1.5°C scenarios (Figure 2.21). Large increases in supply-side electricity investments are projected for low-carbon energy carriers, like wind, solar and nuclear power, amongst others. While the high end of investments in wind and solar tend to extend beyond the

1 range considered in 2°C scenarios, the average investments in nuclear are estimated to be similar.
 2 Finally, embarking on a 1.5°C trajectory also implies investments in a new sector that is non-existent
 3 in baseline scenarios: CO₂ transport and storage. Over the 2010-2030 period, models estimate an
 4 average annual investment of 1-7 billion USD yr⁻¹ (full range) in this sector, which increases to 10-52
 5 billion USD yr⁻¹ in the 2030-2050 period. Ranges between 1.5°C and 2°C scenarios are very similar in
 6 this sector.

7
 8 Overall, the literature on specific investment volumes in line with 1.5°C is still emerging. However,
 9 important shifts in global investment patterns are projected to achieve the emissions reductions
 10 required to pursue a 1.5°C pathway.
 11
 12



13
 14
 15 **Figure 2.21:** Supply-side energy system investments in 1.5°C and related scenarios until mid-century. Top left
 16 panel shows total energy supply investments in 2010 in 9 available 1.5°C scenarios in year-2005
 17 USD. Top middle and right panels show the relationship between cumulative CO₂ mitigation and
 18 average annual investments for the 2010-2030 and 2030-2050 period, respectively. Symbols show
 19 single scenarios with varying levels of climate policy stringency (see legend: baseline – no climate
 20 policy, 4.5 Wm⁻² – weak climate policy, 2.6 Wm⁻² – consistent with WB2C, 1.9 Wm⁻² –
 21 consistent with WB1.5 or Med1.5). Grey lines connect scenarios derived with the same model and
 22 under the same assumptions. Colours indicate the Shared Socioeconomic Pathway underlying the
 23 scenarios. Lower panels show average annual supply-side investments for the 2010-2030 (left) and
 24 2030-2050 period (right) for baseline, 2.6 Wm⁻² and 1.9 Wm⁻² scenarios. Data is shown for
 25 electricity investments for fossil fuels (FOSSIL), wind (WIND), solar (SOLAR), nuclear (NUCL),
 26 and investments in CO₂ transport and storage (CO₂ T&S) and fossil fuel extraction (FSL EXTR).
 27 Whiskers show the minimum-maximum range, boxes the interquartile range, and horizontal black
 28 lines the median. Data from the AIM/CGE, IMAGE, MESSAGE-GLOBIOM, and REMIND-
 29 MAgPIE modelling frameworks based on (Riahi et al. 2017; Rogelj et al. 2017a).
 30
 31
 32
 33
 34

2.3.5 *Delay and carbon lock-in*

Less ambitious CO₂ 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 CO₂ emitted into the atmosphere and global mean temperature rise (Collins et al. 2013a). Besides this clear geophysical trade-off over time, delaying greenhouse gas 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). 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. 2016a) 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 CO₂ emissions from fossil fuels and industry to decline at an annual rate of about 1.4 GtCO₂ 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 greenhouse gas 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 GtCO₂-eq yr⁻¹ in 2030 (Rogelj et al. 2016a; UNFCCC Secretariat 2016). More recent NDC studies have not fundamentally changed this range (Fujimori et al. 2016; Vandyck et al. 2016; Sanderson et al. 2016; Rogelj et al. 2016a; Iyer et al. 2015a; Hof et al. 2017; Rose et al. 2017; Fawcett et al. 2015; Rogelj et al. 2017b). In contrast, 1.5°C scenarios available to this assessment show an interquartile range of 25 to 41 GtCO₂-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. 2016a) or only under assumptions of global cooperation and sustainable lifestyles which would require great efforts to materialise in the real world (Rogelj et al. 2017b).

2.4 **Properties of 1.5°C pathways after mid-century**

The long-term characteristics of mitigation pathways are particularly uncertain due to the deep uncertainty about the ways humankind will use energy and land in the second half of the 21st century. These ways will heavily depend on long-term population levels, secular trends in economic growth and income convergence, behavioural change and technological progress. Despite this deep uncertainty, 1.5°C pathways have to conceptualise the long term future in one way or the other in order to assess their consistency with the goal of limiting warming to 1.5°C. This is because the GHG emissions development after mid-century will critically determine whether warming can remain below 1.5°C or returned to 1.5°C with some likelihood. This section aims to assess robust features of 1.5°C pathways after mid-century as well as to highlight critical assumptions that can lead to very different

1 configurations of 1.5°C societies in the second half of the century. To this end, we will discuss the
2 properties of five selected 1.5°C pathways from five integrated assessment models with different
3 dynamics of energy and land use and the deployment of CDR technologies. Three of these pathways
4 were based on assumptions of SSP1 (low population, high economic growth per capita, high
5 technological progress rate, environmentally oriented technological and behavioural change, low
6 energy and food demand per capita), one on SSP2 (medium levels for all these factors, mixed
7 orientation of technological and behavioural change) and one on SSP5 (low population, very high
8 economic growth per capita, high technological progress rate, ample fossil fuel resources, resource
9 intensive lifestyles, high energy and food demand) (Riahi et al. 2017) (see Box 1.1 on scenarios and
10 pathways). The five selected pathways will be compared to long-term properties of associated well
11 below 2°C (WB2C) pathways and put into the context of the full range of long-term developments in
12 1.5°C pathways currently in the literature (Luderer et al. 2016b; Rogelj et al. 2017a, 2015a).

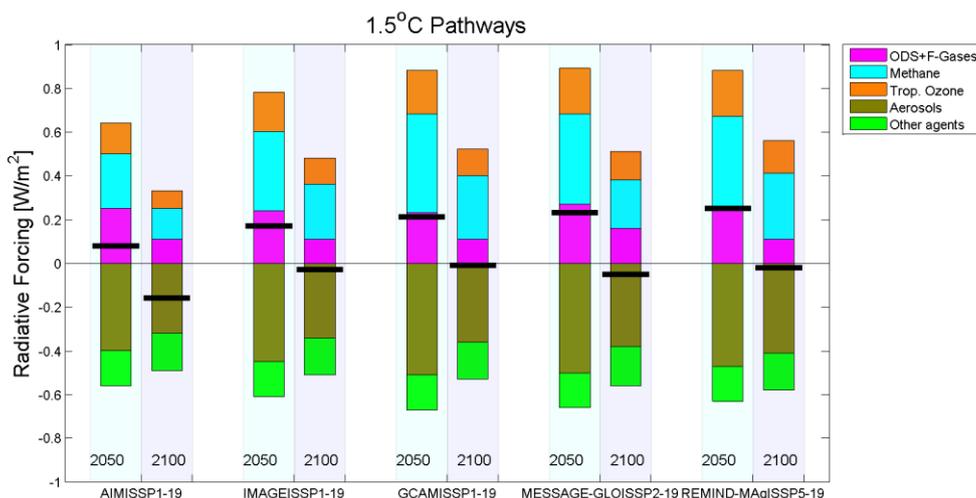
13
14 *[Note on the FOD: The literature on 1.5°C pathways is still evolving. Depending on the state of the*
15 *literature at the time of the SOD, the selection of the five pathways and the ranges deduced from 1.5°C*
16 *pathways in the scenario database for this Report will be updated for the SOD.]*

17 18 19 **2.4.1 Emissions development of 1.5°C pathways after mid-century**

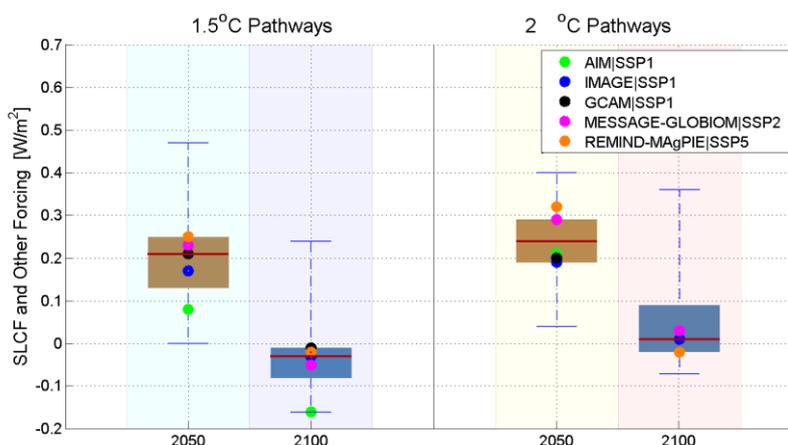
20
21 As assessed in Section 2.2 of this chapter, net CO₂ emissions in 1.5°C pathways are brought to zero
22 between 2040 and 2060. Since warming levels are determined by the cumulative amount of CO₂
23 emissions, reaching the point of carbon neutrality is required for limiting warming (Rogelj et al.
24 2015d; Matthews et al. 2009; IPCC 2013). If the 1.5°C carbon budget was overshoot by the time of
25 carbon neutrality, it would need to be returned to lower values by establishing net negative CO₂
26 emissions (Figure 2.22). Such net negative emissions can be obtained by deployment of CDR
27 technologies (Section 2.4.2). For the non-CO₂ climate forcers, it is important to distinguish between
28 long-lived greenhouse gases (LLGHG) like nitrous oxide (N₂O) and short-lived climate forcers
29 (SLCFs) like methane (see Chapter 1). (Smith et al. 2012; Allen et al. 2016). LLGHGs such as CO₂
30 are cumulative climate pollutants and therefore need to be either phased out in the second half of the
31 century or compensated by net negative CO₂ emissions. In contrast, the warming impact of SLCFs
32 is determined by their rate of emissions, i.e., they do not need to be phased out to halt warming. A
33 reduction of the emissions rate of the warming SLCFs is still beneficial as it will reduce their impact
34 and thus allow a larger budget of CO₂ emissions under the temperature limit.

35 36 37 **2.4.1.1 Short lived climate forcers and fluorinated-gases**

38 Figure 2.22 investigates the post-2050 development of radiative forcing from SLCFs, fluorinated gases
39 (F-gases) and ozone depleting substances (ODS) and a few other forcing agents in the 1.5°C pathways.
40 There is broad agreement across scenarios that positive forcing from methane, tropospheric ozone, F-
41 gases and ODS is more strongly reduced during the second half of the century than net negative
42 forcing from aerosol effects. As a result, the net forcing contribution from these substances vanishes
43 by the end of the century. This is similar to developments in WB2C pathways (Rose et al. 2014b;
44 Riahi et al. 2017) which show only a slightly higher median forcing contributions (by ca. 0.05 W m²)
45 from these forcing agents. Nevertheless, there can be substantial additional gains from deeper
46 reductions of SLCF emissions with positive forcing contribution (also called short-lived climate
47 pollutants or SLCPs). One scenario (AIM) projects particularly deep reductions in methane and ozone
48 forcing leading to a net cooling of almost -0.2 W m⁻² by 2100, which allows a larger CO₂ budget to
49 remain within the 1.5°C temperature limit (Section 2.4.2, see also Section 2.2). ODS and F-gas forcing
50 is controlled by the Montreal protocol and its Kigali Amendment on phasing out hydrofluorocarbons,
51 the largest and fastest growing group of F-gases (Velders et al. 2015). The 1.5°C pathways project
52 around 0.1 W m⁻² residual forcing in 2100, which will need to be compared with updated estimates of
53 the effect of the Kigali Amendment on total ODS and F-gas forcing by 2100.



1



2
3
4
5
6
7
8
9
10

Figure 2.22: Radiative forcing from fluorinated (F) gases, ozone depleting substances (ODS), short-lived climate forcers (incl. methane, tropospheric ozone, sulphate and nitrate aerosols, organic and black carbon, indirect aerosol effects) and other forcing agents (incl. mineral dust, stratospheric ozone and water vapour, land albedo changes) for selected 1.5°C pathways (upper panel) and the range of estimates for net forcing from all substances for 1.5°C and WB2C pathways based on the current version of the SR1.5 scenario database.

11 **2.4.1.2 Long-lived greenhouse gases**

12 The long-term development of LLGHG emissions in 1.5°C pathways is characterised by the need to
13 stay within a very tight carbon budget that at current emissions rates would be exhausted in roughly a
14 decade (Section 2.2). Figure 2.23 shows the net CO₂ and N₂O emissions from various sources in 2050
15 and 2100 in 1.5°C pathways in the literature (Luderer et al. 2016b; Rogelj et al. 2017a, 2015a). All
16 pathways obtain substantial net negative CO₂ emissions by the end of the century (Median: -13 GtCO₂
17 yr⁻¹). This net withdrawal of CO₂ from the atmosphere compensates for an overshoot of the 1.5°C
18 carbon budget before carbon neutrality is reached around mid-century. The majority of net negative
19 CO₂ emissions comes from the energy supply sector augmented by a smaller contribution from the
20 AFOLU sector. Net direct emissions from the energy demand sectors (industry, transportation,
21 residential & commercial sectors) are very low by the end of century (median ~1 GtCO₂ yr⁻¹) and
22 potentially negative.

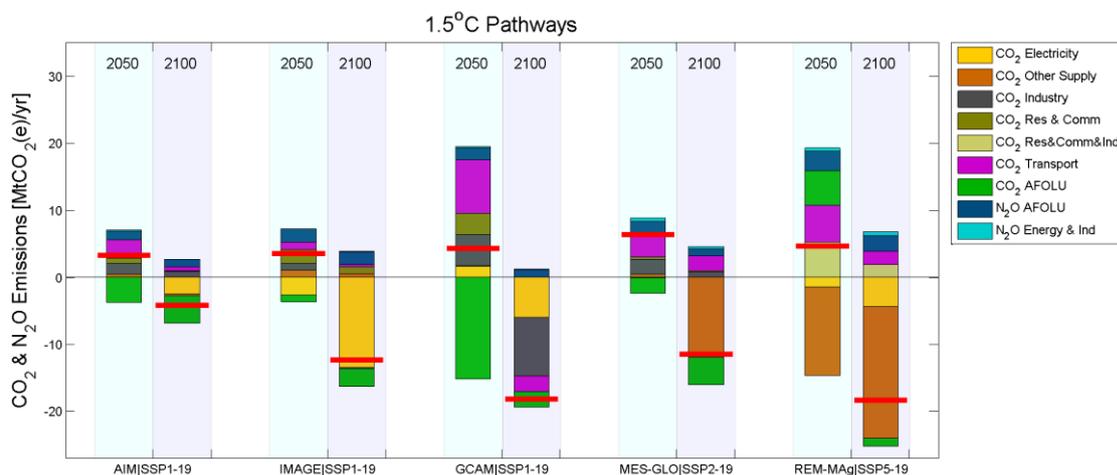
23
24
25
26
27
28

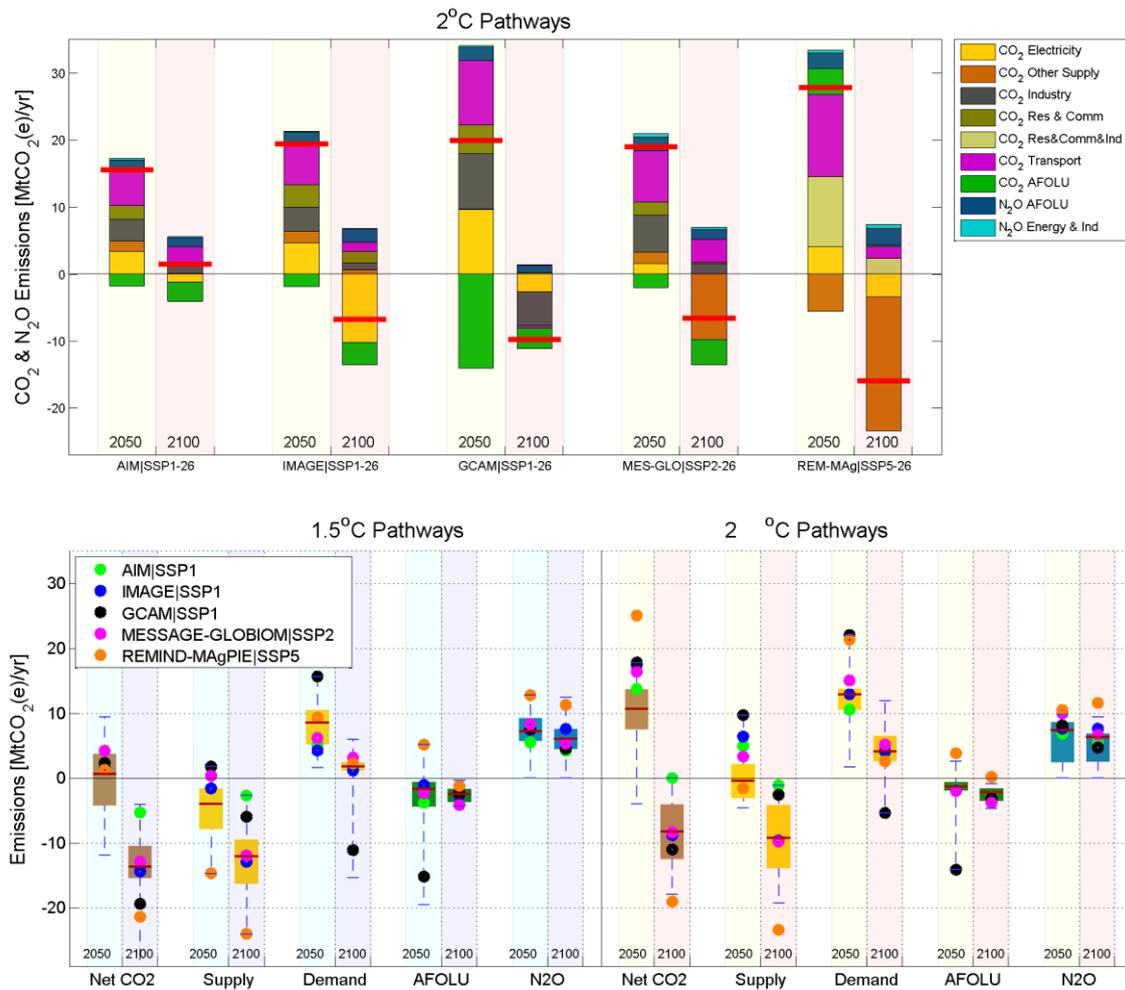
1.5°C pathways maintain substantial levels of N₂O emissions in the 2nd half of the century, which also
have to be compensated for by net negative CO₂ emissions. N₂O emissions show little reduction
between 2050 and 2100 and stay at similar levels as in WB2C pathways. This highlights the difficulty
of eliminating N₂O 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

1 substantial use of nitrogen fertilizer (Popp et al. 2017). As a result, N₂O emissions can be a major
 2 contributor to end of century LLGHG emissions, and measures to effectively mitigate them will be of
 3 continued relevance for 1.5°C societies in the second half of the century. The reduction of nitrogen use
 4 and N₂O emissions from agriculture is already a present-day concern due to unsustainable levels of
 5 nitrogen pollution (Bodirsky et al. 2012).

6
 7 1.5°C pathways differ considerably in the level of net negative emissions obtained by the end of the
 8 century ranging from -5 GtCO₂ yr⁻¹ (AIM) (Fujimori 2017) to -21 GtCO₂ yr⁻¹ (REMIND-MAgPIE)
 9 (Kriegler et al. 2017) in the selected scenarios. This is due to differences in the extent to which they
 10 overshoot the 1.5°C budget and reduce temperature after the warming peak. Part of this variation
 11 stems from differences between underlying assumptions about socio-economic drivers (SSP1 vs.
 12 SSP5) (Riahi et al. 2017), while another part is due to different assumptions about the availability of
 13 carbon dioxide removal technologies and bioenergy (Krey et al. 2014b). A key finding is that 1.5°C
 14 pathways could be identified under a considerable range of assumptions in model studies despite the
 15 tightness of the 1.5°C emissions budget (Rogelj et al. 2017a).

16
 17 Compared to WB2C pathways, the largest differences in CO₂ emissions can be seen around mid-
 18 century. While 1.5°C pathways reach zero CO₂ emissions, WB2C pathways still have median
 19 emissions levels around 10 GtCO₂ yr⁻¹ in 2050 and up to 20 GtCO₂ yr⁻¹ in the selected scenarios.
 20 These emissions mostly come from the energy end-use sectors (industry, transportation, residential
 21 and commercial/buildings), which are more strongly reduced in the first half of the century in 1.5°C
 22 pathways (Rogelj et al. 2015a). The differences in end-of-century emissions levels between 1.5°C and
 23 WB2C pathways are comparatively small. Net negative CO₂ emissions are around 4 GtCO₂ yr⁻¹ lower
 24 in the median, with roughly half of this coming from increased CDR in the energy supply sector and
 25 another half from further reductions in energy demand sectors. Thus, the emissions configuration of
 26 1.5°C and WB2C societies at the end of the century look similar. But the 1.5°C society is already
 27 closer to this configuration by mid-century, hence less additional emissions reductions and less ramp-
 28 up of CDR needs to occur in the 2nd half of the century. This underpins the finding from Section 2.3
 29 that mitigation is accelerated in 1.5°C compared to WB2C pathways.
 30





3 **Figure 2.23:** Emissions of CO₂ and N₂O for selected 1.5°C (upper panel) (Rogelj et al. 2017a) and associated
 4 2°C pathways (middle panel; AIM|SSP1, IMAGE|SSP1 and GCAM|SSP1 are WB2C pathways, MESSAGE-GLOBIOM|SSP2 a medium 2°C pathway, and REMIND-MAgPIE SSP5 slightly
 5 overshoots 2°C in median temperature projections) (Riahi et al. 2017; van Vuuren et al. 2017;
 6 Fricko et al. 2017; Kriegler et al. 2017). The lower panel shows the range of emissions by source
 7 for 1.5°C and WB2C pathways based on the current version of the SR1.5 scenario database.
 8
 9

10 **2.4.2 Carbon dioxide removal in 1.5°C pathways**

11
 12 As almost all 1.5°C pathways in the literature overshoot the 1.5°C emissions budget around mid-
 13 century, it is important to carefully assess the use of CDR technologies for realising such overshoot
 14 behaviour. Three key questions emerge: How strongly does reliance on CDR vary between 1.5°C
 15 pathways in the literature? What is implied for the extent to which limiting warming to 1.5°C by the
 16 end of the century depend on the deployment of large-scale CDR? And what are the implications of
 17 techno-economic and sustainable development considerations for the potential for implementation of
 18 CDR deployment levels in the 1.5°C pathways?
 19
 20

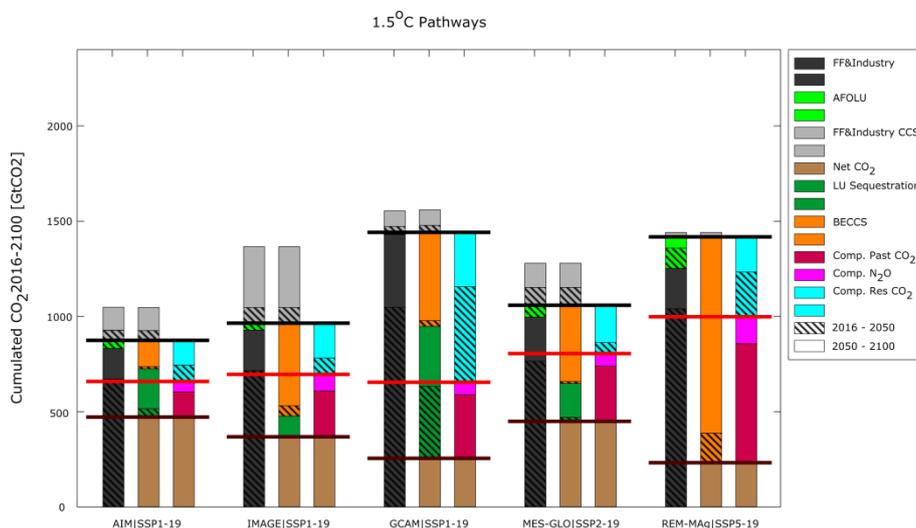
21 **2.4.2.1 Apportion of CDR to different uses in 1.5°C pathways**

22 For a proper accounting of the use and relevance of CDR in 1.5°C and WB2C pathways, it is
 23 important to keep track of the total amount of fossil/geological and terrestrial carbon that is oxidized
 24 by human activity over the 21st century (leftmost bar of grouped bars in Figure 2.24). Subtracting the
 25 geological CO₂ captured at energy and industrial installations (Fossil & Industry CCS in Figure 2.24)
 26 gives the total amount of oxidized anthropogenic carbon entering the atmosphere at some point in time

1 (horizontal black line in Figure 2.24)¹. Anthropogenic CDR from the atmosphere reduces the net flux
 2 of anthropogenic carbon into atmosphere at a given time. As long as this CDR does not exceed the
 3 positive flux of oxidized anthropogenic carbon, net CO₂ emissions remain positive and the cumulated
 4 anthropogenic CO₂ emissions continue to grow until peaking when carbon neutrality is reached
 5 (horizontal red line in Figure 2.24). The difference between the peak in cumulated CO₂ emissions and
 6 the total amount of oxidized carbon entering the atmosphere can be apportioned to CDR compensating
 7 for residual CO₂ emissions at the same point in time (CO₂ in rightmost bars in Figure 2.24). Some of
 8 this compensation occurs before carbon neutrality is reached (dark blue in Figure 2.24) and thus
 9 accelerates the drawdown of net CO₂ emissions towards zero. The other part compensates residual
 10 gross CO₂ emissions after carbon neutrality has been established (light blue in Figure 2.24). If the
 11 amount of CDR exceeds the amount of anthropogenic carbon entering the atmosphere, net negative
 12 CO₂ emissions emerge that in effect draw down the cumulative amount of anthropogenic CO₂ in the
 13 atmosphere. The difference between net cumulative emissions at their peak and by the end of the
 14 century (horizontal brown line in Figure 2.24) indicates the amount of CDR that is used to compensate
 15 for residual emissions of other LLGHG, predominantly N₂O, after the point of carbon neutrality
 16 (Comp. N₂O in Figure 2.24) as well as excess CO₂ emissions in the past that led to an overshoot of the
 17 1.5°C budget (Comp. Past CO₂). Table 2.10 summarizes the different uses of CDR.

18
 19 Figure 2.24 and Table 2.10 show that the amount and use of CDR can vary considerably across 1.5°C
 20 pathways, even among those that are derived under identical shared socio-economic assumptions
 21 (SSP1). In the selected scenarios, cumulated CDR deployment ranges from ca. 400 GtCO₂ (AIM) to
 22 1200 GtCO₂ (GCAM, REMIND-MAGPIE) and is apportioned differently to the various CDR uses.
 23 Some scenarios dedicate half or more of the CDR to the compensation of residual CO₂ emissions
 24 (AIM, GCAM), while other scenarios use half or more of the CDR to compensate for excess emissions
 25 in the past (IMAGE, MESSAGE-GLOBIOM, REMIND-MAGPIE).

26
 27 *[Note on the FOD: Depending on the availability of studies exploring 1.5°C pathways with very*
 28 *limited CDR availability, the assessment of these ranges and the selection of pathway examples will be*
 29 *updated for the SOD.]*
 30



31

¹ Oxidized carbon from bioenergy use is not counted if it does not change the terrestrial carbon pool. In this case it implies a recycling of atmospheric carbon dioxide on annual to decadal timescales. If bioenergy use affects the terrestrial carbon pool (Heck et al. 2016), this side-effect would be accounted for in the AFOLU sector.

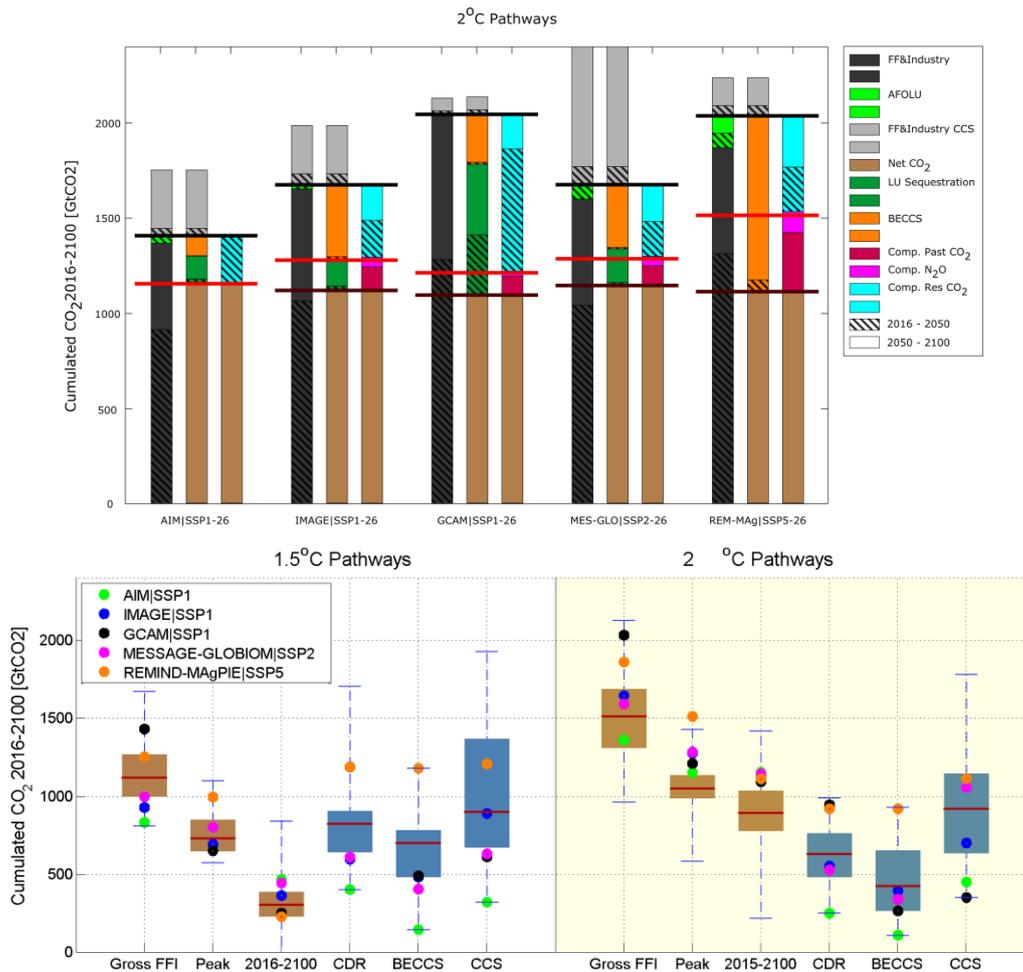


Figure 2.24: Cumulative CO₂ emissions accounting for selected 1.5°C pathways (upper panel) and 2°C pathways (middle panel, see Figure 2.23 for references to these pathways). Each group of three bars presents the accounting for one pathway. Leftmost bars show oxidised anthropogenic carbon separated in fossil combustion and industrial processes without and with CCS and AFOLU. Centre bars show deployment of CDR technologies (land based sequestration and BECCS) and CCS. Rightmost bars apportion CDR to its different uses (see Table 2.10). The lower panel shows the range of cumulative CO₂ emissions (oxidised carbon from fossil fuel combustion and industrial processes entering the atmosphere = Gross FFI; peak net cumulative emissions = Peak, 2016-2100 net cumulative emissions = 2016-2100), CDR (total amount and BECCS) and CCS (including BECCS and CCS at fossil fuel installations) for 1.5°C and WB2C pathways based on the current version of the SR1.5 scenario database.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26

1 **Table 2.10:** Uses of CDR for limiting warming in the long term and cumulative amounts of CO₂ emissions and
 2 CDR in 1.5°C pathways.

	Residual emissions	CDR use	Interquartile range in SR1.5C scenario database (% peak cumulative CO ₂ emissions)
	Keeping temperatures stable (at 1.5°C, but also any other low level)		
	Residual CO ₂ emissions from hard to decarbonise activities like aviation, shipping, and chemical and high temperature processes in industry.	CO ₂ emissions removal required to compensate for residual emissions in order to achieve and maintain carbon neutrality	34-67%
	Residual long-lived non-CO ₂ GHGs	CO ₂ emissions removal beyond carbon neutrality to compensate for warming due to continuing accumulation and committed warming of long-lived GHGs	8-15% (N ₂ O only)
	Deep reductions of SLCF emissions to stable minimum levels	No explicit CO ₂ emissions removal required to limit temperatures (but SLCF-induced warming reduces the CO ₂ budget to stay under a given temperature limit)	N/A
	Declining temperatures after an earlier higher peak		
	N/A	Additional CO ₂ removal beyond compensating for residual CO ₂ and long-lived non-CO ₂ GHGs.	33-52%
	Cumulative emissions and CDR levels in 1.5°C pathways		Interquartile range in SR1.5C scenario database
	Oxidised anthropogenic carbon entering the atmosphere		1050-1320 GtCO ₂
	Peak cumulative emissions in the 21 st century		650-840 GtCO ₂
	Net cumulative emissions 2016-2100		230-380 GtCO ₂
	Total CDR 2016-2100		710-900 GtCO ₂

3
 4 The use of CDR to compensate for excess emissions in the past has received most attention in the
 5 literature since the Fifth Assessment Report (Fuss et al. 2014a) and was often connected to a concern
 6 that the expectation of CDR becoming available at large scale would postpone early mitigation efforts
 7 (Anderson and Peters 2016). Its importance is significantly increased in 1.5°C pathways compared to
 8 WB2C pathways, with CO₂ budget drawdowns of 300-510 GtCO₂ in the former compared to 80-290
 9 GtCO₂ in the latter (interquartile range from the scenarios available in the database to this assessment).
 10 This does not imply, though, that near-term mitigation efforts in 1.5°C pathways are relaxed. In
 11 contrast, they are considerably tightened compared to WB2C pathways as discussed in Section 2.3. In
 12 essence, the 1.5°C budget is so tight that associated pathways imply both very stringent near-term
 13 mitigation and a significant amount of net negative emissions in the second half of the century. To a
 14 lesser extent, this result already held true for WB2C pathways (Clarke et al. 2014). Figure 2.24 (lower
 15 panel) shows that end-of-century budgets are roughly 600 GtCO₂ smaller in 1.5°C than in 2°C
 16 pathways, with approximately two thirds (about 400 GtCO₂) coming from further reductions of gross
 17 anthropogenic emissions of oxidised geological carbon (fossil fuel combustion and industrial
 18 processes; FFI) and the other third (about 200 GtCO₂) from increased net negative emissions via CDR
 19 (comparison of median levels). As a consequence, the total amount of CDR over the 21st century is
 20 approx. 200 GtCO₂ higher in 1.5°C pathway vs. WB2C pathways (comparison of median levels: 820
 21 vs 630 GtCO₂).

22
 23 The REMIND-MAGPIE SSP5 scenarios show consistently larger CO₂ budget drawdowns in both the
 24 1.5°C and 2°C cases. This is due to the underlying socio-economic storyline of resource and energy

1 intensive consumption as well as ample fossil fuel availability (SSP5) with only a gradual phase in of
2 climate policy until 2040 (Kriegler et al. 2017). They therefore exhibit the largest temperature
3 overshoot relative to 2100, barely remaining well below 2°C in their 1.5°C pathway and temporarily
4 exceeding 2°C in the 2°C pathway (which therefore does not fall into the WB2C class). These
5 scenarios were not developed as an example of prudent mitigation strategies towards achieving the
6 1.5°C and 2°C temperature goals, but as a point of comparison with high challenges to mitigation.
7 They are used here in this spirit as well. While the SSP5 assumption still allows reaching the 1.5°C
8 limit by 2100 in this particular model application, it does so at the cost of massive CDR deployment
9 (1200 GtCO₂ yr⁻¹) predominantly used for an extensive drawdown of the CO₂ budget until 2100 (770
10 GtCO₂ yr⁻¹).

11 2.4.2.2 CDR technologies and deployment levels in 1.5°C pathways

12 There are a number of approaches to actively remove carbon dioxide from the atmosphere. They
13 include approaches to enhance terrestrial carbon storage in plants and soils (Lal 2004) such as
14 afforestation and reforestation (Nilsson and Schopfhauser 1995), changing agricultural practices (Lal
15 2004), biochar sequestration (Smith 2016), and restoration of peatlands and wetlands. Other
16 approaches aim to store atmospheric carbon dioxide in geological formations and include the
17 combination of biomass combustion for energy production with carbon capture and storage (BECCS)
18 (Obersteiner et al. 2001; Keith and Rhodes 2002) as well as direct air capture (DAC) of CO₂ using
19 chemical solvents (Zeman and Lackner 2004; Keith et al. 2006). A third group focuses on the
20 mineralisation of atmospheric carbon dioxide (Mazzotti et al. 2005) including enhanced weathering of
21 rocks (Hartmann et al. 2013). A fourth group is concerned with the sequestration of carbon dioxide in
22 the oceans including ocean iron fertilization (Denman 2008) and ocean (Kheshgi 1995; Rau 2011;
23 Ilyina et al. 2013). A fifth group includes approaches to use atmospheric carbon in industrial products
24 so that it is locked away on timescales of centuries (Carbon Capture and Usage – CCU). There are also
25 proposals to remove methane, nitrous oxide and halocarbons via photocatalysis from the atmosphere
26 (De_Richter et al. 2017). Only some of these approaches have so far been considered in integrated
27 assessment and other pathway models. The mitigation scenario literature up to AR5 mostly included
28 BECCS and to a more limited extent afforestation and reforestation (Clarke et al. 2014).
29 Since then, some well below 2°C and 1.5°C pathways including additional CDR options such as
30 Direct Air Capture are becoming available (Chen and Tavoni 2013; Marcucci et al.). Other more
31 speculative approaches, in particular ocean-based CDR and removal of Non-CO₂ gases, have not yet
32 been taken up by the literature on mitigation pathways.
33

34
35 Figure 2.24 shows the deployment of individual CDR measures in 1.5°C pathways. For the time being,
36 this assessment will focus on BECCS and afforestation. Overall the largest contribution comes from
37 BECCS (interquartile range of 480-760 GtCO₂), but afforestation plays a major role in some of the
38 selected pathways (AIM, GCAM). There is correlation between the choice of afforestation vs. BECCS
39 and the extent to which CDR is used for compensating residual CO₂ emissions at a given point in time
40 versus excess emissions in the past. This is due to the timing of the two options in the mitigation
41 pathways. Although the AFOLU sector is a net sink by 2100 in almost all 1.5°C pathways, the amount
42 of end-of-century CO₂ uptake by this sector is much smaller compared to BECCS deployment in the
43 energy sector (Figure 2.23). This can be different around mid-century where for example GCAM
44 projects large terrestrial CDR uptake from large-scale afforestation activities. The temporal profile of
45 CDR via afforestation reflects the fact that CO₂ uptake from afforestation ceases once forests are
46 grown. In 1.5°C pathways afforestation is mostly deployed before and around carbon neutrality, while
47 BECCS is projected to be used predominantly in the 2nd half of the century (Figure 2.25). There are
48 trade-offs between the two technologies when deployed simultaneously due to their shared demand for
49 land. In this case overall CDR increases, while the deployment of each individual measure is reduced
50 (Humpenöder et al. 2014).

51
52 A closer look into the sectorial breakdown of CO₂ emissions in the 1.5°C pathways (Figure 2.23)
53 reveals that late century CDR predominantly comes from BECCS in the energy supply sector. Models
54 differ whether BECCS is primarily applied in electricity generation (e.g., IMAGE, van Vuuren et al.
55 2017) or biofuel production (e.g., MESSAGE-GLOBIOM, Fricko et al. 2017, REMIND-MAGPIE

1 Kriegler et al. 2017). There is also considerable variation in projections of long-term CDR deployment
2 in the industry sector, e.g., bioenergy use coupled with CCS for generating industrial process heat and
3 bioplastics. One model (GCAM) projects the largest CDR contribution in the industry sector,
4 substituting for BECCS deployment in the energy supply sector (Calvin et al. 2017).

5 *[Note on the FOD: This discussion will be updated for the SOD to capture an emerging literature on*
6 *mitigation pathways with extended portfolios of CDR technologies]*

8 2.4.2.3 Sustainability implications of CDR deployment in 1.5°C pathways

9 Individual CDR options have different characteristics and therefore carry different risks for their
10 sustainable deployment at scale (Smith et al. 2016). Terrestrial CDR options, BECCS and enhanced
11 weathering of rock powder distributed on agricultural lands require land. Those options – like
12 afforestation and BECCS that directly compete with other land uses – can have significant impacts on
13 agricultural and food systems (Creutzig et al. 2012; Popp et al. 2017; Kreidenweis et al. 2016; Smith et
14 al. 2016) as well as ecosystems (Heck et al. 2016; Boysen et al. 2016). BECCS using dedicated
15 bioenergy crops can substantially increase agricultural water demand (Bonsch et al. 2014) and
16 nitrogen fertilizer use. DAC and BECCS rely on CCS and require safe storage space in geological
17 formations. Some approaches like DAC have high energy and water demand. There are also a few
18 potential synergies between CDR options. Enhanced weathering of rock powder and biochar may
19 substitute for parts of nitrogen fertilizer use and enhance terrestrial carbon storage. An important
20 consideration for CDR which basically shifts carbon from the atmosphere to the geological, oceanic or
21 terrestrial carbon pools is the permanence of carbon stored in these different pool (Matthews and
22 Caldeira 2008; Jones et al. 2016). Terrestrial carbon storage is subject to particular concerns about
23 permanence as terrestrial carbon can be returned to the atmosphere on decadal timescales by a variety
24 of mechanisms such as soil degradation and forest fires. There are similar concerns about outgassing
25 of CO₂ from the oceans. In contrast, the risk of CO₂ leakage from deep geological storage has been
26 suggested to decline over time after CCS operations have ceased (Torvanger et al. 2012).

27
28 The sustainability implications of CDR options are discussed in greater detail in Chapter 4. Here we
29 focus on the land and CCS requirements of afforestation and BECCS in 1.5°C pathways that are key
30 drivers of many of the sustainability issues raised above (Smith et al. 2016). Figure 2.25 shows the
31 land requirements for BECCS and afforestation in the selected 1.5°C pathways and compares it with
32 related land requirements in WB2C pathways. In pathways that allow for large-scale afforestation in
33 addition to BECCS, land demand for afforestation is larger (600-1600 Mha) than for BECCS (100-800
34 Mha). This is because the amount of carbon to be stored in soils and trees on a unit of land is limited,
35 while BECCS allows continuous sequestration of CO₂ from biomass year by year. The combined land
36 demand of the two CDR options (800-1800 Mha) is realised by a conversion of pasture (400-1200
37 Mha) and cropland for food production (50-800 Mha) as well as expansion into natural land (0-700
38 Mha). These dynamics are heavily influenced by assumptions about future population levels, food
39 crops and livestock demand. An SSP1 world with declining population in the second half the century
40 (from a peak of slightly above 8 billion to 7 billion by 2100), limited meat consumption and food
41 waste, and high agricultural productivity has lower trade-offs for pasture and cropland conversion than
42 worlds with population levels around 9 billion by the end of the century (SSP2) or high calorie and
43 meat consumption levels (SSP5) (Popp et al. 2017). Land use changes do not differ significantly
44 between 1.5°C and WB2C pathways in the majority of selected pathways. The exceptions are AIM
45 SSP1 which projects more than a doubling of land-use changes before mid-century at unchanged land-
46 use change levels thereafter, and REMIND-MAGPIE SSP5 which moves forward a substantial part of
47 land-use changes between 1.5°C and 2°C cases.

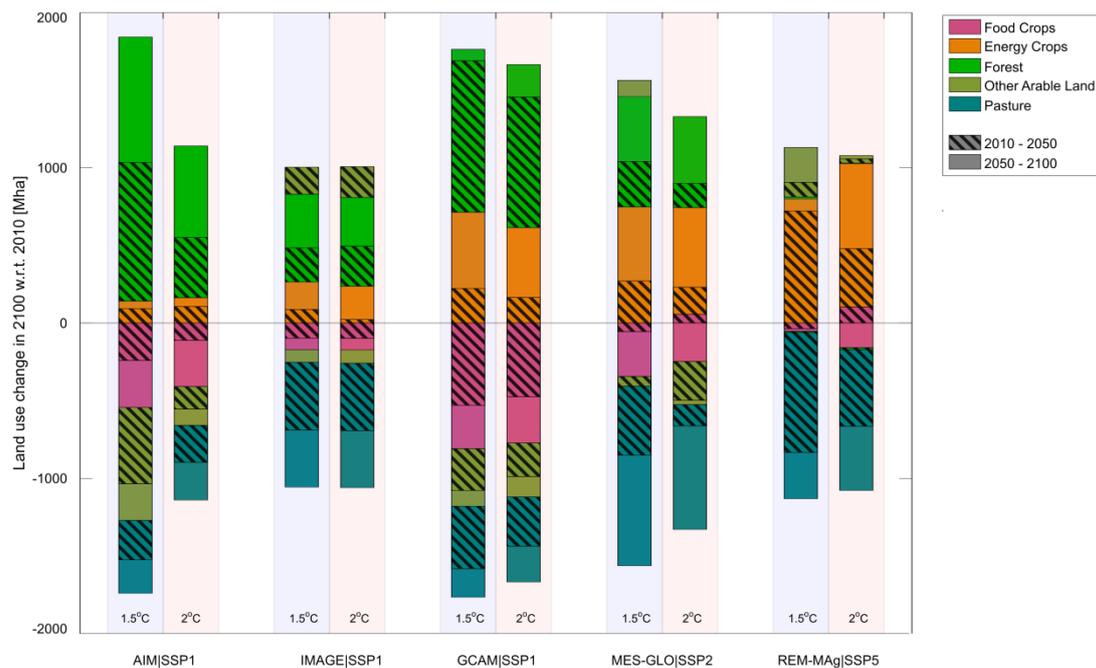


Figure 2.25: Land requirements (in 2100 compared to 2010) for afforestation and BECCS in the selected 1.5°C pathways and compared with associated 2°C pathways from the same models under the same SSPs (see Figure 2.23 for references to these pathways).

The quantity of CO₂ stored over this century in 1.5°C pathways ranges from 750-1360 GtCO₂, which is similar to what is found in WB2C pathways (700-1320 GtCO₂; interquartile ranges from scenario database to this report). The IPCC (2005) found that available evidence suggests that, worldwide, it is *likely* that there is a technical potential of at least about 2000 GtCO₂ 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 geologic storage resource as well as the potential demand for geologic storage of mitigation pathways, and found that the cumulative demand for CO₂ storage was small compared to their practical capacity (as defined by Bachu et al. 2007a) of 3900 GtCO₂ 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 GtCO₂ (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 CO₂ storage exceeds their lower estimate of regional storage available for some regions. However, storage capacity is not solely determined by the geological setting, and Bachu (2015) describes storage engineering practices that could further extend storage capacity estimates.

An important question is to what extent bioenergy and CCS deployment is driven by BECCS. 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 can still be used to substitute fossil-fuel based liquids, gases and solids (Klein et al. 2014). In contrast, CCS deployment is mostly driven by BECCS and, if available, DAC in 1.5°C and WB2C pathways (Marcucci et al.; Rogelj et al. 2017a).

1 *[Note on the FOD: The discussion of the relationship between bioenergy and BECCS will be updated*
2 *for the SOD, depending on the availability of new studies exploring this link.]*
3
4

5 **2.4.3 Energy use in 1.5°C pathways after mid-century**

6

7 As discussed in Section 2.3, 1.5°C pathways require a fundamental transformation of the energy
8 system by mid-century. It is an important question what end points of the energy transformation are
9 projected for the 2nd half of the century. The way humankind produces and uses energy after mid-
10 century will be closely connected to future land use, markets, and societal institutions in a 1.5°C world
11 as it is a key determinant how carbon neutrality can be achieved and maintained. Clear visions of
12 possible end points of the 1.5°C energy transformation are important to set expectations and inform
13 key choices on re-configuring global energy systems today. At the same time it is deeply uncertain
14 which key technologies, preferences and institutions will shape the energy system 50 to 80 years out.
15 It is therefore necessary to explore different visions of the global energy system of the future with a
16 scenario approach (Riahi et al. 2012). Here we will discuss the range of long-term visions presented by
17 model-based 1.5°C pathways in the literature and ask the question to what extent they are similar to
18 energy futures in WB2C pathways. We also ask to what extent they cover the full range of
19 technological and behavioural visions for the global energy transformation. An extended discussion of
20 visions of carbon neutral energy systems will be presented in Chapter 4.
21
22

23 **2.4.3.1 Energy demand**

24 A good starting point to explore long-term energy futures is future demand for energy services. The
25 narratives of the SSPs provide a broad range of visions of energy service demand from resource
26 efficient and environmentally friendly (SSP1) to resource intensive energy consumption patterns
27 (SSP5) (O'Neill et al. 2017). Integrated assessment models adopt these visions as exogenous
28 assumptions under which mitigation pathways are developed (Bauer et al. 2017). The introduction of
29 climate policy further influences the composition of final energy demand for providing these services,
30 both by lowering it due to the carbon penalty on fossil fuels and by re-structuring it towards energy
31 carriers that can be provided in a carbon neutral way more easily than others (i.e., electricity and
32 hydrogen vs. liquids, gases and solids).

33 Figure 2.26 shows the structure of global final energy demand in 2050 and 2100 as projected in 1.5°C
34 pathways. Final energy demand is increased by 20% to 60% relative to 2014 levels (interquartile
35 range, 35% in the median), but several pathways based on SSP1 project lower energy demand than
36 today despite strong growth in economic output until the end of the century. Electrification continues
37 throughout the second half of the century (up to 60-70% of final energy) leading to a four to six fold
38 increase in electricity demand by the end of the century relative to today (Rogelj et al. 2017a). Since
39 the electricity sector is completely decarbonised by mid-century in 1.5°C pathways, electrification is
40 the primary means to decarbonise energy end use. Electrification is strongest in the residential and
41 commercial sector, but many pathways also project the electrification rate of industry to reach 50% or
42 higher levels by the end of the century. Transport electrification rates are projected to be lower due to
43 assumed limits to electrifying aviation, shipping and road freight transport even in the long run. Even
44 though some pathways include an increased use of hydrogen in the transport sector, most continue to
45 rely on liquids and in some cases gases to cover the majority of transport energy demand. This
46 constitutes a decarbonisation bottleneck which keeps the transport sector energy-constrained in the
47 second half of the century in 1.5°C pathways.
48
49

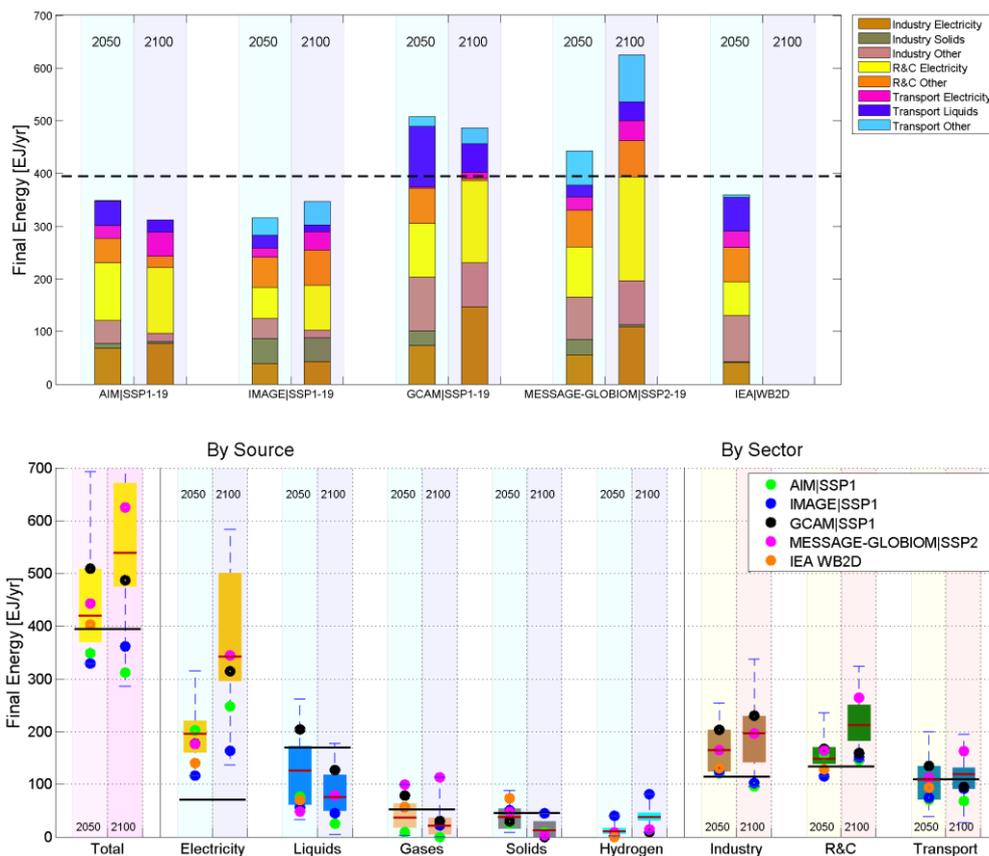


Figure 2.26: Final energy consumption for four selected 1.5°C pathways and the IEA / IRENA 2017) (top panel) and across the range of 1.5°C pathways collected in the SR1.5 database for the assessment in this chapter. Black lines indicate values of final energy consumption in 2014 (IEA 2016).

Combined with increased liquids use in industry, the continued demand for transport liquids keeps liquids the second largest contributor to final energy demand by the end of the century, albeit at half the level of present day liquids use and at four times lower level than end of century electricity demand (median estimates in Figure 4.26). 1.5°C pathways project that around 70-160 EJ of final energy (interquartile range) 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 several 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 CO₂ emissions. However, as discussed in Section 2.4.2., 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).

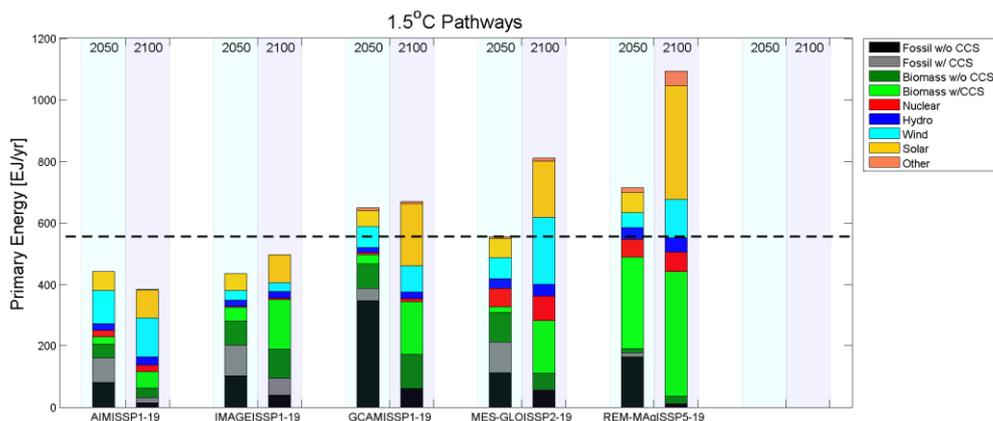
2.4.3.2 Energy Supply

The energy supply mix in 1.5°C pathways is tailored to meet the projected demand of final energy carriers at very low emissions levels. Residual oil and gas use without CCS is limited to 10-70 EJ yr⁻¹ (interquartile range, median 45 EJ yr⁻¹) by the end of the century, reflecting the decarbonisation bottlenecks in the transport sector (Figure 2.17). These residual emissions are neutralised by CDR deployment (Section 2.4.2). Additional fossil fuel combustion combined with CCS occurs at even lower levels at point sources in the industry sector (0-50 EJ yr⁻¹, median 20 EJ yr⁻¹). The remainder of primary energy supply is carbon free. Electricity is predominantly provided by solar and wind power

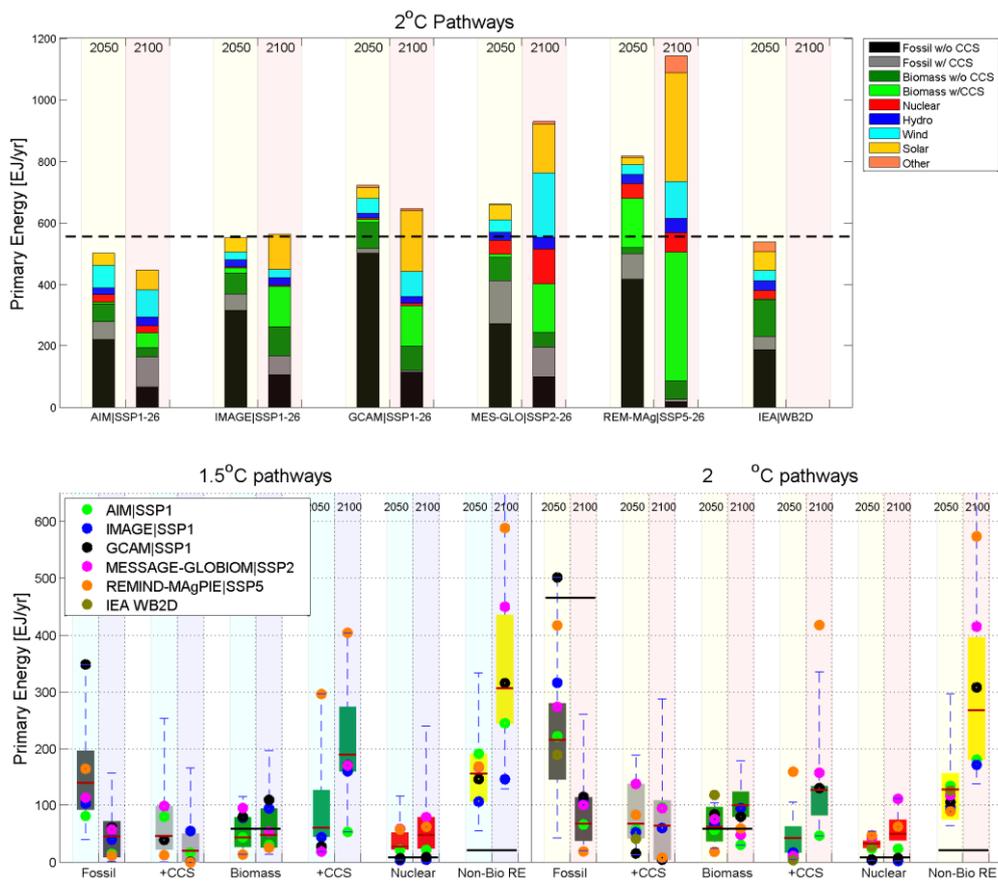
1 in most 1.5°C pathways. As electricity is the dominant final energy carrier in the second half of the
 2 century, non-biomass renewables (including hydro, solar and wind power) make up the largest portion
 3 of primary energy supply by 2100 ranging between 240 and 420 EJ yr⁻¹ (interquartile range, median
 4 320 EJ yr⁻¹) (Luderer et al. 2014; Pietzcker et al. 2016). Nuclear power plays a much smaller role in
 5 the electricity sector with large disagreement between models (Kim et al.). Some 1.5°C pathways no
 6 longer see a role for nuclear fission by the end of the century, while others still project 80 EJ yr⁻¹ of
 7 nuclear power in 2100. Bioenergy is a major supplier of primary energy for reasons discussed above
 8 (220-400 EJ yr⁻¹ interquartile range, median 250 EJ yr⁻¹). The largest part of bioenergy is used in
 9 combination with CCS (Rose et al. 2014a).

10
 11 While the amount and structure of final energy demand is very similar in 1.5°C and WB2C pathways,
 12 there are some significant differences in the underlying primary energy mix. As the energy transition
 13 is accelerated by several decades in 1.5°C pathways, residual fossil-fuel use without CCS is lower in
 14 2050, while combined hydro, solar, wind power deployment is higher. By the end of century, both is
 15 still the case indicating that unabated residual fossil fuel use is further replaced with carbon-free
 16 alternatives rather than neutralised via CDR. Nevertheless, CDR deployment levels are higher in 1.5°C
 17 pathways due to the larger overshoot of the carbon budget (Section 2.4.2). This leads to a substantial
 18 increase of bioenergy for BECCS by around 50 EJ yr⁻¹ (median levels) compared to WB2C pathways.
 19 Fossil fuel use with CCS is strongly reduced in 1.5°C pathways since significantly higher carbon
 20 prices make CCS installation with capture rates below 99% increasingly uneconomic (Rogelj et al.
 21 2017a).

22



23



1

2

3 **Figure 2.27:** Primary energy supply for five selected 1.5°C pathways (top panel) and associated 2°C pathways
 4 plus the IEA’s recently published WB2D scenario (IEA / IRENA 2017) (middle panel) and across
 5 the range of 1.5°C pathways collected in the SR1.5 database for the assessment in this chapter
 6 (lower panel. Black horizontal lines indicate values of primary energy supply in 2014 (IEA 2016).
 7
 8

9 **2.4.3.3 Alternative visions of carbon neutral energy systems**

10 There are a number of alternative visions of carbon neutral energy systems with less reliance on
 11 bioenergy that are currently not yet covered by global mitigation pathway modelling. One option is to
 12 further reduce energy demand for mobility and manufacturing to levels that make residual liquids and
 13 gases use negligible. Associated measures and radical demand reduction scenarios are assessed in
 14 Chapter 4 of this report. To present a qualitative difference from the range of 1.5°C and WB2C
 15 pathways in the literature, those scenarios would need to suggest a combined global energy demand
 16 for industry and transport of less than 100 EJ yr⁻¹ at the end of the century (Figure 2.26).
 17 Other visions rely on a complete substitution of liquids and gases use by electricity, hydrogen or some
 18 other carbon-free energy carrier or on the production of carbon-neutral hydrocarbons, e.g., via
 19 combination of hydrogen generated from renewable electricity and carbon dioxide captured from the
 20 atmosphere (Zeman and Keith 2008). Alternatively, algae are considered as a bioenergy source with
 21 much more limited implications for land use and agricultural systems (Walsh et al. 2016). As a further
 22 alternative, CDR measures with permanent storage (mineralisation and enhanced weathering) are
 23 investigated as a substitute for terrestrial CDR measures and BECCS (Mazzotti et al. 2005; Hartmann
 24 et al. 2013). Progress in the understanding of the potential, economics and viability of these alternative
 25 ways to achieve and maintain carbon neutral energy systems in the second half of the century can
 26 affect the characteristics of 1.5°C mitigation pathways assessed here.

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

This section aims to draw attention to 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 that can be derived from the existing literature and scenario comparison exercises. Attention is also given to uncertainties and critical assumptions underpinning mitigation pathways and associated outcomes. The aspects discussed hereafter indicate unprecedented intra- and intergenerational policy and geopolitical challenges. The challenges and opportunities identified in this section are also further elaborated in Chapters 3, 4 and 5.

2.5.1 Policy narratives and potential implications

More than a decade ago, experiments with integrated assessment models most often created 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 (Clarke et al. 2014). 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).

In the last decade, model experiments have been developed that diverge from these idealised policy assumptions with an 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. Examples of some of the barriers that have been modelled and explored in multi-model comparisons are (i) fragmented policy regimes in which some regions champion immediate climate mitigation action (for example, starting from 2010 or 2020) while other regions join this effort with a delay of one or more decades (Clarke et al. 2009; Blanford et al. 2014; Kriegler et al. 2015a), (ii) prescribed near-term mitigation efforts (until 2020 or 2030) after which a global mitigation targets is attempted to be achieved (Tavoni et al. 2012; Kriegler et al. 2015a; Riahi et al. 2015; Luderer et al. 2013a, 2016c; Rogelj et al. 2013), or (iii) variations in technology preferences in mitigation portfolios (Edenhofer et al. 2010; Tavoni et al. 2012; Luderer et al. 2012; Krey et al. 2014b; Kriegler et al. 2014a; Riahi et al. 2015). In addition to large model intercomparison studies, dedicated single model studies have also explored other policy variations, for example, how the reliability of national institutions influences investment risk and hence climate mitigation investment decisions (Iyer et al. 2015b), and find that stringent mitigation is impaired by these more sophisticated investment assumptions.

Recent integrated modelling activities that use the framework of the Shared Socioeconomic Pathways (O’Neill et al. 2014), and for which also 1.5°C scenarios are available (Rogelj et al. 2017a), apply a structured set of second-best policy assumptions that are consistent with the overall storylines of the respective SSPs. These are called ‘Shared Policy Assumptions’ (SPAs), and play a key role in linking socioeconomic pathways to forcing and climate related outcomes (Kriegler et al. 2014b). These assumptions specify the level of global cooperation in efforts to reduce emissions (particularly in the near term), the level of stringency over time, the sectoral coverage and the level of effectiveness of land-use mitigation (Riahi et al. 2017; Kriegler et al. 2014b). Through a combination of a set of policy assumptions for fossil fuels and industry and for the land-use sector, five distinct policy contexts have been defined in line with each respective SSPs (Table 2.11). All quantified SSP scenarios assume fragmented mitigation policies until 2020, and vary in global convergence thereafter (Riahi et al. 2017). Policy assumptions which imply that climate change mitigation action is delayed from what would be possible in a fully cooperative world strongly influence the achievability of stringent mitigation targets, including limiting warming to 1.5°C (Rogelj et al. 2013; Luderer et al. 2013a).

1 Studies using the structured set of socioeconomic and policy assumptions of the SSPs indicate that the
2 mitigation effort required to achieve a specific climate forcing target greatly depends on the SSP
3 baseline scenario (Riahi et al. 2017; Bauer et al. 2017; Rogelj et al. 2017a), and hence on the path
4 followed in terms of technological and societal development. Policy-driven scenarios that encompass
5 lower energy intensity and limit energy demand reduce the risks of stabilisation targets becoming
6 unreachable (Clarke et al. 2014; Riahi et al. 2015). SSP1 hence translates (by design) into relatively
7 low mitigation challenges, whereas SSP3 and SSP5 describe futures that pose the highest mitigation
8 challenges. This is reflected in the stringent mitigation scenarios in line with 1.5°C that have recently
9 been modelled with the SSPs (Rogelj et al. 2017a). An overview of participating models, successful
10 (feasible) scenarios and related combinations of SSPs and SPAs is provided in Table 2.12. None of the
11 IAMs could produce a 1.5°C scenario under SSP3/SPA3 assumptions, due to the impossibility under
12 its policy assumptions to achieve globally coordinated mitigation action before mid-century. By then,
13 a carbon budget much larger than what is admissible for limiting warming to 1.5°C is already locked
14 in and emitted. Combined with the small technological capacity to reduce or offset CO₂ emissions and
15 the high GHG emissions from the land-use sector, reaching the low forcing levels required to be in
16 line with a warming of 1.5°C is not possible under these policy and socioeconomic assumptions. Also
17 under other socioeconomic and policy assumptions achieving the stringent forcing targets in line with
18 1.5°C becomes very challenging. For example, in the very unequal yet environmentally conscious
19 world of SSP4, some models cannot limit radiative forcing to low levels because of the inability to
20 control emissions from land-use under the assumptions of this SSP. Policy assumptions can also be
21 varied further within one socioeconomic world. For example, one multimodel intercomparison study
22 (Luderer et al. 2016a) explored the effect of assuming implementation of the current NDCs until 2030
23 on 1.5°C pathways and stringent reductions thereafter, and finds that this delay in globally coordinated
24 actions leads to many models finding no options anymore to stay within the carbon budget during the
25 21st century.

26
27

1 **Table 2.11:** Summary of Shared Policy Assumptions assumed for climate change mitigation pathways according to the overall storylines of the respective SSPs and their
 2 associated mitigation challenges. Source: (Riahi et al. 2017)
 3

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	Early accession with full regional cooperation on climate policies targeting emissions from fossil-fuel use and industry after 2020 (F1)	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 (LP)	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	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 (F2)	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 (LD)	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	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 \$ yr ⁻¹ or higher in 2020) join global regime between 2020–2040, while lower income regions start the transition during the period 2030–2050 (F3)	Very limited coverage and limited pricing of land use emissions, due to implementation barriers and high transaction costs. (LN)	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	Early accession with full regional cooperation on climate policies targeting emissions from fossil-fuel use and industry after 2020 (F1)	Intermediately effective coverage and pricing of land use emissions (limited REDD, but effective coverage of agricultural emissions) (LD)	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	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 (F2)	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 (LP)	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.
-----------	---	--	---	---

1

Table 2.12: Summary of models attempting to create scenarios with an end-of-century forcing of 1.9 Wm^{-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 Wm^{-2} target were already found to be unachievable in an earlier study. SSP3 - SPA3 for a more stringent 1.9 Wm^{-2} radiative forcing target have thus not been attempted anew by many modelling teams. Marker implementations of each SSP1 are indicated in blue. Source: (Rogelj et al. 2017a)

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 (OE)	1	1	X	0	1
IMAGE	Hybrid (system dynamic models and GE for agriculture)	1	1	0*	X	X
MESSAGE-GLOBIOM	Hybrid (systems engineering PE model)	1	1	0*	X	X
REMIND-MAgPIE	General equilibrium (GE)	1	1	X	X	1
WITCH-GLOBIOM	General equilibrium (GE)	1	1	0	1	0

2.5.1.1 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, ambitious 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 (Clarke et al. 2014; Luderer et al. 2016c; Blanford et al. 2014), such regimes also include the current NDCs (Fawcett et al. 2015; Rogelj et al. 2017b; Hof et al. 2017). In other words, weak short-term policy mitigation efforts and fragmented scenarios use up a large share of the long-term cumulative carbon budget before 2030-2050, increasing the probability of exceeding the carbon budget in line with limiting warming to below 1.5°C or 2°C (van Vuuren et al. 2016; Bertram et al. 2015a).

Moving from a 2°C to a 1.5°C target requires higher levels of transformative policy regimes in the short run, which allow deep decarbonisation pathways to emerge and a net zero energy-economy system to be achieved by 2040-2060 (Bataille et al. 2016b; Rogelj et al. 2015a). This requires higher levels of technological deployment (Sections 2.3 and 2.4) and assumes more profound social, economic and political transformation. Aggressive policies addressing energy demand appear to be central in keeping 1.5°C within reach during this century and lowering mitigation costs (Rogelj et al. 2013; Luderer et al. 2013a; Rogelj et al. 2015a). Model assumptions indicate that effective behavioural and societal change are critically needed for achieving a 1.5°C pathway (details in Chapter 4). Modelled policy options allow global emission to peak by 2020 and can drive the complete decarbonisation of the energy-economy system by approximately mid-century. Despite inherent levels of uncertainty attached to modelling studies (for example, 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; Riahi et al. 2015; Kriegler et al. 2014a). 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 (Riahi et al. 2017; Bauer et al. 2017; Popp et al. 2017; Rogelj et al. 2017a). Studies also show that technology policies could 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 seem to be necessary to ensure efficient reductions in GHG emissions (Kriegler et al. 2015a). Model results underscore the need for an integrated and ambitious global response to

1 climate change mitigation (for feasibility aspects of global multilateral policy regimes, see Chapter 4).
2 Even if values of lower probability of equilibrium climate sensitivity (ECS) and transient climate
3 response (TCR) are considered, the urgency for robust mitigation policies for temperature goals more
4 stringent than 2°C remains (Rogelj et al. 2014b).

5
6 The near-term stringency of the policies also has implications for the use and deployment of CDR
7 options (e.g. to compensate for residual emissions in the long-term). Delayed mitigation policies
8 increase the need for the full portfolio of mitigation measures, including CDR (Riahi et al. 2015;
9 Clarke et al. 2014). At the same time, CDR deployment is already substantial in immediate policy
10 scenarios (see Sections 2.3 and 2.4). Policies driving bioenergy use show a similar or higher share of
11 bioenergy when BECCS is excluded than when it is allowed (Klein et al. 2014).

12 Multiple factors can affect the efficiency and effectiveness of stringent policy options. Stringent
13 mitigation policies can interact with a wider portfolio of pre-existing policy instruments that address
14 multiple areas (e.g., technology markets, economic growth, poverty alleviation, climate adaptation)
15 and deal with various market failures and behavioural anomalies (e.g., information asymmetries,
16 heuristics) that prevent mitigation actions. Furthermore, policies may also not exclusively address
17 mitigation but also target other objectives (e.g., public health, energy security) (Shindell et al. 2012;
18 Jewell et al. 2016). Climate impacts can also affect the effectiveness of mitigation policies, but are
19 generally not taken into account in integrated assessment models. These aspects generate interactions
20 and frictions over time so overlaps and synergies exist. In addition to stringent policy options which
21 are tightened over time, critical issues driving results in mitigation pathways relate to compliance
22 levels, international cooperation and political acceptability (Blanford et al. 2014; Riahi et al. 2017;
23 Kriegler et al. 2013; Peters 2016).

24
25 Implementation limits and hurdles that mitigation pathways entail from a practical policy point of
26 view have to be addressed explicitly (Kriegler et al. 2014b). Whereas the policy issues identified in
27 this section pertain to the theoretical dimension of mitigation pathways, aspects related to 1.5°C
28 mitigation policies in practice are of prime importance. For instance, questions and solutions related
29 to institutional capacity, distributional equity, consumption preferences, economic conditions, market
30 development, societal change and energy demand, and intra- and inter-generational issues need to be
31 confronted with a real world perspective; including historical precedents. These issues are discussed in
32 detail in Chapters 3, 4 and 5.

33 34 35 *2.5.1.2 Limitations of IAMs in examining all policy options*

36 Although model-based assessments project drastic near, medium and long-term transformations in
37 1.5°C, projections also often struggle to capture today's transformative change and the dynamics
38 associated with it: including disruption, innovation, and nonlinear change in human behaviour
39 (Rockström et al. 2017). Regular revisions and adjustments are standard for expert and mode
40 projections, for example, to account for new information like the adoption of the Paris Agreement.
41 However, it is informative to note that the deployment pace of key mitigation technologies, like solar
42 photovoltaic installations and renewables, has been consistently underestimated by key experts over
43 the past decade, showing the difficulty of adequately estimating social and technological transitions
44 (Haegel et al. 2017; Figueres et al. 2017), and illustrating the challenges of producing scenarios
45 consistent with a quickly evolving market (Sussams and Leaton 2017).

46
47 Some studies describe the transitions that are deemed necessary in the short term at the sector level to
48 keep the door open for a 1.5°C pathway (Climate Action Tracker 2016; Rockström et al. 2017),
49 indicating their pace should be governed by novel schemes rather than by inertia imposed by
50 incumbent technologies (Rockström et al. 2017). These studies also aim at providing signs that a
51 transition of the magnitude required for a 1.5°C transition is in principle possible, and in some cases is
52 already happening (see Table 2.13).

1 **Table 2.13:** Transitions that need to happen in key sectors in the short term for a 1.5°C pathway, based on available studies.
2

	Energy	Cities & Infrastructure	Transport	Industry	Food Systems	Afforestation
A roadmap for rapid decarbonisation (Rockström et al. 2017)	Coal will be about to exit 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 supraconductive 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 ²		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.

² The analyses conducted for energy supply and end-use sectors in this report refer to the sector-specific results of (Rogelj et al. 2015a) as the point of departure. Technology-specific assessments are based on various technical studies including the IPCC AR5 (IPCC 2014), IEA Energy Perspectives 2016 (IEA 2016), and the Climate Action Tracker’s own calculations.

Low Carbon Technology Partnership Initiative (LCTPI) ³	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 21 st century;	Cement industry emission reductions in the range of 20-25% in 2030 compared to BAU. 0.4 GtCO ₂ e 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.	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)

1

³ Available at lctpi.wbcsd.org/wp-content/uploads/2015/11/LCTPI-PWC-Impact-Analysis.pdf

1 At the same time, modelling in traditional silos, instead of allowing systemic approaches, fails to capture
2 cross-sectoral efficiencies and synergies. This is particularly relevant for urban systems and food systems
3 (Lucon et al. 2014; Smith and Bustamante 2014). Urban areas could achieve lower emissions if the role of
4 urban planning and density were captured (e.g., see Güneralp et al. 2017). Urban planning could also reduce
5 GHG emissions from urban transport between 20% and 50% (Creutzig 2016). Regarding food systems,
6 technical GHG reduction potentials related to behavioural changes, such as dietary shifts toward more
7 healthy nutrition, improved livestock managements, and food waste reduction, strongly exceed the potentials
8 of supply-side mitigation options in this sector (Smith and Bustamante 2014; Gerber et al. 2013).
9 Although demand-side solutions are promising, they are not given the same level of attention as
10 technological supply-side solutions in assessments, modelling efforts, and research and development in
11 general (Wilson et al. 2012). This is partly because demand-side solutions are often embedded in a complex
12 network of social institutions and practices, and thus less prone to quantitative analysis and clear-cut
13 implementation. Comparability between economic potentials at the supply side and technical potentials at the
14 demand side is limited because demand-side options are difficult to judge in terms of cost-benefit analyses
15 (Creutzig 2016) partly due to complications of how to define their scope when determining required
16 investments (Grubler and Wilson 2014).

17
18 Furthermore, there are also substantial uncertainties in mitigation options which depend, on the one hand, on
19 model development and the inclusion of options (see Section 2.3.1) and, on the other hand, on modellers'
20 beliefs and preferences. For example, in addition to the aforementioned behavioural changes and their
21 effects on methane from agriculture, there are substantial uncertainties in the mitigation potential of HFCs
22 (Purohit and Höglund-Isaksson 2017) and several air quality-related pollutants because of uncertainties about
23 which reference emissions in absence of mitigation measure to assume. In the case of HFCs, current
24 emissions are very low, so the mitigation potential depends almost entirely on hypothetical reference
25 emissions against which low emission scenarios are compared. The same applies for several air quality
26 related pollutants. IAMs often assume in line with historical experience that economic growth leads to a
27 reduction in local air pollution as populations become richer (i.e., an environmental Kuznets curve) (Rao et
28 al. 2017). In such cases, the mitigation potential is small because reference emissions that take into account
29 this economic development effect are already low in scenarios which see continued economic development
30 over their modelling time horizon. Other studies do not apply this historically observed relationship arguing
31 that it would not necessarily hold in the future, and assume keep air pollution emissions or control standards
32 constant at some historical level, absent of technological or societal economic development (Amann et al.
33 2013). Assumption about reference emissions are important because high reference emissions lead to high
34 perceived mitigation potentials and potential overestimates of the actual benefit, particularly in the context of
35 mitigation for HFCs and BC-rich sectors, while low reference emissions lead to low perceived benefits of
36 mitigation measures and thus less incentives to address these important climate and air pollutants (Shindell et
37 al. 2012; Rogelj et al. 2014a; Velders et al. 2015; Gschrey et al. 2011; Amann et al. 2013; Shah et al. 2015).

40 **Box 2.1:** Economics of 1.5°C Pathways and the Social Cost of Carbon

41
42 **Authors:** Mustafa Babiker, Johannes Emmerling, Sabine Fuss, Elmar Kriegler, Jean-Charles Hourcade, Anil
43 Markandya, Luis Mundaca, Joyashree Roy, Drew Shindell

44
45 Two approaches have been commonly used to assess alternative emissions pathways: **cost-effectiveness**
46 **analysis (CEA)** and **cost-benefit analysis (CBA)**. CEA aims at identifying emissions pathways minimising
47 the total mitigation costs of achieving a given warming or greenhouse gas (GHG) limit (Clarke et al. 2014).
48 CBA has the goal to identify the optimal emissions trajectory minimising the discounted flows of abatement
49 expenditures and monetised climate change damages (Boardman 2006; Stern 2007). A third concept, the
50 **Social Cost of Carbon (SCC)** measures the total net damages of an extra metric ton of CO₂ emissions due
51 to the associated climate change (Nordhaus 2014; Pizer et al. 2014). Negative and positive impacts are
52 monetised, discounted and the net value is expressed as an equivalent loss of consumption today. The SCC
53 can be evaluated for any emissions pathway under policy consideration (Rose 2012; National Academies of
54 Sciences and Medicine 2016).

55
56 Along the optimal trajectory determined by CBA, the SCC equals the discounted value of the marginal
57 abatement cost of a metric ton of CO₂ emissions. Equating the present value of future damages and marginal

1 abatement costs includes a number of critical value judgments in the formulation of the social welfare
2 function (SWF), particularly in how non-market damages and the distribution of damages across countries
3 and individuals and between current and future generations are valued. For example, since climate damages
4 accrue to a larger extent in the farther future and can persist for many years, assumptions about the social
5 discount rate and social welfare function (discounted utilitarian SWF vs. undiscounted prioritarian SWF) can
6 heavily influence CBA outcomes and associated estimates of SCC (Nordhaus 2007; Pizer et al. 2014; Adler
7 and Treich 2015; Adler et al. 2017; National Academies of Sciences and Medicine 2016).

8
9 In CEA, the marginal abatement cost of carbon is determined by the climate goal under consideration. Policy
10 goals like the goals of limiting warming to 1.5°C or well below 2°C do not result from a money metric trade-
11 off between mitigation and damages. In this context, the SCC can be interpreted as the social cost of an
12 additional ton of emissions reduction under the climate goal. It is the **shadow price of carbon** associated
13 with a climate objective treated as a political constraint and can be interpreted as the willingness to
14 pay for this constraint. Value judgments that are explicit in CBA are to a large extent concentrated in the
15 choice of climate goal. For example, assumptions about the social discount rate no longer affect the overall
16 abatement levels now set by the climate goal, but only the choice and timing of investments in individual
17 measures to reach these levels.

18
19 Although both CBA-based and CEA-based assessment of SCC are subject to large uncertainty about socio-
20 techno-economic trends, policy developments and climate response, the range of uncertainty in SCC
21 estimates along an optimal trajectory determined by CBA is far higher than for estimates of the shadow price
22 of carbon in CEA-based approaches. In CBA, the controversies on the value judgments about inter- and
23 intra-generational equity combine with criticisms of the type of climate damage functions assumed,
24 including their empirical basis (Pindyck 2013; Stern 2013; Revesz et al. 2014b). In a CEA-based approach,
25 the value judgments about the aggregate welfare function matter less and uncertainty about climate response
26 and impacts can be tied into various climate targets and related emissions budgets (Clarke et al. 2014).

27
28 The CEA- and CBA-based SCC estimates are derived with a different set of tools. They are all summarised
29 as integrated assessment models (IAMs) but in fact are of very different nature (Weyant 2017). Detailed
30 process IAMs such as AIM (Fujimori 2017), GCAM (Thomson et al. 2011; Calvin et al. 2017), IMAGE (van
31 Vuuren et al. 2017, 2011a), MESSAGE-GLOBIOM (Riahi et al. 2011; Havlík et al. 2014; Fricko et al.
32 2017), REMIND-MAGPIE (Popp et al. 2010; Kriegler et al. 2017; Luderer et al. 2013b) and WITCH (Bosetti
33 et al. 2006, 2008, 2009) include a process-based representation of energy and land systems, but in most cases
34 lack a comprehensive representation of climate damages, and are typically used for CEA. CBA IAMs such
35 as DICE (Nordhaus and Boyer 2000; Nordhaus 2013, 2017), PAGE (Hope 2006) and FUND (Tol 1999;
36 Anthoff and Tol 2009) capture the full feedback from climate response to socio-economic damages in an
37 aggregated manner, but are usually much more stylised than detailed process IAMs. There is currently a
38 discussion in the literature to what extent they underestimate the SCC due to, for example, a limited
39 treatment or difficulties in addressing damages to human wellbeing, labour productivity, value of capital
40 stock, ecosystem services and the risks of catastrophic climate change for future generations (Ackerman and
41 Stanton 2012; Moore and Diaz 2015; Revesz et al. 2014a; Stern 2016). However, there has been progress in
42 ‘bottom-up’ empirical analyses of climate damages (Hsiang et al. 2017), the insights of which could be
43 integrated into these models (Dell et al. 2014). Most of the models used in Chapter 2 on 1.5°C mitigation
44 pathways are detailed process IAMs. The CBA literature on SCC estimates is briefly assessed in Chapter 3 to
45 the extent it pertains to the subject of 1.5°C warming.

46
47 An important question is how results from CEA- and CBA-type approaches can be compared and
48 synthesised. Such synthesis needs to be done with care, since estimates of the shadow price of carbon under
49 the climate goal and SCC estimates from CBA might not be directly comparable due to different tools,
50 approaches and assumptions used to derive them. Acknowledging this caveat, the SCC literature has
51 identified a range of factors, assumptions and value judgements that support SCC values above \$100 tCO₂⁻¹
52 that are also found as net present values of the shadow price of carbon in 1.5°C pathways. These factors
53 include the accounting for tipping points in the climate system (Lemoine and Traeger 2014; Lontzek et al.
54 2015; Cai et al. 2015), a low social discount rate (Stern 2007; Nordhaus 2005) and inequality aversion
55 (Schmidt et al. 2013; Dennig et al. 2015; Adler et al. 2017).

56
57 The SCC is not merely a theoretical concept (Pizer et al. 2014; Revesz et al. 2014a; Stiglitz and Stern 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, the SCC could be translated into a carbon price. As stated by the report of the High-Level Commission on Carbon Pricing (Stiglitz and Stern 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, United Kingdom 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 impacts from greenhouse gases and air pollutants including air quality should be included in social costs (Shindell et al. 2017b; Sarofim et al. 2017) and that the overall macroeconomic and development implications of the 1.5°C and well below 2°C climate goals have to be considered. This is why the Paris Agreement (Article 108) refers to the Social Value of Mitigation activities (SVMA).

2.5.2 Economic implications of 1.5°C Scenarios

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, or equivalent carbon prices in line with an efficient implementation of the emission reduction objective. A discussion of macro-economic impacts of mitigation is provided in Box 2.1, and investments in the energy supply system are discussed in Section 2.3.4.4. We hence focus here on the carbon price characteristics of 1.5°C pathways as a metric to investigate the economic implications of stringent mitigation pathways. Under a cost-effective analysis (CEA) framework, carbon prices reflect the stringency of mitigation requirements at the margin (i.e., cost of mitigating one extra unit of emission) (see Cross-Chapter Box Economics of 1.5°C Pathways and the Social Cost of Carbon). Emissions prices are usually expressed in carbon (equivalent) prices using the GWP-100 metric as exchange rate for pricing emissions of non-CO₂ greenhouse gases controlled under internationally climate agreements (like CH₄, N₂O and fluorinated gases, see Cross-Chapter Box on Balance and Metrics in Chapter 1).⁴ 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, but can be used as a point of comparison (see Box 2.2 on Economics of 1.5°C Pathways and the Social Cost of Carbon).

Reported equivalent carbon prices vary substantially across models and scenarios, and their value increase with mitigation efforts (Clarke et al. 2014; Guivarch and Rogelj 2017). Various CEA-based studies have already shown that estimates of carbon prices in stringent mitigation pathways depend on projected energy demand, resulting emissions, mitigation potentials, technology availability, abatement costs and interactions with other policy instruments, amongst other aspects (Clarke et al. 2014; Riahi et al. 2017; Rogelj et al. 2015c; Kriegler et al. 2015a). CEA studies also reveal no unique carbon pricing path (Bertram et al. 2015a; Riahi et al. 2017; Kriegler et al. 2015a).

[More quantitative estimates and discussion of macro-economic mitigation costs may be included in the SOD as data becomes available.]

Box 2.2: Macro-economic impacts of mitigation

Authors: Mustafa Babiker, Johannes Emmerling, Sabine Fuss, Elmar Kriegler, Jean-Charles Hourcade, Anil Markandya, Luis Mundaca, Joyashree Roy, Drew Shindell

Studies using cost-effectiveness analysis (CEA, see Box 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

⁴ Also other metrics to compare emissions have been suggested and adopted by governments nationally (Kandlikar 1995; Marten et al. 2015; Shindell 2015; Interagency Working Group on Social Cost of Greenhouse Gases 2016).

1 employment levels and trade balances. Those variations are measured against a hypothetical baseline without
2 mitigation policy or a policy reference scenario (Section 2.5.2) at various points in time or discounted over a
3 given time period.

4
5 If GDP and consumption variations fall below the baseline, they are reported as losses or macro-economic
6 costs⁵. This is a frequent source of misunderstanding. Such cost estimates give an indication how economic
7 activity slows in the long-term relative to the baseline, they do not describe a reduction of output and
8 consumption levels relative to previous years. Macro-economic costs of mitigation need to be clearly
9 distinguished from the marginal abatement costs that describe the cost of reducing the last unit of emissions
10 (Paltsev and Capros 2013). Macro-economic mitigation costs aggregate the cost of all emissions abatement
11 that took place up to the level of marginal abatement costs. A country with a large abatement potential at low
12 marginal abatement cost levels may spend more on overall abatement than a country with high marginal
13 abatement costs and low abatement potential. If the marginal abatement cost is equated throughout the
14 world, a country with a high dependence to carbon intensive industry (developing countries in a catch-up
15 phase) can be more impacted than a country relying on services and low carbon intensive activities (Tavoni et
16 al. 2013, 2014).

17
18 Aggregate mitigation costs depend strongly on assumptions about the baseline providing the yardstick
19 against which policy costs are measured. The baseline is therefore a critical concept in CEA. When assuming
20 well-functioning, forward-looking and globally integrated markets in the baseline – a situation Working
21 Group 3 called “idealised implementation environment” in the IPCC Fifth Assessment Report (Clarke et al.
22 2014; Krey et al. 2014a) – the least cost strategy to internalise a climate goal constitutes a globally uniform
23 emissions price minimising the discounted sum of mitigation costs over time. In the real world, perfect
24 expectations and perfect markets do not exist; rather climate policies will interact with existing policies and
25 other distortions in labour, energy, capital, and land markets. In this case the optimal policies in a so called
26 first best world might no longer apply (Lipsey and Lancaster 1957).

27
28 Starting from a non-optimal baseline might lead either to more pessimistic conclusions about the macro-
29 economic costs of climate policies (in case of absence of compensating transfers or of market imperfections
30 slowing down the adaptation of economic actors) or to more optimistic conclusions if policy reforms are
31 conducted synergistically with the climate objective. A strand of literature has explored ways of using the
32 revenues of carbon prices (principally carbon taxes) to conduct fiscal reforms that reduce more distortionary
33 taxes and offer, under certain conditions, a “double dividend” by providing both environmental benefits and
34 an aggregate economic gain especially in the form of higher employment (Goulder 1995, 2013; Bovenberg
35 and De Mooij 1994; Bovenberg and Goulder 1996; Bovenberg and van der Ploeg 1994; Bovenberg 1999).
36 Yet, the magnitude of these effects depends on country specific circumstances, notably implementation and
37 revenue recycling schemes (Fullerton and Metcalf 1997), behaviour of labour markets (Guivarch et al.
38 2011), the price elasticity of imports, and exports and the capacity to reduce tax evasion (Liu 2013).

39
40 In the aftermath of the 2008 financial crisis, a strand of literature developed, sometimes referring to the
41 notion of green growth (New Climate Economy 2014), to examine how the low carbon transition could open
42 a new long-term growth cycle (Stern and Rydge 2012) and new development opportunities (Jakob et al.
43 2016). Whether new economic opportunities might be unlocked (OECD 2017) will depend upon the capacity
44 to avoid a crowding out effect between carbon saving investments and other investments (Pollitt and
45 Mercure 2017) and to maximise spill-over effects (Popp and Newell 2012). This capacity will also depend
46 upon the possibility of using the low carbon transition to reduce the ‘savings glut’ (Hourcade and Shukla
47 2013) that has been associated with the risk of ‘secular stagnation’ (Krugman 2009; Summers 2016).

48
49 Ultimately, the macro-economy of climate policies concerns primarily their short and medium term impacts
50 in a world far from an equilibrium, whereas the mitigation pathways literature assessed in Chapter 2 of this
51 report conveys important information about the long-term economic equilibrium of low carbon development
52 paths.

53 Carbon prices in 1.5°C pathways are markedly higher than in 2°C pathways, as it demands a much faster

⁵ 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. 2014a). Here we only summarise a few key concepts relevant for the assessment of the economics of 1.5°C pathways in Chapter 2.

1 near-term decarbonisation of the energy-economy system (Section 2.3). Under ‘well-below 1.5°C’ pathways
2 (WB1.5C, see Table 2.3 for definitions of the scenario classes used here), carbon prices range from
3 approximately 1–160 US\$ tCO₂⁻¹ in 2020 to 240–32000 US\$ tCO₂⁻¹ in 2100 (Figure 2.28; Note: this is
4 excluding scenarios that attempt to reach a 1.5°C pathway from NDC levels in 2030). Under ‘well below
5 2°C’ (WB2C) scenarios, carbon prices range from approximately 1–30 US\$ tCO₂⁻¹ in 2020 to 140–8300 US\$
6 tCO₂⁻¹ by the end of the century. Due to the variety of modelling approaches underlying the available
7 scenario set, the relative increase in carbon prices of WB1.5C scenarios is particularly pronounced in the
8 near term. For instance, carbon prices in 2040 under WB1.5C scenarios are higher by a factor of 10 (21–3)
9 compared to WB2C scenarios. The scenario providing the high estimate in these ranges has limited
10 flexibility of substituting fossil fuels with low carbon technologies and the associated need to compensate
11 fossil-fuel emissions with CDR options (e.g., BECCS) in the model which produced (WITCH-GLOBIOM,
12 SSP1), as described in a different context in (Kriegler et al. 2015b). This distribution of carbon prices
13 highlights the importance of being aware of potential sampling bias in scenario ensembles towards outcomes
14 derived from models which are more flexible, have more mitigation options, and have cheaper cost
15 assumptions and thus can provide feasible scenarios in contrast to other who are unable to do so (Tavoni and
16 Tol 2010; Kriegler et al. 2015b). However, in a like-with-like comparison of WB2C and WB1.5C scenario
17 pairs, average discounted carbon prices between WB1.5C and WB2C scenarios differ by about a factor of
18 two to eight across models and socioeconomic assumptions (here approximated by three SSP marker
19 scenarios for which both WB1.5C and WB2C scenarios are available, Figure 2.28). Consistent with the
20 literature (Luderer et al. 2013a; Hof et al. 2017; Rogelj et al. 2013), the estimates suggest that mitigation
21 costs increase significantly when a higher level of stringency is pursued. Despite marked differences in
22 absolute terms between carbon prices in WB1.5C pathways, the correlation between carbon prices and GH
23 reductions when moving from WB2C to WB1.5C pathways suggests agreement among models regarding the
24 relative increase in carbon prices between the two scenario classes.

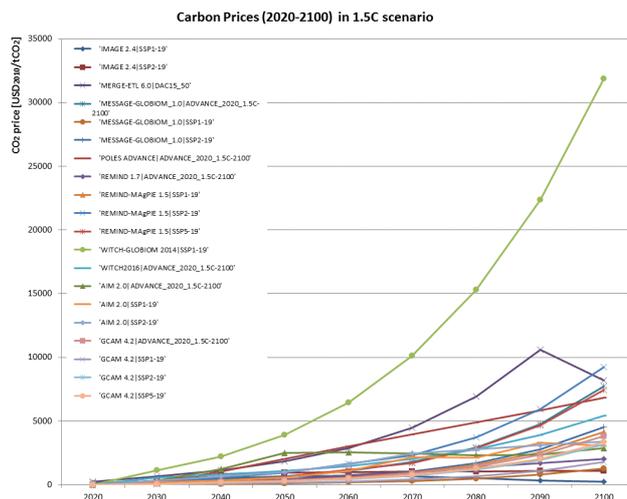
25
26 Irrespective of the stringency of the climate objective, socioeconomic conditions also strongly influence
27 carbon price levels. The characteristics of the technology portfolio, particularly in terms of costs, availability
28 and performance been shown to play a key role (Clarke et al. 2014; Luderer et al. 2013a, 2016c; Rogelj et al.
29 2015c; Riahi et al. 2015). Models that encompass a higher degree of technology granularity and that entail
30 more flexibility regarding mitigation response, often produce relatively lower mitigation costs than those that
31 show less mitigation flexibility (Kriegler et al. 2015b). Technology limitations increase mitigation costs and
32 technology improvements or breakthroughs reduces costs (Rogelj et al. 2015c; Riahi et al. 2015). The SSPs
33 allow here for a structured comparison. Models that provide scenarios for both SSP1 (‘sustainability’) and
34 SSP5 (‘fossil-fuelled development’) narratives (i.e., REMIND and GCAM, see Section 2.5.1) consistently
35 show lower values under SSP1 than SSP5. For example, discounted average WB15C carbon prices (2020-
36 2100) differ by about a factor of two in these two modelling frameworks, from 35–80 US\$ tCO₂⁻¹ under
37 SSP1 to 65–135 US\$ tCO₂⁻¹ in SSP5. A factor of three is found in WB2C scenario pairs. This illustrates
38 quantitatively the lower economic mitigation challenges under SSP1 assumptions compared to SSP5. Also
39 earlier, demand-side measures that increase energy efficiency or limit energy demand have been identified as
40 a critical enabling factor reducing mitigation costs for stringent mitigation scenarios across the board (Riahi
41 et al. 2012; Clarke et al. 2014; Bertram et al. 2015a).

42
43 Finally, delayed near-term mitigation policies and measures, including limited extent of international global
44 cooperation, increases total economic mitigation costs, corresponding carbon prices and transitional
45 challenges (Clarke et al. 2014; Luderer et al. 2013a), because stronger efforts are required in the period after
46 the delay to counterbalance the higher emissions in the near-term. Mitigation challenges are further increased
47 by failures to adopt strong and effective policies in the near term (2020-2030), as more fossil-based capacity
48 investments are stranded (Luderer et al. 2016c; Johnson et al. 2015; Bertram et al. 2015a) and mitigation
49 pathway in line with 1.5°C become more dependent on costlier CDR options (Smith et al. 2015). Staged
50 accession scenarios produce higher costs than immediate action mitigation scenarios under the same
51 stringency level of emissions (Kriegler et al. 2015a).

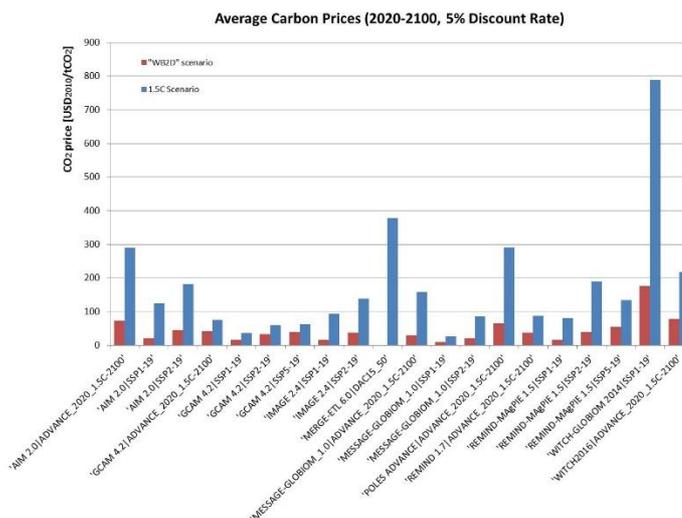
52
53 Carbon pricing is becoming an increasingly important and expanding instrument of climate and energy
54 policy around the world. Over 40 national and 24 subnational initiatives have explicitly created a price for
55 carbon emissions (World Bank et al. 2016). Approximately 13% of global GHG emissions were priced
56 directly via a tax or emissions trading system (ETS) in 2016 (World Bank et al. 2016). As of April 2017,
57 observed carbon prices in practice ranged from 1 US\$ tCO₂⁻¹ (e.g., Chongqing pilot ETS) to about 130 US\$

1 tCO₂⁻¹ (Sweden carbon tax), with approximately three quarters of emissions being priced below 10 US\$
 2 tCO₂⁻¹ (World Bank et al. 2016). The value of carbon markets worldwide was about US\$ 50 billion US\$ in
 3 2016 (World Bank et al. 2016). In most cases, emissions taxes and emission market price levels,
 4 respectively, are considerably lower than carbon prices (marginal abatement cost) estimates in least-cost
 5 1.5°C pathways. The gap may reflect political economy considerations, a low prioritisation for climate
 6 mitigation, or an emphasis on trade-offs with other societal objectives (see Chapter 4).

7
 8 Emissions tax levels or emissions targets are usually chosen based on a multitude of considerations beyond a
 9 long-term climate goal or an estimated social welfare impact of climate change (Newell et al. 2014; Stern
 10 2007; Baranzini et al. 2017). Carbon markets also operate simultaneously with pre-existing taxes and other
 11 policy options such as renewable portfolio standards, energy efficiency obligations, emissions standards and
 12 early retirement of fossil-fuel installations (Goulder and Parry 2008; Koch et al. 2014; Goulder and Schein
 13 2013; Sorrell and Sijm 2003; Mundaca 2008). If emissions abatement is partly achieved by those measures,
 14 emissions prices will only reflect the marginal abatement costs of remaining emissions reductions under the
 15 target, which are lower than the marginal costs of the full emissions abatement (Bertram et al. 2015b).
 16 Carbon market prices can also be affected by a variety of factors, such as information asymmetries across
 17 markets actors, market risks, credibility, emission uncertainties, market power and regulatory uncertainty
 18 (Rannou and Barneto 2016; Jiang et al. 2014; Fan et al. 2010; Goulder and Schein 2013; Zachmann and
 19 Hirschhausen 2008; Cramton and Kerr 2002; Mundaca and Richter 2013; Newell et al. 2014). Considering
 20 incomplete and uncertain information, an optimal carbon tax of the magnitude estimated by modelled 1.5°C
 21 and 2°C pathways needs to be compared with what is politically feasible at the global, national, regional and
 22 sectoral level (see Chapter 4).



23



24
 25
 26
 27

Figure 2.28: Global average carbon prices. (top panel) global annual carbon prices in selected WB1.5C scenarios; (bottom panel) global carbon prices averaged and discounted with 5% over the 2020-2100 period in WB1.5C and WB2C for selected scenario pairs.

2.5.3 Sustainable development features of 1.5°C pathways

Since AR5, an increasing number of modelling studies show that sustainable development objectives and climate policy targets are interrelated, and that synergies and trade-offs can be identified (Jakob and Steckel 2016; von Stechow et al. 2016). Synergies include aspects related, for example, to air quality, ocean acidification, water use, biodiversity, fuel poverty and job creation. Identified co-impacts also include poverty alleviation, improved energy security and public health. 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), or food production and land-based mitigation measures or bioenergy production (Popp et al. 2017; Jakob and Steckel 2016; von Stechow et al. 2016). Mitigation costs can vary significantly when climate and sustainability scenarios are simultaneously assessed (Jakob and Steckel 2016). 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 Chapter 5).

In the past, model-analysis of 1.5°C and 2°C pathways focused almost exclusively on climate policy. However, it is increasingly suggested in international climate policy that many countries will only accept costly climate policies if these align with achieving other societal goals, such as the Sustainable Development Goals or other local or national priorities like energy security or public health (e.g., see Kennel, F. et al. 2012; Jewell et al. 2016). Potential synergies between climate and development policies are an emerging and active field of research. The SSP framework allows for first steps in the exploration of these interactions. 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. 2017). 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 (Riahi et al. 2017; Popp et al. 2017).

A qualitative assessment of the synergies and trade-offs of individual mitigation measures and sustainable development goals across relevant SDGs’ outcomes has been carried out in Chapter 5. These insights can be synthesised and linked to the portfolios of mitigation measures found in 1.5°C pathways in this chapter, thus allowing a first order mapping of 1.5°C mitigation pathways and SDG interactions. This assessment is based on a set of possible individual mitigation measures (i.e., technologies, processes or practices) and a set of portfolios (i.e., different combinations of mitigations measures) compatible with 1.5°C (Section 2.3.4), and their interactions with sustainable development dimensions (Chapter 5). It allows to better understand the impact of alternative mitigation pathways towards the same 1.5°C objective, with particular attention to socioeconomic, institutional, political, behavioural and technological aspects. Based on the forthcoming assessment of Chapter 5 (which will be finalised for the SOD), a table will graphically rank alternative scenarios based on their sustainability profile for thematic clusters of sustainable development dimensions.

2.6 Assessment tools and knowledge gaps

The literature on mitigation pathways assessed in this chapter is based on a broad 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.

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

1 emissions pathways to climate response. Finally, the chapter also aims to place the quantitative literature on
2 mitigation pathways into the context of the transition and development literature where possible and
3 relevant. This section gives a short overview on how this literature relates to 1.5°C mitigation pathways.
4
5

6 **2.6.1 Integrated and sector-specific assessment models**

7

8 Integrated assessment models (IAMs) lie at the basis of the assessment of mitigation pathways in this chapter
9 as much of the quantitative global scenario literature is derived with such models. IAMs combine insights
10 from various disciplines in a single framework resulting in a dynamic description of the coupled energy-
11 economy-land-climate system that cover the largest sources of anthropogenic greenhouse gas emissions from
12 different sectors. Over time, the system coverage of integrated assessment models has also increased. Many
13 of the IAMs that contributed mitigation scenarios to this assessment now include a process-based description
14 of the land system in addition to the energy system (for example, Wise et al. 2014; Kriegler et al. 2017;
15 Fricko et al. 2017), and some have been extended to cover air pollutants, water, and material use. These
16 features makes them increasingly apt to explore questions beyond those that touch upon climate mitigation
17 only. In addition to the process-based IAMs that provide integrated scenarios, this chapter also draws from
18 insights from sector specific assessment models. Such models typically focus on a specific sector, like the
19 building (Lucon et al. 2014) or transport (Sims et al. 2014) sector.
20

21 The IAMs used in the mitigation pathway assessment in this chapter are detailed process-based models, with
22 limited to no coverage of climate impacts in their model structure. This is fundamentally different from
23 much more aggregated cost-benefit IAMs (see Box 6.1 in Clarke et al. 2014) which balance monetised costs
24 of mitigation and climate damages to identify emissions pathways that optimise global welfare. A detailed
25 discussion of the strengths and weaknesses of cost-benefit IAMs is provided in AR5 (Kunreuther et al. 2014;
26 Kolstad et al. 2014; Clarke et al. 2014), and an overview discussion comparing contributions of both
27 process-based and cost-benefit IAMs is provided in (Weyant 2017).
28

29 Ultimately, the IAMs that provided input to this assessment are fundamentally not different from those
30 underlying the IPCC AR5 assessment of transformation pathways (Clarke et al. 2014) and an overview of
31 these integrated modelling tools can be found there. Furthermore, since AR5, a harmonised model
32 documentation of IAMs and underlying assumptions has been established within the framework of the EU
33 ADVANCE project: <http://www.fp7-advance.eu/content/model-documentation>.
34
35

36 **2.6.2 Geophysical assessment tools**

37 The geophysical assessment in this chapter draws upon results from both complex climate models and
38 reduced complexity climate models. Complex general circulation models (GCMs) and Earth system models
39 (ESMs) simulate the fully coupled Earth system, including its atmospheric and ocean circulation, ESMs
40 additionally include vegetation feedbacks and multiple biogeochemical cycles, including the carbon or the
41 nitrogen cycle. The report also employs results from reduced complexity climate models such as MAGICC
42 (Meinshausen et al. 2011a). These two classes of geophysical assessment tools come with their own
43 strengths and limitations but take up complementary roles. GCMs and ESMs reflect our most detailed up-to-
44 date understanding of the Earth system, but the computational cost of such tools is excessively high to
45 simulate a large ensemble of scenarios. Reduced complexity climate models are developed to closely
46 emulate GCMs based on physical principles, they can be run multiple thousands of times, but make simple
47 approximations and typically do not simulate regional responses.
48

49 The IAM pathways considered in this chapter and throughout the report have used estimates of radiative
50 forcing and global mean surface temperature derived from the MAGICC model, calibrated to previous CMIP
51 phases of coupled model results (Meinshausen et al. 2011a). The same model was extensively employed to
52 assess scenarios within IPCC AR5 WG3 (Clarke et al. 2014). The spread of equilibrium climate sensitivity
53 (ECS) simulated by MAGICC is similar to that exhibited by CMIP5 models, but the AR5 assessment of ECS

1 had a smaller likely lower bound (1.5 K) than seen in the models (Collins et al. 2013a). Tuning to C4MIP
2 would also suggest a larger sensitivity to rising CO₂ compared to CMIP5 models, although a multi-model
3 intercomparison indicated that the default MAGICC calibration is close to the median of other model
4 approaches (Joos et al. 2013). Complex ESMs can exhibit non-linearity in their carbon cycle response,
5 especially in high emission scenarios that simple models do not capture (Frölicher 2016; Tokarska et al.
6 2016). These are less relevant for the low emission pathways discussed here, more important is the hysteresis
7 found in the carbon cycle response when transitioning between periods of positive and negative CO₂
8 emissions (Zickfeld et al. 2016). Such a hysteresis in the carbon cycle response may not be correctly
9 captured by simple models such as MAGICC and could be important for overshooting scenarios assessed in
10 this report (see Section 2.2.2). Nevertheless, the MAGICC model was able to represent the range of
11 temperature projections exhibited by the CMIP5 models, across most RCP scenarios (see Collins et al. 2013a
12 Figure 12.8 and Clarke et al. 2014 Figure 6.12), both in terms of its median temperature response and 5-95%
13 uncertainty range. This good fit was not true of RCP2.6, where MAGICC underestimated the spread in
14 climate response compared to CMIP5 models. This can be traced to: 1) a single treatment of short-lived
15 climate forcers within MAGICC compared to a diversity within CMIP5 models, and 2) a lack of internal
16 variability in MAGICC (Collins et al. 2013a).

17
18 For this report, we adopt the MAGICC setup as employed in WG3 IPCC AR5 to assess carbon budgets and
19 determine the evolution of atmospheric composition and global mean temperature from the scenario
20 literature. Improvements in the geophysical knowledge of climate sensitivity, carbon cycle responses and in
21 radiative forcing are expected for IPCC AR6 which could alter this report's findings (see Sections 2.2.2 and
22 2.6.4).

23 24 25 **2.6.3 Sociotechnical transitions literature**

26
27 Sociotechnical transitions literature puts significant attention to the role of actors, such as citizens,
28 businesses, stakeholder groups or governments, as well as the interplay of technical, behavioural,
29 institutional and socio-political dimensions in shaping mitigation pathways. The transitions literature thus
30 complements insights from integrated and sector-specific assessment models that primarily point to the
31 mitigation solutions involving technology, fuel switching, efficiency improvements, infrastructure, and to
32 some extent behaviour change. Transitions literature is very diverse body of research. One stream revolves
33 around historical case studies, such as the conceptual analysis of German and UK energy transitions in 1990-
34 2014 (Geels et al. 2016). Similar historical case studies inform development of a theoretical framework
35 (Geels and Schot 2007) and this framework is applied in elaborating future transitions (Verbong and Geels
36 2010). Such historical analyses thus identify ideal patterns of change from the past and apply these patterns
37 qualitatively to the future, without specifying how future transition could actually unfold (Turnheim et al.
38 2015). As historically-informed sociotechnical transitions literature does not provide quantitative or global-
39 level insights on future mitigation pathways, some efforts have been undertaken for developing
40 sociotechnical transition models (Li et al. 2015). These models, however, are still at very early stages of
41 development and validation.

42
43 Another stream of sociotechnical literature relies on initiative-based learning in local studies (Turnheim et al.
44 2015), including local experiments (Raven et al. 2008) and so-called living labs (Liedtke et al. 2015).
45 Initiative-based learning assumes that to achieve a wanted transition, the relevant actors need to be involved
46 in defining and legitimising this transition and hence the actors' motives and strategies must be studied
47 (Turnheim et al. 2015). These initiative-based learning case studies often prioritise the end-use and localised
48 solutions for mitigation which often are less fleshed out in integrated or sector-based models (Wilson et al.
49 2012). However, insights from these initiative-based learning case studies cannot be easily scaled up to
50 provide quantitative global-level insights on future mitigation pathways.

51
52 As integrated and sector-specific assessment models and methods from sociotechnical transitions literature
53 appear complementary, there have been efforts to combine these approaches for deriving joint transition
54 insights and mitigation solutions. Conceptual strategies for aligning and bridging modelling-based studies,
55 historical sociotechnical analyses and initiative-based learning have been suggested (Turnheim et al. 2015).
56 Qualitative storylines of, for example, historically-informed energy transition governance have been
57 quantified for the decades ahead using multiple energy system models (Trutnevyte et al. 2014). Systematic

1 qualitative scenario methods, such as Cross Impact Balance, have been also used to elaborate sociotechnical
2 transition pathways as an interplay of global, national and sector-specific drivers and then quantified with a
3 model (Vögele et al. 2017). However, there are only few experiments of bridging sociotechnical transitions
4 literature and integrated or sector-specific assessment models.

7 **2.6.4 Knowledge gaps**

9 IAMs attempting to be as comprehensive as possible in order to explore interactions between various societal
10 subsystems, like the economy, land, and energy system. They hence include stylised and simplified
11 representations of these subsystems. In several cases, sectorial assessment models have identified different
12 (and often larger) mitigation potentials for single sectors than what is available in global IAMs (for example,
13 see Lucon et al. 2014). A certain lag in the integration of the latest knowledge in global IAMs is to be
14 expected and highlights the importance of continuously updating models with the latest sectorial insights.
15 Moreover, a general underrepresentation of studies and research exploring end-use measures to climate
16 mitigation has been identified in the literature (Wilson et al. 2012). In recent years, IAMs have shifted from
17 modelling scenarios for ideal worlds (so-called first-best worlds) to also exploring scenarios in which
18 important barriers are explicitly assumed. These barriers can come under the form of unavailable or limited
19 mitigation technology options (for example, Krey et al. 2014b; Kriegler et al. 2014a), delayed or fragmented
20 mitigation policies (for example, Riahi et al. 2015; Kriegler et al. 2015a), or variations in the regional risk to
21 investments (Iyer et al. 2015b), amongst other aspects. Also the various socioeconomic developments as
22 explored with the Shared Socioeconomic Pathways (O'Neill et al. 2017; Riahi et al. 2017) follow this
23 general evolution, and include narratives with relatively low barriers to mitigation as well as narratives with
24 high mitigation challenges. Finally, IAMs typically do not include climate impacts on societal subsystems
25 (van Vuuren et al. 2012). This affects both baselines (in which climate impacts can, for example, affect the
26 efficiency of power generation and agricultural productivity), and mitigation scenarios (which, for example,
27 can rely on larger bioenergy shares that can be affected by climate impacts). A full coupling of IAMs and
28 ESMs can lead to shifts in optimal mitigation pathways (Thornton et al. 2017).

30 In terms of sociotechnical transitions literature, there are clear complementarities between integrated and
31 sector-specific assessment models that provide quantitative aggregated representation of future mitigation
32 pathways and the insights on the role and interplay of the key actors, behavioural, institutional and socio-
33 political dimensions. Sociotechnical literature today, however, remains diverse and at times scattered due to
34 its focus on local or specialised case studies. The link between insights from historical transitions analyses or
35 initiative-based learning case studies and the integrated and sector-specific assessment models are also not
36 straightforward to establish. Although strategies to combine the strengths of these different approaches are
37 emerging, they are still relatively scarce.

39 The climate sensitivity and carbon cycle responses remain uncertain and radiative forcing estimates of
40 greenhouse gases and aerosols are continuously being improved. AR5 assessed ECS to be with a likely
41 (>66%) range of 1.5-4.5K. This is a lower low-estimate compared to the range of CMIP5 models (Collins et
42 al. 2013a), and also the MAGICC ECS distribution has not explicitly been selected to reflect this. This
43 caveat could skew the range of MAGICC results quoted here towards smaller remaining carbon budgets and
44 higher temperature change. However, work since AR5 is suggesting that the lower bound of ECS will likely
45 be revised upwards (Gregory and Andrews 2016; Armour 2017; Marvel et al. 2016; Shindell 2014; Zhai et
46 al. 2015; Tan et al. 2016; Sherwood et al. 2014; Proistosescu and Huybers 2017), helping to justify the
47 MAGICC ECS range. Estimates of greenhouse gas (notably methane) and other forcings such the aerosol
48 forcing are also undergoing revisions (Etminan et al. 2016; Carslaw et al. 2013). At present it is too early to
49 determine potential biases in MAGICC's physical response. In the version used here, MAGICC is run in the
50 same setup as for AR5, which did not include MAGICC's permafrost module (Schneider von Deimling et al.
51 2012). The setup used here does hence not account for possible increased methane emissions from
52 permafrost melting or wetlands possibly leading to an overestimate of the remaining carbon budget and an
53 underestimate of future temperature projections, although permafrost contributions for the levels of warming
54 assessed here are estimated to be small (Schneider von Deimling et al. 2012).

1 **References**

- 2
3 Ackerman, F., and E. A. Stanton, 2012: Climate Risks and Carbon Prices: Revising the Social Cost of Carbon. *Econ. Open-Access, Open-Assessment E-Journal*, **6**, 1, doi:10.5018/economics-ejournal.ja.2012-10.
4 <http://www.economics-ejournal.org/economics/journalarticles/2012-10> (Accessed July 4, 2017).
5
6 Adler, M., D. Anthoff, V. Bosetti, G. Garner, K. Keller, and N. Treich, 2017: Priority for the worse-off and the social
7 cost of carbon. *Nat. Clim. Chang.*, **7**, 443–449. <http://dx.doi.org/10.1038/nclimate3298>.
8
9 Adler, M. D., and N. Treich, 2015: Prioritarianism and Climate Change. *Environ. Resour. Econ.*, **62**, 279–308,
10 doi:10.1007/s10640-015-9960-7. <http://link.springer.com/10.1007/s10640-015-9960-7> (Accessed July 4, 2017).
11
12 Allen, M. R., D. J. Frame, C. Huntingford, C. D. Jones, J. A. Lowe, M. Meinshausen, and N. Meinshausen, 2009:
13 Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, **458**, 1163–1166,
14 doi:10.1038/nature08019. <http://www.nature.com/doi/10.1038/nature08019> (Accessed June 26, 2017).
15
16 ———, J. S. Fuglestvedt, K. P. Shine, A. Reisinger, R. T. Pierrehumbert, and P. M. Forster, 2016: New use of global
17 warming potentials to compare cumulative and short-lived climate pollutants. *Nat. Clim. Chang.*, **6**, 1–5,
18 doi:10.1038/nclimate2998. <http://www.nature.com/doi/10.1038/nclimate2998>.
19
20 Allwood, J. M., M. F. Ashby, T. G. Gutowski, and E. Worrell, 2011: Material efficiency: A white paper. *Resour. Conserv. Recycl.*, **55**, 362–381, doi:10.1016/j.resconrec.2010.11.002.
21 <http://www.sciencedirect.com/science/article/pii/S0921344910002405>.
22
23 ———, ———, ———, and ———, 2013: Material efficiency: providing material services with less material production. *Phil. Trans. R. Soc. A*, **371**, 20120496, doi:10.1098/rsta.2012.0496.
24 <http://rsta.royalsocietypublishing.org/content/371/1986/20120496>.
25
26 Amann, M., Z. Klimont, and F. Wagner, 2013: Regional and Global Emissions of Air Pollutants: Recent Trends and
27 Future Scenarios. *Annu. Rev. Environ. Resour.*, **38**, 31–55, doi:10.1146/annurev-environ-052912-173303.
28 <http://www.annualreviews.org/doi/10.1146/annurev-environ-052912-173303> (Accessed July 22, 2017).
29
30 Anderson, K., and G. Peters, 2016: The trouble with negative emissions. *Science (80-.)*, **354**, 182–183,
31 doi:10.1126/science.aah4567. <http://science.sciencemag.org/content/354/6309/182>.
32
33 Anenberg, S. C., and Coauthors, 2012: Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate
34 Change through Methane and Black Carbon Emission Controls. *Environ. Health Perspect.*, **120**, 831–839,
35 doi:10.1289/ehp.1104301. <http://ehp.niehs.nih.gov/1104301> (Accessed July 21, 2017).
36
37 Anthoff, D., and R. S. J. Tol, 2009: The impact of climate change on the balanced growth equivalent: An application of
38 FUND. *Environ. Resour. Econ.*, **43**, 351–367, doi:10.1007/s10640-009-9269-5.
39
40 Armour, K. C., 2017: Energy budget constraints on climate sensitivity in light of inconstant climate feedbacks. *Nat. Clim. Chang.*, **7**, 331–335. <http://dx.doi.org/10.1038/nclimate3278>.
41
42 Bachu, S., 2015: Review of CO2 storage efficiency in deep saline aquifers. *Int. J. Greenh. Gas Control*, **40**, 188–202,
43 doi:10.1016/j.ijggc.2015.01.007.
44
45 ———, D. Bonijoly, J. Bradshaw, R. Burruss, N. P. Christensen, S. Holloway, O.-M. Mathiassen, and C. S. L. Forum,
46 2007a: *Phase II Final Report from the Task Force for Review and Identification of Standards for CO2 Storage Capacity Estimation*. 43 pp.
47 <http://www.cslforum.org/publications/documents/PhaseIIReportStorageCapacityMeasurementTaskForce.pdf>.
48
49 ———, ———, ———, ———, S. Holloway, N. P. Christensen, and O. M. Mathiassen, 2007b: CO2 storage capacity
50 estimation: Methodology and gaps. *Int. J. Greenh. Gas Control*, **1**, 430–443, doi:10.1016/S1750-5836(07)00086-
51 2.
52
53 Banerjee, R., and Coauthors, 2012: GEA Chapter 8 – Energy End Use: Industry. *Global Energy Assessment - Toward a Sustainable Future*, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International
54 Institute for Applied Systems Analysis, Laxenburg, Austria, 513–574 <http://www.globalenergyassessment.org>.
55
56 Baranzini, A., J. C. J. M. van den Bergh, S. Carattini, R. B. Howarth, E. Padilla, and J. Roca, 2017: Carbon pricing in
57 climate policy: seven reasons, complementary instruments, and political economy considerations. *Wiley Interdiscip. Rev. Clim. Chang.*, **8**, e462, doi:10.1002/wcc.462. <http://doi.wiley.com/10.1002/wcc.462> (Accessed
58 June 21, 2017).
59
60 Bataille, C., H. Waisman, M. Colombier, L. Segafredo, and J. Williams, 2016a: The Deep Decarbonization Pathways
61 Project (DDPP): insights and emerging issues. *Clim. Policy*, **16**, S1–S6, doi:10.1080/14693062.2016.1179620.
62
63 ———, ———, ———, ———, ———, and F. Jotzo, 2016b: The need for national deep decarbonization pathways for effective
64 climate policy. *Clim. Policy*, **16**, S7–S26, doi:10.1080/14693062.2016.1173005.
65 <http://www.tandfonline.com/doi/full/10.1080/14693062.2016.1173005> (Accessed April 6, 2017).
66
67 Bauer, N., and Coauthors, 2017: Shared Socio-Economic Pathways of the Energy Sector - Quantifying the Narratives. *Glob. Environ. Chang.*, **42**, 316–330, doi:10.1016/j.gloenvcha.2016.07.006.
68 <http://dx.doi.org/10.1016/j.gloenvcha.2016.07.006>.
69
70 Bentham, M., T. Mallocks, J. Lowndes, and A. Green, 2014: CO2 STORAGE evaluation database (CO2 Stored). The
71 UK's online storage atlas. *Energy Procedia*, **63**, 5103–5113, doi:10.1016/j.egypro.2014.11.540.
72
73 Bertram, C., N. Johnson, G. Luderer, K. Riahi, M. Isaac, and J. Eom, 2015a: Carbon lock-in through capital stock
74 inertia associated with weak near-term climate policies. *Technol. Forecast. Soc. Change*, **90**, 62–72,
75 doi:10.1016/j.techfore.2013.10.001. <http://dx.doi.org/10.1016/j.techfore.2013.10.001>.

- 1 ———, G. Luderer, R. C. Pietzcker, E. Schmid, E. Kriegler, and O. Edenhofer, 2015b: Complementing carbon prices
2 with technology policies to keep climate targets within reach. *Nat. Clim. Chang.*, **5**, 235–239,
3 doi:10.1038/nclimate2514. <http://www.nature.com/doi/finder/10.1038/nclimate2514>.
- 4 Blanford, G. J., E. Kriegler, and M. Tavoni, 2014: Harmonization vs. fragmentation: Overview of climate policy
5 scenarios in EMF27. *Clim. Change*, **123**, 383–396, doi:10.1007/s10584-013-0951-9.
- 6 Boardman, A. ., 2006: *Cost-Benefit Analysis: Concepts and Practice*. Pearson / Prentice Hall, 560 pp.
- 7 Bodirsky, B. L., A. Popp, I. Weindl, J. P. Dietrich, S. Rolinski, L. Scheffele, C. Schmitz, and H. Lotze-Campen, 2012:
8 N2O emissions from the global agricultural nitrogen cycle-current state and future scenarios. *Biogeosciences*, **9**,
9 4169–4197, doi:10.5194/bg-9-4169-2012.
- 10 Bodirsky, B. L., and Coauthors, 2014: Reactive nitrogen requirements to feed the world in 2050 and potential to
11 mitigate nitrogen pollution. *Nat. Commun.*, **5**, doi:10.1038/ncomms4858.
12 <http://www.nature.com/ncomms/2014/140513/ncomms4858/full/ncomms4858.html> (Accessed May 13, 2014).
- 13 Bond, T. C., and Coauthors, 2013: Bounding the role of black carbon in the climate system: A scientific assessment. *J.*
14 *Geophys. Res. Atmos.*, **118**, 5380–5552, doi:10.1002/jgrd.50171. <http://doi.wiley.com/10.1002/jgrd.50171>
15 (Accessed July 20, 2017).
- 16 Bonsch, M., and Coauthors, 2014: Trade-offs between land and water requirements for large-scale bioenergy
17 production. *GCB Bioenergy*, n/a–n/a, doi:10.1111/gcbb.12226.
18 <http://onlinelibrary.wiley.com/doi/10.1111/gcbb.12226/abstract> (Accessed June 15, 2015).
- 19 Borges, A. V., and Coauthors, 2015: Globally significant greenhouse-gas emissions from African inland waters. *Nat.*
20 *Geosci.*, **8**, 637–642, doi:10.1038/ngeo2486.
- 21 Bosetti, V., C. Carraro, M. Galeotti, E. Massetti, and M. Tavoni, 2006: WITCH - A world induced technical change
22 hybrid model. *Energy Journal, Spec. Issue. Hybrid Model. Energy-Environment Policies Reconciling Bottom-up*
23 *Top-down*, 13–38.
- 24 ———, C. Carraro, E. Massetti, and M. Tavoni, 2008: International energy R&D spillovers and the economics of
25 greenhouse gas atmospheric stabilization. *Energy Econ.*, **30(6)**, 2912–2929, doi:10.1016/j.eneco.2008.04.008.
- 26 Bosetti, V., C. Carraro, A. Sgobbi, and M. Tavoni, 2009: Delayed action and uncertain stabilisation targets. How much
27 will the delay cost? *Clim. Change*, **96**, 299–312, doi:10.1007/s10584-009-9630-2.
28 <http://link.springer.com/article/10.1007/s10584-009-9630-2> (Accessed November 13, 2014).
- 29 Boucher, O., and Coauthors, 2013: Clouds and Aerosols. *Climate Change 2013: The Physical Science Basis.*
30 *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*
31 *Change*, 571–657.
- 32 Bovenberg, A. L., 1999: Green tax reforms and the double dividend: an updated reader's guide. *Int. Tax Public Financ.*,
33 **6**, 421–443. <http://link.springer.com/article/10.1023/A:1008715920337> (Accessed July 31, 2013).
- 34 ———, and R. A. De Mooij, 1994: Environmental levies and distortionary taxation. *Am. Econ. Rev.*, **84**, 1085–1089.
35 <http://www.jstor.org/stable/10.2307/2118046> (Accessed September 18, 2013).
- 36 Bovenberg, A. L., and F. van der Ploeg, 1994: Environmental policy, public finance and the labour market in a second-
37 best world. *J. Public Econ.*, **55**, 349–390. <http://www.sciencedirect.com/science/article/pii/004727279301398T>
38 (Accessed October 17, 2013).
- 39 Bovenberg, A. L., and L. H. Goulder, 1996: Optimal Environmental Taxation in the Presence of Other Taxes: General -
40 Equilibrium Analyses. *Am. Econ. Rev.*, **86**, 985–1000.
- 41 Bowen, A., E. Campiglio, and M. Tavoni, 2014: A macroeconomic perspective on climate change mitigation: Meeting
42 the financing challenge. *Clim. Chang. Econ.*, **5**, 1440005, doi:10.1142/S2010007814400053.
43 <http://www.worldscientific.com/doi/abs/10.1142/S2010007814400053>.
- 44 Bowerman, N. H. A., D. J. Frame, C. Huntingford, J. A. Lowe, and M. R. Allen, 2011: Cumulative carbon emissions,
45 emissions floors and short-term rates of warming: implications for policy. *Philos. Trans. R. Soc. A Math. Phys.*
46 *Eng. Sci.*, **369**, 45–66, doi:10.1098/rsta.2010.0288.
- 47 Bowerman, N. H. A., D. J. Frame, C. Huntingford, J. A. Lowe, S. M. Smith, and M. R. Allen, 2013: The role of short-
48 lived climate pollutants in meeting temperature goals. *Nat. Clim. Chang.*, **3**, 1021–1024,
49 doi:10.1038/nclimate2034.
50 <http://dx.doi.org/10.1038/nclimate2034%5Cnhttp://www.nature.com/nclimate/journal/vaop/ncurrent/full/nclimate>
51 [2034.html](http://www.nature.com/nclimate/journal/vaop/ncurrent/full/nclimate2034.html).
- 52 Boysen, L. R., W. Lucht, D. Gerten, and V. Heck, 2016: Impacts devalue the potential of large-scale terrestrial CO2
53 removal through biomass plantations. *Environ. Res. Lett.*, **11**, 1–10, doi:10.1088/1748-9326/11/9/095010.
- 54 Bruckner, T., I. A. Bashmakov, and Y. Mulugetta, 2014: Energy Systems. *Clim. Chang. 2014 Mitig. Clim. Chang.*
55 *Contrib. Work. Gr. III to Fifth Assess. Rep. Intergov. Panel Clim. Chang.*, 511–598.
- 56 Cai, Y., K. L. Judd, T. M. Lenton, T. S. Lontzek, and D. Narita, 2015: Environmental tipping points significantly affect
57 the cost-benefit assessment of climate policies. *Proc. Natl. Acad. Sci.*, **112**, 4606–4611,
58 doi:10.1073/pnas.1503890112. <http://www.pnas.org/content/112/15/4606> (Accessed April 17, 2015).
- 59 Calvin, K., and Coauthors, 2017: The SSP4: A world of deepening inequality. *Glob. Environ. Chang.*, **42**, 284–296,
60 doi:10.1016/j.gloenvcha.2016.06.010. <http://dx.doi.org/10.1016/j.gloenvcha.2016.06.010>.
- 61 Cameron, C., S. Pachauri, N. D. Rao, D. McCollum, J. Rogelj, and K. Riahi, 2016: Policy trade-offs between climate
62 mitigation and clean cook-stove access in South Asia. *Nat. Energy*, **1**, 15010, doi:10.1038/nenergy.2015.10.
63 <https://www.nature.com/articles/nenergy201510.pdf> (Accessed July 23, 2017).

- 1 Carlsaw, K. S., and Coauthors, 2013: Large contribution of natural aerosols to uncertainty in indirect forcing. *Nature*,
2 **503**, doi:10.1038/nature12674.
- 3 Chen, C., and M. Tavoni, 2013: Direct air capture of CO₂ and climate stabilization: A model based assessment. *Clim.*
4 *Change*, **118**, 59–72, doi:10.1007/s10584-013-0714-7. [http://link.springer.com/article/10.1007/s10584-013-0714-](http://link.springer.com/article/10.1007/s10584-013-0714-7)
5 [7](http://link.springer.com/article/10.1007/s10584-013-0714-7) (Accessed April 15, 2014).
- 6 Ciais, P., and Coauthors, 2013: Carbon and Other Biogeochemical Cycles. *Climate Change 2013: The Physical Science*
7 *Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on*
8 *Climate Change*, 465–570
9 http://www.ipcc.ch/report/ar5/wg1/docs/review/WG1AR5_SOD_Ch06_All_Final.pdf5Cn[http://ebooks.cambrid](http://ebooks.cambridge.org/ref/id/CBO9781107415324A023)
10 [ge.org/ref/id/CBO9781107415324A023](http://ebooks.cambridge.org/ref/id/CBO9781107415324A023).
- 11 Clarke, L., J. Edmonds, V. Krey, R. Richels, S. Rose, and M. Tavoni, 2009: International climate policy architectures:
12 Overview of the EMF 22 International Scenarios. *Energy Econ.*, **31**, S64–S81, doi:10.1016/j.eneco.2009.10.013.
13 <http://linkinghub.elsevier.com/retrieve/pii/S0140988309001960> (Accessed June 20, 2017).
- 14 Clarke, L. E., and Coauthors, 2014: Assessing transformation pathways. *Climate Change 2014: Mitigation of Climate*
15 *Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on*
16 *Climate Change*, O. Edenhofer et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New
17 York, NY, USA, 413–510.
- 18 Climate Action Tracker, 2016: *10 steps - The ten most important short-term steps to limiting warming to 1.5°C*. 48 pp.
19 http://climateactiontracker.org/assets/publications/publications/CAT_10_Steps_for_1o5.pdf.
- 20 Collins, M., and Coauthors, 2013a: Long-term Climate Change: Projections, Commitments and Irreversibility. *Clim.*
21 *Chang. 2013 Phys. Sci. Basis. Contrib. Work. Gr. I to Fifth Assess. Rep. Intergov. Panel Clim. Chang.*, 1029–
22 1136, doi:10.1017/CBO9781107415324.024.
- 23 ———, and Coauthors, 2013b: Long-term Climate Change: Projections, Commitments and Irreversibility. *Climate*
24 *Change 2013 - The Physical Science Basis*, Cambridge University Press, 1029–1136.
- 25 Cramton, P., and S. Kerr, 2002: Tradeable carbon permit auctions. *Energy Policy*, **30**, 333–345, doi:10.1016/S0301-
26 4215(01)00100-8. <http://linkinghub.elsevier.com/retrieve/pii/S0301421501001008> (Accessed July 6, 2017).
- 27 Crespo Cuaresma, J., 2017: Income projections for climate change research: A framework based on human capital
28 dynamics. *Glob. Environ. Chang.*, **42**, 226–236, doi:10.1016/j.gloenvcha.2015.02.012.
29 <http://www.sciencedirect.com/science/article/pii/S0959378015000382> (Accessed April 4, 2017).
- 30 Creutzig, F., 2016: Evolving Narratives of Low-Carbon Futures in Transportation. *Transp. Rev.*, **36**, 341–360,
31 doi:10.1080/01441647.2015.1079277. <http://www.tandfonline.com/doi/full/10.1080/01441647.2015.1079277>
32 (Accessed July 18, 2017).
- 33 ———, A. Popp, R. Plevin, G. Luderer, J. Minx, and O. Edenhofer, 2012: Reconciling top-down and bottom-up
34 modelling on future bioenergy deployment. *Nat. Clim. Chang.*, **2**, 320–327, doi:10.1038/nclimate1416.
35 <http://dx.doi.org/10.1038/nclimate1416>.
- 36 ———, and Coauthors, 2015: Bioenergy and climate change mitigation: An assessment. *GCB Bioenergy*, **7**, 916–944,
37 doi:10.1111/gcbb.12205.
- 38 De_Richter, R., T. Ming, P. Davies, W. Liu, and S. Caillol, 2017: Removal of non-CO₂ greenhouse gases by large-
39 scale atmospheric solar photocatalysis. *Prog. Energy Combust. Sci.*, **60**, 68–96, doi:10.1016/j.peccs.2017.01.001.
40 <http://linkinghub.elsevier.com/retrieve/pii/S0360128516300569> (Accessed March 18, 2017).
- 41 Dell, M., B. F. Jones, and B. A. Olken, 2014: What Do We Learn from the Weather? The New Climate–Economy
42 Literature. *J. Econ. Lit.*, **52**, 740–798, doi:10.3386/w19578.
- 43 Dellink, R., J. Chateau, E. Lanzi, and B. Magné, 2017: Long-term economic growth projections in the Shared
44 Socioeconomic Pathways. *Glob. Environ. Chang.*, **42**, 1–15, doi:10.1016/j.gloenvcha.2015.06.004.
45 <http://linkinghub.elsevier.com/retrieve/pii/S0959378015000837>.
- 46 Denman, K. L., 2008: Climate change, ocean processes and ocean iron fertilization. *Mar. Ecol. Prog. Ser.*, **364**, 219–
47 225. <http://www.int-res.com/abstracts/meps/v364/p219-225/>.
- 48 Dennig, F., M. B. Budolfson, M. Fleurbaey, A. Siebert, and R. H. Socolow, 2015: Inequality, climate impacts on the
49 future poor, and carbon prices. *Proc. Natl. Acad. Sci.*, **112**, 15827–15832, doi:10.1073/pnas.1513967112.
50 <http://www.pnas.org/content/112/52/15827> (Accessed January 6, 2016).
- 51 Dietz, T., G. Gardner, J. Gilligan, P. Stern, and M. Vandenberg, 2009: Household actions can provide a behavioral
52 wedge to rapidly reduce US carbon emissions. *Proc. Natl. Acad. Sci.*, **106**, 18452–18456.
- 53 DOE, NRCAN, and SENER, 2012: *The North American Carbon Storage Atlas*. 52 pp.
54 <https://www.netl.doe.gov/research/coal/carbon-storage/natcarb-atlas>.
- 55 Dooley, J. J., 2013: Estimating the supply and demand for deep geologic CO₂ storage capacity over the course of the
56 21st century: A meta-analysis of the literature. *Energy Procedia*, **37**, 5141–5150,
57 doi:10.1016/j.egypro.2013.06.429.
- 58 Duce, R. A., and Coauthors, 2008: Impacts of Atmospheric Anthropogenic Nitrogen on the Open Ocean. *Science (80-*
59 *),* **320**, 893–897.
- 60 Edelenbosch, O. Y., and Coauthors, 2016: Decomposing passenger transport futures: Comparing results of global
61 integrated assessment models. *Transp. Res. Part D Transp. Environ.*, doi:10.1016/j.trd.2016.07.003.
62 <http://linkinghub.elsevier.com/retrieve/pii/S1361920916301304> (Accessed July 18, 2017).
- 63 Edenhofer, O., and Coauthors, 2010: The Economics of Low Stabilization: Model Comparison of Mitigation Strategies

- 1 and Costs. *Energy J.*, **31**, 11–48, doi:10.2307/41323490. <https://www.jstor.org/stable/41323490> (Accessed June
2 20, 2017).
- 3 Etminan, M., G. Myhre, E. J. Highwood, and K. P. Shine, 2016: Radiative forcing of carbon dioxide, methane, and
4 nitrous oxide: A significant revision of the methane radiative forcing. *Geophys. Res. Lett.*, **43**, 12,614–12,623,
5 doi:10.1002/2016GL071930. <http://doi.wiley.com/10.1002/2016GL071930> (Accessed April 5, 2017).
- 6 Fan, L., B. F. Hobbs, and C. S. Norman, 2010: Risk aversion and CO2 regulatory uncertainty in power generation
7 investment: Policy and modeling implications. *J. Environ. Econ. Manage.*, **60**, 193–208,
8 doi:10.1016/j.jeem.2010.08.001. <http://linkinghub.elsevier.com/retrieve/pii/S009506961000080X> (Accessed July
9 6, 2017).
- 10 FAOSTAT, 2017: Database Collection of the Food and Agriculture Organization of the United Nations.
11 <http://www.fao.org/faostat/en/>.
- 12 Fawcett, A. A., and Coauthors, 2015: Can Paris pledges avert severe climate change? *Science (80-.)*, **350**, 1168–1169,
13 doi:10.1126/science.aad5761. <http://www.sciencemag.org/content/350/6265/1168> (Accessed December 4, 2015).
- 14 Figueres, C., H. J. Schellnhuber, G. Whiteman, J. Rockström, A. Hobley, and S. Rahmstorf, 2017: Three years to
15 safeguard our climate. *Nature*, **546**, 593–595, doi:10.1038/546593a.
16 <http://www.nature.com/doi/10.1038/546593a> (Accessed July 21, 2017).
- 17 Fishedick, M., and Coauthors, 2014: Industry. *Climate Change 2014: Mitigation of Climate Change. Contribution of*
18 *Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 739–810.
- 19 Fricko, O., S. C. Parkinson, N. Johnson, M. Strubegger, M. T. van Vliet, and K. Riahi, 2016: Energy sector water use
20 implications of a 2 °C climate policy. *Environ. Res. Lett.*, **11**, 34011, doi:10.1088/1748-9326/11/3/034011.
- 21 ———, and Coauthors, 2017: The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road
22 scenario for the 21st century. *Glob. Environ. Chang.*, **42**, 251–267, doi:10.1016/j.gloenvcha.2016.06.004.
23 <http://dx.doi.org/10.1016/j.gloenvcha.2016.06.004>.
- 24 Friedlingstein, P., and Coauthors, 2014: Persistent growth of CO2 emissions and implications for reaching climate
25 targets. *Nat. Geosci.*, **7**, 709–715, doi:10.1038/ngeo2248. <http://www.nature.com/doi/10.1038/ngeo2248>
26 (Accessed April 4, 2017).
- 27 Frölicher, T. L., 2016: Climate response: Strong warming at high emissions. *Nat. Clim. Chang.*, **6**, 823–824,
28 doi:10.1038/nclimate3053.
- 29 Fujimori, S., 2017: SSP3: AIM Implementation of Shared Socioeconomic Pathways. *Glob. Environ. Chang.*, **42**, 268–
30 283, doi:10.1016/j.gloenvcha.2016.06.009. <http://dx.doi.org/10.1016/j.gloenvcha.2016.06.009>.
- 31 ———, X. Su, J.-Y. Liu, T. Hasegawa, K. Takahashi, T. Masui, and M. Takimi, 2016: Implication of Paris Agreement in
32 the context of long-term climate mitigation goals. *Springerplus*, **5**, 1620, doi:10.1186/s40064-016-3235-9.
33 <http://www.ncbi.nlm.nih.gov/pubmed/27652193> (Accessed April 6, 2017).
- 34 Fullerton, D., and G. E. Metcalf, 1997: *Environmental Taxes and the Double-Dividend Hypothesis: Did You Really*
35 *Expect Something for Nothing?*
- 36 Fuss, S., W. H. Reuter, J. Szolgayov?, and M. Obersteiner, 2013: Optimal mitigation strategies with negative emission
37 technologies and carbon sinks under uncertainty. *Clim. Change*, **118**, 73–87, doi:10.1007/s10584-012-0676-1.
- 38 ———, and Coauthors, 2014a: Betting on negative emissions. *Nat. Clim. Chang.*, **4**, 850–853, doi:10.1038/nclimate2392.
39 <http://www.nature.com/nclimate/journal/v4/n10/full/nclimate2392.html> (Accessed June 15, 2015).
- 40 Fuss, S., J. G. Canadell, G. P. Peters, and M. Tavoni, 2014b: Betting on negative emissions : Nature Climate Change :
41 Nature Publishing Group. *Nat. Clim.*
- 42 Geels, F. W., and J. Schot, 2007: Typology of sociotechnical transition pathways. *Res. Policy*, **36**, 399–417,
43 doi:10.1016/j.respol.2007.01.003. <http://linkinghub.elsevier.com/retrieve/pii/S0048733307000248> (Accessed July
44 11, 2017).
- 45 ———, F. Kern, G. Fuchs, N. Hinderer, G. Kungl, J. Mylan, M. Neukirch, and S. Wassermann, 2016: The enactment of
46 socio-technical transition pathways: A reformulated typology and a comparative multi-level analysis of the
47 German and UK low-carbon electricity transitions (1990–2014). *Res. Policy*, **45**, 896–913,
48 doi:10.1016/j.respol.2016.01.015. <http://linkinghub.elsevier.com/retrieve/pii/S0048733316300087> (Accessed July
49 11, 2017).
- 50 Gerber, P. J., H. Steinfeld, B. Henderson, A. Mottet, C. Opio, J. Dijkman, A. Falcucci, and G. Tempio, 2013: *Tackling*
51 *climate change through livestock : a global assessment of emissions and mitigation opportunities*. Rome, 115 pp.
- 52 Gernaat, D. E. H. J., K. Calvin, P. L. Lucas, G. Luderer, S. A. C. Otto, S. Rao, J. Strefler, and D. P. van Vuuren, 2015:
53 Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. *Glob. Environ. Chang.*,
54 **33**, 142–153, doi:10.1016/j.gloenvcha.2015.04.010. <http://dx.doi.org/10.1016/j.gloenvcha.2015.04.010>.
- 55 Gillett, N. P., V. K. Arora, D. Matthews, and M. R. Allen, 2013: Constraining the Ratio of Global Warming to
56 Cumulative CO2 Emissions Using CMIP5 Simulations. *J. Clim.*, **26**, 6844–6858, doi:10.1175/JCLI-D-12-
57 00476.s1.
- 58 Global CCS Institute, 2016: *The global status of CCS: 2016 summary report*.
- 59 Goulder, L., and A. Schein, 2013: Carbon Taxes vs. Cap and Trade: A Critical Review. *Clim. Chang. Econ.*, **4**,
60 1350010, doi:10.1142/S2010007813500103.
61 <http://www.worldscientific.com/doi/abs/10.1142/S2010007813500103> (Accessed July 6, 2017).
- 62 Goulder, L. H., 1995: Environmental taxation and the double dividend: a reader’s guide. *Int. Tax Public Financ.*, **2**,
63 157–183.

- 1 Goulder, L. H., 2013: Climate change policy's interactions with the tax system. *Energy Econ.*, **40**, **Supple**, S3–S11,
2 doi:10.1016/j.eneco.2013.09.017.
- 3 Goulder, L. H., and I. W. H. Parry, 2008: Instrument Choice in Environmental Policy. *Rev. Environ. Econ. Policy*, **2**,
4 152–174, doi:10.1093/reep/ren005. <https://academic.oup.com/reep/article-lookup/doi/10.1093/reep/ren005>
5 (Accessed July 6, 2017).
- 6 Gregory, J. M., and T. Andrews, 2016: Variation in climate sensitivity and feedback parameters during the historical
7 period. *Geophys. Res. Lett.*, **43**, 3911–3920, doi:10.1002/2016GL068406.
8 <http://doi.wiley.com/10.1002/2016GL068406> (Accessed April 5, 2017).
- 9 Griggs, D., and Coauthors, 2014: An integrated framework for sustainable development goals. *Ecol. Soc.*, **19**,
10 doi:10.5751/ES-07082-190449.
- 11 Grubler, A., and C. Wilson, 2014: *Energy Technology Innovation - Learning from Historical Successes and Failures*.
12 Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied
13 Systems Analysis, Laxenburg, Austria, 400 pp.
- 14 Gschrey, B., W. Schwarz, C. Elsner, and R. Engelhardt, 2011: High increase of global F-gas emissions until 2050.
15 *Greenh. Gas Meas. Manag.*, **1**, 85–92, doi:10.1080/20430779.2011.579352.
16 <http://www.tandfonline.com/doi/abs/10.1080/20430779.2011.579352> (Accessed July 22, 2017).
- 17 Guivarch, C., and J. Rogelj, 2017: *Carbon price variations in 2°C scenarios explored*. 15 pp.
18 <https://static1.squarespace.com/static/54ff9c5ce4b0a53deccfb4c/t/592bd365414fb5ddd39de548/1496044396189>
19 [/Guivarch%2C+Rogelj+--+Carbon+prices+2C.pdf](#) (Accessed July 22, 2017).
- 20 Guivarch, C., R. Crassous, O. Sassi, and S. Hallegatte, 2011: The costs of climate policies in a second-best world with
21 labour market imperfections. *Clim. Policy*, **11**, 768–788, doi:10.3763/cpol.2009.0012.
22 <http://dx.doi.org/10.3763/cpol.2009.0012>.
- 23 Güneralp, B., and Coauthors, 2017: Global scenarios of urban density and its impacts on building energy use through
24 2050. *Proc. Natl. Acad. Sci. U. S. A.*, 201606035, doi:10.1073/pnas.1606035114.
25 <http://www.ncbi.nlm.nih.gov/pubmed/28069957> (Accessed July 12, 2017).
- 26 Haegel, N. M., and Coauthors, 2017: Terawatt-scale photovoltaics: Trajectories and challenges. *Science (80-.)*, **356**.
27 <http://science.sciencemag.org/content/356/6334/141> (Accessed July 21, 2017).
- 28 Hartmann, J., A. J. West, P. Renforth, P. Köhler, C. L. De La Rocha, D. A. Wolf-Gladrow, H. H. Dürr, and J.
29 Scheffran, 2013: Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon
30 dioxide, supply nutrients, and mitigate ocean acidification. *Rev. Geophys.*, **51**, 113–149, doi:10.1002/rog.20004.
31 <http://onlinelibrary.wiley.com/doi/10.1002/rog.20004/abstract> (Accessed January 6, 2014).
- 32 Havlík, P., and Coauthors, 2014: Climate change mitigation through livestock system transitions. *Proc. Natl. Acad. Sci.*
33 *U. S. A.*, **111**, 3709–3714, doi:10.1073/pnas.1308044111. <http://www.ncbi.nlm.nih.gov/pubmed/24567375>
34 (Accessed July 10, 2017).
- 35 Heck, V., D. Gerten, W. Lucht, and L. R. Boysen, 2016: Is extensive terrestrial carbon dioxide removal a “green” form
36 of geoengineering? A global modelling study. *Glob. Planet. Change*, **137**, 123–130,
37 doi:10.1016/j.gloplacha.2015.12.008.
- 38 Held, I. M., and Coauthors, 2010: Probing the Fast and Slow Components of Global Warming by Returning Abruptly to
39 Preindustrial Forcing. *J. Clim.*, **23**, 2418–2427, doi:10.1175/2009JCLI3466.1.
- 40 Herrington, T., and K. Zickfeld, 2014: Path independence of climate and carbon cycle response over a broad range of
41 cumulative carbon emissions. *Earth Syst. Dynam.*, **5**, 409–422, doi:10.5194/esd-5-409-2014.
- 42 Hoesly, R. M., and Coauthors, 2017: Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols
43 from the Community Emission Data System (CEDS). *Geosci. Model Dev. Discuss.*, **2017**, 1–41,
44 doi:10.5194/gmd-2017-43. <https://www.geosci-model-dev-discuss.net/gmd-2017-43/>.
- 45 Hof, A. F., M. G. J. den Elzen, A. Admiraal, M. Roelfsema, D. E. H. J. Gernaat, and D. P. van Vuuren, 2017: Global
46 and regional abatement costs of Nationally Determined Contributions (NDCs) and of enhanced action to levels
47 well below 2 °C and 1.5 °C. *Environ. Sci. Policy*, **71**, 30–40, doi:10.1016/j.envsci.2017.02.008.
48 <http://linkinghub.elsevier.com/retrieve/pii/S1462901116308978> (Accessed March 20, 2017).
- 49 Höglund-Isaksson, L., P. Purohit, M. Amann, I. Bertok, P. Rafaj, W. Schöpp, and J. Borken-Kleefeld, 2017: Cost
50 estimates of the Kigali Amendment to phase-down hydrofluorocarbons. *Environ. Sci. Policy*, **75**, 138–147,
51 doi:10.1016/j.envsci.2017.05.006. <http://linkinghub.elsevier.com/retrieve/pii/S146290111730120X> (Accessed
52 July 21, 2017).
- 53 Hope, C., 2006: The Marginal Impact of CO₂ from PAGE2002: An Integrated Assessment Model Incorporating the
54 IPCC's Five Reasons for Concern. *Integr. Assess. J.*, **6**, 16–56.
- 55 Houghton, R. A., 2007: Balancing the Global Carbon Budget. *Annu. Rev. Earth Planet. Sci.*, **35**, 313–347,
56 doi:10.1146/annurev.earth.35.031306.140057.
- 57 Hourcade, J.-C., and P. Shukla, 2013: Triggering the low-carbon transition in the aftermath of the global financial crisis.
58 *Clim. Policy*, **13**, 22–35, doi:10.1080/14693062.2012.751687. <http://dx.doi.org/10.1080/14693062.2012.751687>.
- 59 Hsiang, S., and Coauthors, 2017: Estimating economic damage from climate change in the United States. *Science (80-.)*,
60 **356**, 1362 LP-1369. <http://science.sciencemag.org/content/356/6345/1362.abstract>.
- 61 Humpenöder, F., and Coauthors, 2014: Investigating afforestation and bioenergy CCS as climate change mitigation
62 strategies. *Environ. Res. Lett.*, **9**, 64029, doi:10.1088/1748-9326/9/6/064029. [http://iopscience.iop.org/1748-
63 9326/9/6/064029](http://iopscience.iop.org/1748-9326/9/6/064029) (Accessed June 24, 2014).

- 1 Huntingford, C., and J. Lowe, 2007: Overshoot scenarios and climate change. *Science* (80-.), **316**, 829,
2 doi:10.1126/science.316.5826.829b.
- 3 IEA, 2016: Key World Energy Statistics 2016 Edition. *Report*,.
- 4 IEA / IRENA, 2017: Perspectives for the energy transition – investment needs for a low-carbon energy system. *Report*,.
- 5 Ilyina, T., D. Wolf-Gladrow, G. Munhoven, and C. Heinze, 2013: Assessing the potential of calcium-based artificial
6 ocean alkalization to mitigate rising atmospheric CO₂ and ocean acidification. *Geophys. Res. Lett.*, **40**, 5909–
7 5914, doi:10.1002/2013GL057981. <http://doi.wiley.com/10.1002/2013GL057981> (Accessed July 21, 2017).
- 8 Interagency Working Group on Social Cost of Greenhouse Gases, 2016: *Technical Support Document: - Technical*
9 *Update of the Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866*. United
10 States, 35 pp. https://www.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf
11 (Accessed July 22, 2017).
- 12 International Energy Agency (IEA), 2014a: *Energy Balances of OECD Countries 2014*. <http://www.oecd->
13 [ilibrary.org/energy/energy-balances-of-oecd-countries-2014_energy_bal_oecd-2014-en](http://www.oecd-ilibrary.org/energy/energy-balances-of-oecd-countries-2014_energy_bal_oecd-2014-en).
- 14 —, 2014b: *Energy Technology Perspectives 2014*. Paris, France, 382 pp.
- 15 —, 2015a: *Energy Balances of non-OECD Countries 2015*.
- 16 —, 2015b: *Energy Technology Perspectives 2015*. Paris, France, 418 pp.
- 17 —, 2016: *Energy Technology Perspectives 2016*. Paris, France, 418 pp.
- 18 —, 2017: *Energy Technology Perspectives 2017*. Paris, France, 443 pp.
- 19 IPCC, 2005: *IPCC special report on carbon dioxide capture and storage*. 442 pp.
- 20 —, 2013: *IPCC, 2013: Climate Change 2013: The Physical Science Basis*. Cambridge Univ Press, Cambridge,
21 United Kingdom and New York, NY, USA,.
- 22 —, 2014: Summary for Policymakers - Climate Change 2014: Mitigation of climate change. Contribution of
23 Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *Climate*
24 *Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of*
25 *the Intergovernmental Panel on Climate Change*, O. Edenhofer et al., Eds., Cambridge University Press,
26 Cambridge, UK, and New York, NY, USA, 1–30.
- 27 Iyer, G. C., and Coauthors, 2015a: The contribution of Paris to limit global warming to 2 °C. *Environ. Res. Lett.*, **10**,
28 125002, doi:10.1088/1748-9326/10/12/125002. <http://stacks.iop.org/1748-9326/10/i=12/a=125002>.
- 29 —, L. E. Clarke, J. A. Edmonds, B. P. Flannery, N. E. Hultman, H. C. McJeon, and D. G. Victor, 2015b: Improved
30 representation of investment decisions in assessments of CO₂ mitigation. *Nat. Clim. Chang.*, **5**, 436–440,
31 doi:10.1038/nclimate2553. <http://www.nature.com/nclimate/journal/v5/n5/full/nclimate2553.html> (Accessed
32 April 23, 2015).
- 33 Jaboyedoff, P., C.-A. Roulet, V. Dorer, A. Weber, and A. Pfeiffer, 2004: Energy in air-handling units—results of the
34 AIRLESS European Project. *Energy Build.*, **36**, 391–399, doi:10.1016/j.enbuild.2004.01.047.
35 <http://linkinghub.elsevier.com/retrieve/pii/S0378778804000477> (Accessed July 13, 2017).
- 36 Jakob, M., and J. C. Steckel, 2016: Implications of climate change mitigation for sustainable development. *Environ.*
37 *Res. Lett.*, **11**, 104010, doi:10.1088/1748-9326/11/10/104010. <http://stacks.iop.org/1748->
38 [9326/11/i=10/a=104010?key=crossref.4cd77602bc9540b790e45408383c5286](http://stacks.iop.org/1748-9326/11/i=10/a=104010?key=crossref.4cd77602bc9540b790e45408383c5286) (Accessed April 5, 2017).
- 39 —, C. Chen, S. Fuss, A. Marxen, N. D. Rao, and O. Edenhofer, 2016: Carbon Pricing Revenues Could Close
40 Infrastructure Access Gaps. *World Dev.*, **84**, 254–265, doi:10.1016/j.worlddev.2016.03.001.
41 <http://linkinghub.elsevier.com/retrieve/pii/S0305750X16000425> (Accessed July 22, 2017).
- 42 Jewell, J., and Coauthors, 2016: Comparison and interactions between the long-term pursuit of energy independence
43 and climate policies. *Nat. Energy*, **1**, 16073, doi:10.1038/nenergy.2016.73.
44 <http://www.nature.com/articles/nenergy201673> (Accessed June 8, 2016).
- 45 Jiang, J. J., B. Ye, and X. M. Ma, 2014: The construction of Shenzhen's carbon emission trading scheme. *Energy*
46 *Policy*, **75**, 17–21, doi:10.1016/j.enpol.2014.02.030.
47 <http://linkinghub.elsevier.com/retrieve/pii/S0301421514001190> (Accessed July 6, 2017).
- 48 Johnson, N., V. Krey, D. L. McCollum, S. Rao, K. Riahi, and J. Rogelj, 2015: Stranded on a low-carbon planet:
49 Implications of climate policy for the phase-out of coal-based power plants. *Technol. Forecast. Soc. Change*, **90**,
50 89–102, doi:10.1016/j.techfore.2014.02.028.
51 <http://www.sciencedirect.com/science/article/pii/S0040162514000924> (Accessed April 5, 2017).
- 52 Jones, C. D., and Coauthors, 2016: Simulating the Earth system response to negative emissions. *Environ. Res. Lett.*, **11**,
53 95012, doi:10.1088/1748-9326/11/9/095012.
- 54 Joos, F., and Coauthors, 2013: Carbon dioxide and climate impulse response functions for the computation of
55 greenhouse gas metrics: a multi-model analysis. *Atmos. Chem. Phys.*, **13**, 2793–2825, doi:10.5194/acp-13-2793-
56 2013.
- 57 Joshi, S. K. L. and B. B. B. B. and M. M., 2016: An investigation into linearity with cumulative emissions of the
58 climate and carbon cycle response in HadCM3LC. *Environ. Res. Lett.*, **11**, 65003.
- 59 Kandlikar, M., 1995: The relative role of trace gas emissions in greenhouse abatement policies. *Energy Policy*, **23**, 879–
60 883, doi:10.1016/0301-4215(95)00108-U. <http://linkinghub.elsevier.com/retrieve/pii/030142159500108U>
61 (Accessed July 22, 2017).
- 62 Kauppila, J., G. Chen, E. Windisch, and L. Martinez, Mobility in cities with 1.5°C climate target: Need for disruptive
63 innovation and accelerated action. *Curr. Opin. Environ. Sustain.*,.

- 1 KC, S., and W. Lutz, 2017: The human core of the shared socioeconomic pathways: Population scenarios by age, sex
2 and level of education for all countries to 2100. *Glob. Environ. Chang.*, **42**, 181–192,
3 doi:10.1016/j.gloenvcha.2014.06.004. <http://dx.doi.org/10.1016/j.gloenvcha.2014.06.004>.
- 4 Kearns, J., G. Teletzke, J. Palmer, H. Thomann, H. Kheshgi, Y.-H. Y.-H. Chen, S., S. Paltsev, and H. Herzog, 2017:
5 Developing a consistent database for regional geologic CO₂ storage capacity worldwide. *Energy Procedia*, **In**
6 **Press**.
- 7 Keith, D. W., and J. S. Rhodes, 2002: Bury, Burn or Both: A Two-for-One Deal on Biomass Carbon and Energy. *Clim.*
8 *Change*, **54**, 375–377. <http://dx.doi.org/10.1023/A:1016187420442>.
- 9 ———, M. Ha-Duong, and J. K. Stolaroff, 2006: Climate Strategy with CO₂ Capture from the Air. *Clim. Change*, **74**, 17–
10 45, doi:10.1007/s10584-005-9026-x. <http://link.springer.com/10.1007/s10584-005-9026-x> (Accessed April 16,
11 2015).
- 12 Kennel, F., C., V. Ramanathan, and D. Victor, G., 2012: The climate change threat we can beat. *Foreign Aff.*, **91**, 112.
- 13 Kermeli, K., H. Wina, J. Graus, and E. Worrell, 2014: Energy efficiency improvement potentials and a low energy
14 demand scenario for the global industrial sector. *Energy Effici.*, **7**, 987.
15 <http://search.proquest.com/openview/0cb2cbe1cd6fed521b679952022e3bf/1?pq-origsite=gscholar&cbl=54357>.
- 16 Kheshgi, H. S., 1995: Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. *Energy*, **20**, 915–922,
17 doi:10.1016/0360-5442(95)00035-F. <http://linkinghub.elsevier.com/retrieve/pii/036054429500035F> (Accessed
18 April 1, 2017).
- 19 Kim, S. H., K. Wada, A. Kurosawa, and M. Roberts, Nuclear energy response in the {EMF}27 study. *Clim. Change*, 1–
20 18, doi:10.1007/s10584-014-1098-z. <http://link.springer.com/article/10.1007/s10584-014-1098-z> (Accessed
21 March 28, 2014).
- 22 Klein, D., and Coauthors, 2014: The value of bioenergy in low stabilization scenarios: An assessment using REMIND-
23 MAgPIE. *Clim. Change*, **123**, 705–718, doi:10.1007/s10584-013-0940-z.
- 24 Koch, N., S. Fuss, G. Grosjean, and O. Edenhofer, 2014: Causes of the EU ETS price drop: Recession, CDM,
25 renewable policies or a bit of everything?—New evidence. *Energy Policy*, **73**, 676–685,
26 doi:10.1016/j.enpol.2014.06.024. <http://linkinghub.elsevier.com/retrieve/pii/S0301421514003966> (Accessed July
27 6, 2017).
- 28 Kolstad, C., and Coauthors, 2014: Social, Economic and Ethical Concepts and Methods. *Climate Change 2014:*
29 *Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the*
30 *Intergovernmental Panel on Climate Change*.
- 31 Krasting, J. P., J. P. Dunne, E. Shevliakova, and R. J. Stouffer, 2014: Trajectory sensitivity of the transient climate
32 response to cumulative carbon emissions. *Geophys. Res. Lett.*, **41**, 2520–2527, doi:10.1002/(ISSN)1944-8007.
- 33 Kreidenweis, U., F. Humpenöder, M. Stevanović, B. L. Bodirsky, E. Kriegler, H. Lotze-Campen, and A. Popp, 2016:
34 Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects. *Environ.*
35 *Res. Lett.*, **11**, 85001, doi:10.1088/1748-9326/11/8/085001. [http://stacks.iop.org/1748-
36 9326/11/i=8/a=085001?key=crossref.498dab12c59b27f71805e8cdbaf36f1](http://stacks.iop.org/1748-9326/11/i=8/a=085001?key=crossref.498dab12c59b27f71805e8cdbaf36f1) (Accessed August 1, 2016).
- 37 Krey, V., and Coauthors, 2014a: Annex II: Metrics & Methodology. *Climate Change 2014: Mitigation of Climate*
38 *Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on*
39 *Climate Change*, 1281–1328.
- 40 ———, G. Luderer, L. Clarke, and E. Kriegler, 2014b: Getting from here to there - energy technology transformation
41 pathways in the EMF27 scenarios. *Clim. Change*, **123**, 369–382, doi:10.1007/s10584-013-0947-5.
- 42 Kriegler, E., O. Edenhofer, L. Reuster, G. Luderer, and D. Klein, 2013: Is atmospheric carbon dioxide removal a game
43 changer for climate change mitigation? *Clim. Change*, **118**, doi:10.1007/s10584-012-0681-4.
- 44 ———, and Coauthors, 2014a: The role of technology for achieving climate policy objectives: Overview of the EMF 27
45 study on global technology and climate policy strategies. *Clim. Change*, **123**, doi:10.1007/s10584-013-0953-7.
- 46 Kriegler, E., J. Edmonds, S. Hallegatte, K. L. Ebi, T. Kram, K. Riahi, H. Winkler, and D. P. van Vuuren, 2014b: A new
47 scenario framework for climate change research: the concept of shared climate policy assumptions. *Clim. Change*,
48 **122**, 401–414, doi:10.1007/s10584-013-0971-5. <http://dx.doi.org/10.1007/s10584-013-0971-5>.
- 49 ———, and Coauthors, 2015a: Making or breaking climate targets: The AMPERE study on staged accession scenarios
50 for climate policy. *Technol. Forecast. Soc. Change*, **90**, 24–44, doi:10.1016/j.techfore.2013.09.021.
- 51 ———, and Coauthors, 2015b: Diagnostic indicators for integrated assessment models of climate policy. *Technol.*
52 *Forecast. Soc. Change*, **90**, 45–61, doi:10.1016/j.techfore.2013.09.020.
53 <http://dx.doi.org/10.1016/j.techfore.2013.09.020>.
- 54 ———, and Coauthors, 2017: Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st
55 century. *Glob. Environ. Chang.*, **42**, 297–315, doi:10.1016/j.gloenvcha.2016.05.015.
- 56 Krugman, P. R., 2009: *The Return of Depression Economics and the Crisis of 2008*. W.W. Norton & Company, Inc.,
57 New York,.
- 58 Kunreuther, H., and Coauthors, 2014: Integrated Risk and Uncertainty Assessment of Climate Change Response
59 Policies. *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth*
60 *Assessment Report of the Intergovernmental Panel on Climate Change*.
- 61 Kuramochi, T., A. Ramírez, W. Turkenburg, and A. Faaij, 2012: Comparative assessment of CO₂ capture technologies
62 for carbon-intensive industrial processes. *Prog. Energy Combust. Sci.*, **38**, 87–112,
63 doi:10.1016/j.pecs.2011.05.001. <http://www.sciencedirect.com/science/article/pii/S0360128511000293>.

- 1 Lal, R., 2004: Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science* (80-.), **304**,
2 1623 LP-1627. <http://science.sciencemag.org/content/304/5677/1623.abstract>.
- 3 Lamarque, J.-F., G. P. Kyle, M. Meinshausen, K. Riahi, S. J. Smith, D. P. van Vuuren, A. J. Conley, and F. Vitt, 2011:
4 Global and regional evolution of short-lived radiatively-active gases and aerosols in the Representative
5 Concentration Pathways. *Clim. Change*, **109**, 191–212, doi:10.1007/s10584-011-0155-0.
- 6 Lambin, E. F., and P. Meyfroidt, 2011: Global land use change, economic globalization, and the looming land scarcity.
7 *Proc. Natl. Acad. Sci. U. S. A.*, **108**, 3465–3472, doi:10.1073/pnas.1100480108.
8 <http://www.ncbi.nlm.nih.gov/pubmed/21321211> (Accessed July 10, 2017).
- 9 Leimbach, M., E. Kriegler, N. Roming, and J. Schwanitz, 2017: Future growth patterns of world regions – A GDP
10 scenario approach. *Glob. Environ. Chang.*, **42**, 215–225, doi:10.1016/j.gloenvcha.2015.02.005.
11 <http://www.sciencedirect.com/science/article/pii/S0959378015000242> (Accessed April 4, 2017).
- 12 Lemoine, D., and C. Traeger, 2014: Watch your step: {Optimal} policy in a tipping climate. *Am. Econ. J. Econ. Policy*,
13 **6**, 137–166. <http://www.ingentaconnect.com/content/aea/aejep/2014/00000006/00000001/art00006> (Accessed
14 March 9, 2016).
- 15 Li, F. G. N., E. Trutnevyte, and N. Strachan, 2015: A review of socio-technical energy transition (STET) models.
16 *Technol. Forecast. Soc. Change*, **100**, 290–305, doi:10.1016/j.techfore.2015.07.017. [http://ac.els-
17 cdn.com/S0040162515002267/1-s2.0-S0040162515002267-main.pdf?_tid=f1dbeeae-663b-11e7-ae03-
18 00000aacb35f&acdnat=1499779511_2019ac2970e2c30b68ae6df039540ccf](http://ac.els-cdn.com/S0040162515002267/1-s2.0-S0040162515002267-main.pdf?_tid=f1dbeeae-663b-11e7-ae03-00000aacb35f&acdnat=1499779511_2019ac2970e2c30b68ae6df039540ccf) (Accessed July 11, 2017).
- 19 Liedtke, C., C. Baedeker, M. Hasselkuß, H. Rohn, and V. Grinewitschus, 2015: User-integrated innovation in
20 Sustainable LivingLabs: an experimental infrastructure for researching and developing sustainable product
21 service systems. *J. Clean. Prod.*, **97**, 106–116, doi:10.1016/j.jclepro.2014.04.070.
22 <http://linkinghub.elsevier.com/retrieve/pii/S0959652614004338> (Accessed July 11, 2017).
- 23 Liousse, C., and Coauthors, 2010: Western african aerosols modelling with updated biomass burning emission
24 inventories in the frame of the AMMA-IDAF program. *Atmos. Chem. Phys. Discuss.*, **10**, 7347–7382,
25 doi:10.5194/acpd-10-7347-2010.
- 26 Lipsey, R. G., and K. Lancaster, 1957: The General Theory of Second Best. *Rev. Econ. Stud.*, **24**, 11–32.
- 27 Liu, A. A., 2013: Tax evasion and optimal environmental taxes. *J. Environ. Econ. Manage.*, **66**, 656–670.
- 28 Lontzek, T. S., Y. Cai, K. L. Judd, and T. M. Lenton, 2015: Stochastic integrated assessment of climate tipping points
29 indicates the need for strict climate policy. *Nat. Clim. Chang.*, **5**, 441–444.
30 <http://www.nature.com/nclimate/journal/v5/n5/full/nclimate2570.html> (Accessed March 9, 2016).
- 31 Lucon, O., and Coauthors, 2014: Buildings. *Climate Change 2014: Mitigation of Climate Change. Contribution of
32 Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 671–738.
- 33 Luderer, G., V. Bosetti, M. Jakob, M. Leimbach, J. C. Steckel, H. Waisman, and O. Edenhofer, 2012: The economics of
34 decarbonizing the energy system—results and insights from the RECIPE model intercomparison. *Clim. Change*,
35 **114**, 9–37, doi:10.1007/s10584-011-0105-x. <http://link.springer.com/10.1007/s10584-011-0105-x> (Accessed June
36 20, 2017).
- 37 ———, R. C. Pietzcker, C. Bertram, E. Kriegler, M. Meinshausen, and O. Edenhofer, 2013a: Economic mitigation
38 challenges: how further delay closes the door for achieving climate targets. *Environ. Res. Lett.*, **8**, 34033,
39 doi:10.1088/1748-9326/8/3/034033.
- 40 ———, R. C. R. C. Pietzcker, C. Bertram, E. Kriegler, M. Meinshausen, and O. Edenhofer, 2013b: Economic mitigation
41 challenges: how further delay closes the door for achieving climate targets. *Environ. Res. Lett.*, **8**, 34033,
42 doi:10.1088/1748-9326/8/3/034033.
- 43 ———, V. Krey, K. Calvin, J. Merrick, S. Mima, R. Pietzcker, J. Van Vliet, and K. Wada, 2014: The role of renewable
44 energy in climate stabilization: results from the {EMF}27 scenarios. *Clim. Change*, **123**, 427–441,
45 doi:10.1007/s10584-013-0924-z. <http://link.springer.com/article/10.1007/s10584-013-0924-z> (Accessed June 17,
46 2014).
- 47 ———, and Coauthors, 2016a: *Deep Decarbonization towards 1.5°C – 2°C stabilization: Policy findings from the
48 ADVANCE project*. 23 pp. [http://www.fp7-advance.eu/sites/default/files/documents/WP7/ADVANCE-Synthesis-
49 Report.pdf](http://www.fp7-advance.eu/sites/default/files/documents/WP7/ADVANCE-Synthesis-Report.pdf).
- 50 ———, and Coauthors, 2016b: *Deep Decarbonization towards 1.5°C – 2°C stabilization: Policy findings from the
51 ADVANCE project*.
- 52 ———, C. Bertram, K. Calvin, E. De Cian, and E. Kriegler, 2016c: Implications of weak near-term climate policies on
53 long-term mitigation pathways. *Clim. Change*, **136**, 127–140, doi:10.1007/s10584-013-0899-9.
- 54 Lutz, W., and S. KC, 2011: Global Human Capital: Integrating Education and Population. *Science* (80-.), **333**.
55 <http://science.sciencemag.org/content/333/6042/587> (Accessed July 16, 2017).
- 56 MacDougall, A. H., K. Zickfeld, R. Knutti, and H. D. Matthews, 2015: Sensitivity of carbon budgets to permafrost
57 carbon feedbacks and non-CO₂ forcings. *Environ. Res. Lett.*, **10**, 125003, doi:10.1088/1748-9326/10/12/125003.
- 58 ———, N. C. Swart, N. C. Swart, and R. Knutti, 2017: The Uncertainty in the Transient Climate Response to Cumulative
59 CO₂ Emissions Arising from the Uncertainty in Physical Climate Parameters. *dx.doi.org*, **30**, 813–827,
60 doi:10.1175/JCLI-D-16-0205.1.
- 61 Mahowald, N. M., R. Scanza, J. Brahney, C. L. Goodale, P. G. Hess, J. K. Moore, and J. Neff, 2017: Aerosol
62 Deposition Impacts on Land and Ocean Carbon Cycles. *Curr. Clim. Chang. Reports*, **3**, 16–31,
63 doi:10.1007/s40641-017-0056-z.

- 1 Marangoni, G., and M. Tavoni, 2014: The Clean Energy R&D Strategy for 2°C. *Clim. Chang. Econ.*, **5**, 1440003,
2 doi:10.1142/S201000781440003X. <http://www.worldscientific.com/doi/abs/10.1142/S201000781440003X>
3 (Accessed July 19, 2017).
- 4 Marangoni, G., and Coauthors, 2017: Sensitivity of projected long-term CO2 emissions across the Shared
5 Socioeconomic Pathways. *Nat. Clim. Chang.*, **7**, 6–8, doi:10.1038/nclimate3199.
6 <http://www.nature.com/doi/abs/10.1038/nclimate3199>.
- 7 Marcucci, A., S. Kypreos, and E. Panos, 2017: The road to achieving the long-term Paris targets: Energy transition and the
8 role of direct air capture. *Clim. Change*, **in review**.
- 9 Marten, A. L., E. A. Kopits, C. W. Griffiths, S. C. Newbold, and A. Wolverton, 2015: Incremental CH4 and N2O
10 mitigation benefits consistent with the US Government’s SC-CO2 estimates. *Clim. Policy*, **15**, 272–298,
11 doi:10.1080/14693062.2014.912981. <http://www.tandfonline.com/doi/full/10.1080/14693062.2014.912981>
12 (Accessed July 22, 2017).
- 13 Marvel, K., G. A. Schmidt, R. L. Miller, and L. S. Nazarenko, 2016: Implications for climate sensitivity from the
14 response to individual forcings. *Nat. Clim. Chang.*, **6**, 386–389, doi:10.1038/NCLIMATE2888.
15 <https://www.nature.com/nclimate/journal/v6/n4/pdf/nclimate2888.pdf> (Accessed July 11, 2017).
- 16 Matthews, H. D., and K. Caldeira, 2008: Stabilizing climate requires near-zero emissions. *Geophys. Res. Lett.*, **35**, 1–5,
17 doi:10.1029/2007GL032388.
- 18 —, N. P. Gillett, P. A. Stott, and K. Zickfeld, 2009: The proportionality of global warming to cumulative carbon
19 emissions. *Nature*, **459**, 829–832, doi:10.1038/nature08047.
- 20 Mazzotti, M., and Coauthors, 2005: Mineral carbonation and industrial uses of carbon dioxide. *IPCC Spec. Rep.*
21 *Carbon dioxide Capture Storage*, 319–338. http://www.ipcc.ch/pdf/special-reports/srccs/srccs_chapter7.pdf.
- 22 McCollum, D. L., Y. Nagai, K. Riahi, G. Marangoni, K. Calvin, R. Pietzcker, J. van Vliet, and B. van der Zwaan, 2013:
23 Energy Investments Under Climate Policy: a Comparison of Global Models. *Clim. Chang. Econ.*, **4**,
24 doi:10.1142/s2010007813400101.
- 25 Meinshausen, M., N. Meinshausen, W. Hare, S. C. B. Raper, K. Frieler, R. Knutti, D. J. Frame, and M. R. Allen, 2009:
26 Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature*, **458**, 1158–1162,
27 doi:10.1038/nature08017.
- 28 Meinshausen, M., S. C. B. Raper, and T. M. L. Wigley, 2011a: Emulating coupled atmosphere-ocean and carbon cycle
29 models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmos. Chem. Phys.*, **11**,
30 1417–1456, doi:10.5194/acp-11-1417-2011.
- 31 Meinshausen, M., T. M. L. Wigley, and S. C. B. Raper, 2011b: Emulating atmosphere-ocean and carbon cycle models
32 with a simpler model, MAGICC6 – Part 2: Applications. *Atmos. Chem. Phys.*, **11**, 1457–1471, doi:10.5194/acp-
33 11-1457-2011.
- 34 Moore, F. C., and D. B. Diaz, 2015: Temperature impacts on economic growth warrant stringent mitigation policy. *Nat.*
35 *Clim. Chang.*, **5**, 127–131, doi:10.1038/nclimate2481.
- 36 Moss, T., and Coauthors, 2014: *Balancing Energy Access and Environmental Goals in Development Finance: The Case*
37 *of the OPIC Carbon Cap*. Washington D.C., USA, 14 pp. [https://www.cgdev.org/publication/balancing-energy-
38 access-and-environmental-goals-development-finance-case-opic-carbon-cap](https://www.cgdev.org/publication/balancing-energy-access-and-environmental-goals-development-finance-case-opic-carbon-cap) (Accessed July 23, 2017).
- 39 Mundaca, L., 2008: Markets for energy efficiency: Exploring the implications of an EU-wide “Tradable White
40 Certificate” scheme. *Energy Econ.*, <http://www.sciencedirect.com/science/article/pii/S0140988308000467>
41 (Accessed July 6, 2017).
- 42 —, and J. Richter, 2013: Challenges for New Zealand’s carbon market. *Nat. Clim. Chang.*,
43 <https://www.nature.com/nclimate/journal/v3/n12/full/nclimate2052.html> (Accessed July 6, 2017).
- 44 Myhre, G., and Coauthors, 2013: Anthropogenic and Natural Radiative Forcing. *Climate Change 2013: The Physical*
45 *Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel*
46 *on Climate Change*, 659–740.
- 47 Nägele, F., T. Kasper, and B. Girod, 2017: Turning up the heat on obsolete thermostats: A simulation-based comparison
48 of intelligent control approaches for residential heating systems. *Renew. Sustain. Energy Rev.*, **75**, 1254–1268,
49 doi:10.1016/j.rser.2016.11.112. <http://linkinghub.elsevier.com/retrieve/pii/S1364032116308577> (Accessed July
50 13, 2017).
- 51 Nakicenovic, N., and Coauthors, 2000: *IPCC Special Report on Emissions Scenarios*. Nebojsa Nakicenovic and Rob
52 Swart, Eds. Cambridge University Press, Cambridge, 570 pp.
53 <http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0> (Accessed April 4, 2017).
- 54 National Academies of Sciences and Medicine, E., 2016: *Assessment of Approaches to Updating the Social Cost of*
55 *Carbon: Phase I Report on a Near-Term Update*. Washington D.C., USA,
56 <https://www.nap.edu/catalog/21898/assessment-of-approaches-to-updating-the-social-cost-of-carbon>.
- 57 New Climate Economy, 2014: Better Growth Better Climate. *Better growth, Better Clim. New Clim. Econ. Rep.*, 2–33,
58 doi:ISBN:9780990684503.
- 59 Newell, R., W. Pizer, and D. Raimi, 2014: Carbon markets: past, present, and future. *Annu. Rev. Resour. Econ.*,
60 <http://www.annualreviews.org/doi/abs/10.1146/annurev-resource-100913-012655> (Accessed July 6, 2017).
- 61 Nilsson, S., and W. Schopfhauser, 1995: The carbon-sequestration potential of a global afforestation program. *Clim.*
62 *Change*, **30**, 267–293, doi:10.1007/BF01091928. <http://dx.doi.org/10.1007/BF01091928>.
- 63 Nohara, D., J. Tsutsui, S. Watanabe, K. Tachiiri, T. Hajima, H. Okajima, and T. Matsuno, 2015: Examination of a

- 1 climate stabilization pathway via zero-emissions using Earth system models. *Environ. Res. Lett.*, **10**, 95005,
2 doi:10.1088/1748-9326/10/9/095005. [http://stacks.iop.org/1748-](http://stacks.iop.org/1748-9326/10/i=9/a=095005?key=crossref.4e5e0374e7c14332fa54ac1533086f06)
3 [9326/10/i=9/a=095005?key=crossref.4e5e0374e7c14332fa54ac1533086f06](http://stacks.iop.org/1748-9326/10/i=9/a=095005?key=crossref.4e5e0374e7c14332fa54ac1533086f06) (Accessed April 5, 2017).
- 4 Nordhaus, W., 2014: Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and
5 Alternative Approaches. *J. Assoc. Environ. Resour. Econ.*, **1**, 273–312, doi:10.1086/676035.
6 <http://www.jstor.org/stable/10.1086/676035> (Accessed August 20, 2015).
- 7 Nordhaus, W. D., 2005: A Review of The Stern Review on the Economics of Climate Change. *J. Econ. Lit.*, **XLV**, 686–
8 702.
- 9 ———, 2013: *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World*. Yale University Press, 392
10 pp.
- 11 Nordhaus, W. D., 2017: Revisiting the social cost of carbon. *Proc. Natl. Acad. Sci.*, **114**, 1518–1523,
12 doi:10.1073/pnas.1609244114. <http://www.pnas.org/content/114/7/1518> (Accessed February 16, 2017).
- 13 ———, and J. Boyer, 2000: *Warming the World: Economic Models of Global Warming*. MIT Press, Cambridge, MA.,
- 14 O’Neill, B. C., 2008: Learning and climate change: an introduction and overview. *Clim. Change*, **89**, 1–6,
15 doi:10.1007/s10584-008-9443-8. <http://link.springer.com/10.1007/s10584-008-9443-8> (Accessed July 21, 2017).
- 16 O’Neill, B. C., E. Kriegler, K. Riahi, K. L. Ebi, S. Hallegatte, T. R. Carter, R. Mathur, and D. P. van Vuuren, 2014: A
17 new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Clim.*
18 *Change*, **122**, 387–400, doi:10.1007/s10584-013-0905-2.
- 19 ———, and Coauthors, 2017: The roads ahead: Narratives for shared socioeconomic pathways describing world futures
20 in the 21st century. *Glob. Environ. Chang.*, **42**, 169–180, doi:10.1016/j.gloenvcha.2015.01.004.
21 <http://dx.doi.org/10.1016/j.gloenvcha.2015.01.004>.
- 22 Obersteiner, M., and Coauthors, 2001: Managing Climate Risk. *Science (80-.)*, **294**, 786–787.
- 23 OECD, 2017: *Investing in Climate, Investing in Growth*. OECD Publishing, Paris, France.,
- 24 Ogawa, T., S. Nakanishi, T. Shidahara, T. Okumura, and E. Hayashi, 2011: Saline-aquifer CO₂ sequestration in Japan-
25 methodology of storage capacity assessment. *Int. J. Greenh. Gas Control*, **5**, 318–326,
26 doi:10.1016/j.ijggc.2010.09.009.
- 27 Otto, A., and Coauthors, 2013: Energy budget constraints on climate response. *Nat. Geosci.*, **6**, 415–416.
28 <http://dx.doi.org/10.1038/ngeo1836>.
- 29 Paltsev, S., and P. Capros, 2013: Cost Concepts for Climate Change Mitigation. *Clim. Chang. Econ.*, **4**, 1340003,
30 doi:10.1142/S2010007813400034. <http://www.worldscientific.com/doi/abs/10.1142/S2010007813400034>.
- 31 Pellegrino, M., M. Simonetti, and G. Chiesa, 2016: Reducing thermal discomfort and energy consumption of Indian
32 residential buildings: Model validation by in-field measurements and simulation of low-cost interventions. *Energy*
33 *Build.*, **113**, 145–158, doi:10.1016/j.enbuild.2015.12.015.
34 <http://linkinghub.elsevier.com/retrieve/pii/S0378778815304515> (Accessed July 13, 2017).
- 35 Peters, G. P., 2016: The “best available science” to inform 1.5 °C policy choices. *Nat. Clim. Chang.*, **6**, 646–649,
36 doi:10.1038/nclimate3000.
- 37 Peters, G. P., R. M. Andrew, J. G. Canadell, S. Fuss, R. B. Jackson, J. I. Korsbakken, C. Le Quééré, and N. Nakicenovic,
38 2017: Key indicators to track current progress and future ambition of the Paris Agreement. *Nat. Clim. Chang.*,
39 **advance on**, doi:10.1038/nclimate3202.
- 40 Pietzcker, R. C., and Coauthors, 2016: System integration of wind and solar power in integrated assessment models: A
41 cross-model evaluation of new approaches. *Energy Econ.*, doi:10.1016/j.eneco.2016.11.018.
42 <http://www.sciencedirect.com/science/article/pii/S0140988316303395> (Accessed January 11, 2017).
- 43 Pindyck, R. S., 2013: Climate Change Policy: What Do the Models Tell Us? *J. Econ. Lit.*, **51**, 1–23,
44 doi:10.1257/jel.51.3.860.
45 <http://www.nber.org/papers/w19244%5Cnhttp://pubs.aeaweb.org/doi/abs/10.1257/jel.51.3.860>.
- 46 Pizer, W., and Coauthors, 2014: Using and improving the social cost of carbon. *Science (80-.)*, **346**, 1189 LP-1190.
47 <http://science.sciencemag.org/content/346/6214/1189.abstract>.
- 48 Pollitt, H., and J.-F. Mercure, 2017: The role of money and the financial sector in energy-economy models used for
49 assessing climate and energy policy. *Clim. Policy*, **0**, 1–14, doi:10.1080/14693062.2016.1277685.
50 <http://dx.doi.org/10.1080/14693062.2016.1277685>.
- 51 Popp, A., H. Lotze-Campen, and B. Bodirsky, 2010: Food consumption, diet shifts and associated non- $\{CO_2\}$
52 greenhouse gases from agricultural production. *Glob. Environ. Chang.*, **20**, 451–462,
53 doi:10.1016/j.gloenvcha.2010.02.001. <http://linkinghub.elsevier.com/retrieve/pii/S0959378010000075> (Accessed
54 August 14, 2012).
- 55 ———, and Coauthors, 2014a: Land-use protection for climate change mitigation. *Nat. Clim. Chang.*, **4**, 1095–1098,
56 doi:10.1038/nclimate2444. <https://www.nature.com/nclimate/journal/v4/n12/pdf/nclimate2444.pdf> (Accessed
57 July 10, 2017).
- 58 ———, and Coauthors, 2014b: Land-use transition for bioenergy and climate stabilization: Model comparison of drivers,
59 impacts and interactions with other land use based mitigation options. *Clim. Change*, **123**, 495–509,
60 doi:10.1007/s10584-013-0926-x.
- 61 ———, and Coauthors, 2017: Land-use futures in the shared socio-economic pathways. *Glob. Environ. Chang.*, **42**,
62 doi:<http://dx.doi.org/10.1016/j.gloenvcha.2016.10.002>.
63 <http://www.sciencedirect.com/science/article/pii/S0959378016303399>.

- 1 Popp, D., and R. Newell, 2012: Where does energy R&D come from? Examining crowding out from energy R&D.
2 *Energy Econ.*, **34**, 980–991.
- 3 Proistosescu, C., and P. J. Huybers, 2017: Slow climate mode reconciles historical and model-based estimates of
4 climate sensitivity. *Sci. Adv.*, **3**. <http://advances.sciencemag.org/content/3/7/e1602821.abstract>.
- 5 Purohit, P., and L. Höglund-Isaksson, 2017: Global emissions of fluorinated greenhouse gases 2005–2050 with
6 abatement potentials and costs. *Atmos. Chem. Phys.*, **17**, 2795–2816, doi:10.5194/acp-17-2795-2017.
7 <https://www.atmos-chem-phys.net/17/2795/2017/> (Accessed July 21, 2017).
- 8 Le Quééré, C., and Coauthors, 2016: Global Carbon Budget 2016. *ESSD*, **8**, 605–649, doi:10.5194/essd-8-605-2016.
- 9 Ramanathan, V., and Y. Xu, 2010: The Copenhagen Accord for limiting global warming: criteria, constraints, and
10 available avenues. *Proc. Natl. Acad. Sci. U. S. A.*, **107**, 8055–8062, doi:10.1073/pnas.1002293107.
- 11 Rannou, Y., and P. Barneto, 2016: Futures trading with information asymmetry and OTC predominance: Another look
12 at the volume/volatility relations in the European carbon markets. *Energy Econ.*, **53**, 159–174,
13 doi:10.1016/j.eneco.2014.10.010. <http://linkinghub.elsevier.com/retrieve/pii/S0140988314002552> (Accessed July
14 6, 2017).
- 15 Rao, S., and Coauthors, 2017: Future air pollution in the Shared Socio-economic Pathways. *Glob. Environ. Chang.*, **42**,
16 346–358, doi:10.1016/j.gloenvcha.2016.05.012.
- 17 Rau, G. H., 2011: CO₂ Mitigation via Capture and Chemical Conversion in Seawater. *Environ. Sci. Technol.*, **45**, 1088–
18 1092, doi:10.1021/es102671x. <http://dx.doi.org/10.1021/es102671x>.
- 19 Raven, R. P. J. M., E. Heiskanen, R. Lovio, M. Hodson, and B. Brohmann, 2008: The Contribution of Local
20 Experiments and Negotiation Processes to Field-Level Learning in Emerging (Niche) Technologies. *Bull. Sci.*
21 *Technol. Soc.*, **28**, 464–477, doi:10.1177/0270467608317523.
22 <http://journals.sagepub.com/doi/10.1177/0270467608317523> (Accessed July 11, 2017).
- 23 Regnier, P., and Coauthors, 2013: Anthropogenic perturbation of the carbon fluxes from land to ocean. *Nat. Geosci.*, **6**,
24 597–607, doi:10.1038/ngeo1830.
- 25 Revesz, R., P. Howard, K. Arrow, L. Goulder, R. Kopp, M. Livermore, M. Oppenheimer, and T. Sterner, 2014a: Global
26 warming: Improve economic models of climate change. *Nature*, **508**, 173–175.
- 27 Revesz, R. L., P. H. Howard, K. Arrow, L. H. Goulder, R. E. Kopp, M. A. Livermore, M. Oppenheimer, and T. Sterner,
28 2014b: Improve economic models of climate change. *Nature*, **508**, 173–175.
- 29 Riahi, K., and Coauthors, 2011: RCP 8.5? A scenario of comparatively high greenhouse gas emissions. *Clim. Change*,
30 **109**, 33–57, doi:10.1007/s10584-011-0149-y.
- 31 ———, and Coauthors, 2012: Chapter 17 - Energy Pathways for Sustainable Development. *Global Energy Assessment -*
32 *Toward a Sustainable Future*, Cambridge University Press, Cambridge, UK and New York, NY, USA and the
33 International Institute for Applied Systems Analysis, Laxenburg, Austria, 1203–1306.
- 34 ———, and Coauthors, 2015: Locked into Copenhagen pledges - Implications of short-term emission targets for the cost
35 and feasibility of long-term climate goals. *Technol. Forecast. Soc. Change*, **90**, 8–23,
36 doi:10.1016/j.techfore.2013.09.016. <http://dx.doi.org/10.1016/j.techfore.2013.09.016>.
- 37 ———, and Coauthors, 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas
38 emissions implications: An overview. *Glob. Environ. Chang.*, **42**, 153–168, doi:10.1016/j.gloenvcha.2016.05.009.
- 39 Rigby, M., and Coauthors, 2010: History of atmospheric SF₆ from 1973 to 2008. *Atmos. Chem. Phys. Atmos. Chem.*
40 *Phys.*, **10**, 10305–10320, doi:10.5194/acp-10-10305-2010.
- 41 Riis, F., and E. Halland, 2014: CO₂ storage atlas of the Norwegian Continental shelf: Methods used to evaluate
42 capacity and maturity of the CO₂ storage potential. *Energy Procedia*, **63**, 5258–5265,
43 doi:10.1016/j.egypro.2014.11.557.
- 44 Rockström, B. J., O. Gaffney, J. Rogelj, M. Meinshausen, N. Nakicenovic, and H. Joachim, 2017: A roadmap for rapid
45 decarbonization. *Science (80-.)*, **355**, 1269–1271, doi:10.1126/science.aah3443.
- 46 Rogelj, J., and Coauthors, 2011: Emission pathways consistent with a 2 °C global temperature limit. *Nat. Clim. Chang.*,
47 **1**, 413–418, doi:10.1038/nclimate1258.
- 48 ———, D. L. McCollum, A. Reisinger, M. Meinshausen, and K. Riahi, 2013: Probabilistic cost estimates for climate
49 change mitigation. *Nature*, **493**, 79–83, doi:10.1038/nature11787.
50 <http://www.nature.com/nature/journal/v493/n7430/full/nature11787.html> (Accessed December 3, 2014).
- 51 ———, and Coauthors, 2014a: Disentangling the effects of CO₂ and short-lived climate forcer mitigation. *Proc. Natl.*
52 *Acad. Sci. U. S. A.*, **111**, 16325–16330, doi:10.1073/pnas.1415631111.
- 53 ———, M. Meinshausen, J. Sedláček, and R. Knutti, 2014b: Implications of potentially lower climate sensitivity on
54 climate projections and policy. *Environ. Res. Lett.*, **9**, 31003, doi:10.1088/1748-9326/9/3/031003.
- 55 ———, G. Luderer, R. C. Pietzcker, E. Kriegler, M. Schaeffer, V. Krey, and K. Riahi, 2015a: Energy system
56 transformations for limiting end-of-century warming to below 1.5 °C. *Nat. Clim. Chang.*, **5**, 519–527,
57 doi:10.1038/nclimate2572. <http://www.nature.com/doi/10.1038/nclimate2572>.
- 58 ———, M. Meinshausen, M. Schaeffer, R. Knutti, and R. Keywan, 2015b: Impact of short-lived non-CO₂ mitigation on
59 carbon budgets for stabilizing global warming. *Environ. Res. Lett.*, **10**, 75001, doi:10.1088/1748-
60 9326/10/7/075001. <http://stacks.iop.org/1748-9326/10/i=7/a=075001>.
- 61 ———, A. Reisinger, D. L. McCollum, R. Knutti, K. Riahi, and M. Meinshausen, 2015c: Mitigation choices impact
62 carbon budget size compatible with low temperature goals. *Environ. Res. Lett.*, **10**, 75003, doi:10.1088/1748-
63 9326/10/7/075003.

- 1 —, M. Schaeffer, M. Meinshausen, R. Knutti, J. Alcamo, K. Riahi, and W. Hare, 2015d: Zero emission targets as
2 long-term global goals for climate protection. *Environ. Res. Lett.*, **10**, 105007, doi:10.1088/1748-
3 9326/10/10/105007. <http://stacks.iop.org/1748-9326/10/i=10/a=105007>.
- 4 —, and Coauthors, 2016a: Paris Agreement climate proposals need a boost to keep warming well below 2 °C.
5 *Nature*, **534**, 631–639, doi:10.1038/nature18307. [http://0-
6 www.nature.com.wam.city.ac.uk/nature/journal/v534/n7609/pdf/nature18307.pdf](http://0-www.nature.com.wam.city.ac.uk/nature/journal/v534/n7609/pdf/nature18307.pdf).
- 7 —, M. Schaeffer, P. Friedlingstein, N. P. Gillett, D. P. van Vuuren, K. Riahi, M. Allen, and R. Knutti, 2016b:
8 Differences between carbon budget estimates unravelled. *Nat. Clim. Chang.*, **6**, 245–252,
9 doi:10.1038/nclimate2868. <http://www.nature.com/doi/10.1038/nclimate2868>.
- 10 —, and Coauthors, 2017a: Transition pathways towards limiting climate change below 1.5°C. *Nat. Clim. Chang.*, **in
11 review**.
- 12 —, O. Fricko, M. Meinshausen, V. Krey, J. J. Zilliacus, and K. Riahi, 2017b: Understanding the origin of Paris
13 Agreement emission uncertainties. *Nat. Commun.*, **8**, 15748, doi:10.1038/ncomms15748.
14 <http://www.nature.com/doi/10.1038/ncomms15748> (Accessed June 14, 2017).
- 15 Rose, S. K., 2012: The role of the social cost of carbon in policy. *Wiley Interdiscip. Rev. Clim. Chang.*, **3**, 195–212,
16 doi:10.1002/wcc.163. <http://dx.doi.org/10.1002/wcc.163>.
- 17 —, E. Kriegler, R. Bibas, K. Calvin, A. Popp, D. P. van Vuuren, and J. Weyant, 2013: Bioenergy in energy
18 transformation and climate management. *Clim. Change*, **123**, 477–493, doi:10.1007/s10584-013-0965-3.
19 <http://link.springer.com/article/10.1007/s10584-013-0965-3> (Accessed February 8, 2016).
- 20 Rose, S. K., E. Kriegler, R. Bibas, K. Calvin, A. Popp, D. P. van Vuuren, and J. Weyant, 2014a: Bioenergy in energy
21 transformation and climate management. *Clim. Change*, **123**, 477–493, doi:10.1007/s10584-013-0965-3.
- 22 —, R. Richels, S. Smith, K. Riahi, J. Strefler, and D. P. van Vuuren, 2014b: Non-Kyoto radiative forcing in long-run
23 greenhouse gas emissions and climate change scenarios. *Clim. Change*, **123**, 511–525, doi:10.1007/s10584-013-
24 0955-5.
- 25 —, —, G. Blanford, and T. Rutherford, 2017: The Paris Agreement and next steps in limiting global warming.
26 *Clim. Change*, 1–16, doi:10.1007/s10584-017-1935-y. <http://link.springer.com/10.1007/s10584-017-1935-y>
27 (Accessed April 6, 2017).
- 28 Rotstayn, L. D., M. A. Collier, D. T. Shindell, O. Boucher, L. D. Rotstayn, M. A. Collier, D. T. Shindell, and O.
29 Boucher, 2015: Why Does Aerosol Forcing Control Historical Global-Mean Surface Temperature Change in
30 CMIP5 Models? *J. Clim.*, **28**, 6608–6625, doi:10.1175/JCLI-D-14-00712.1.
- 31 Salon, D., M. G. Boarnet, S. Handy, S. Spears, and G. Tal, 2012: How do local actions affect VMT? A critical review
32 of the empirical evidence. *Transp. Res. Part D Transp. Environ.*, **17**, 495–508, doi:10.1016/j.trd.2012.05.006.
33 <http://linkinghub.elsevier.com/retrieve/pii/S136192091200051X> (Accessed July 13, 2017).
- 34 Samset, B. H., and Coauthors, 2016: Fast and slow precipitation responses to individual climate forcings: A PDRMIP
35 multimodel study. *Geophys. Res. Lett.*, **43**, doi:10.1002/2016GL068064.
- 36 Sanderson, B. M., B. C. O'Neill, and C. Tebaldi, 2016: What would it take to achieve the Paris temperature targets?
37 *Geophys. Res. Lett.*, **43**, 7133–7142, doi:10.1002/2016GL069563. <http://doi.wiley.com/10.1002/2016GL069563>
38 (Accessed April 6, 2017).
- 39 Sarofim, M. C., S. T. Waldhoff, and S. C. Anenberg, 2017: Valuing the Ozone-Related Health Benefits of Methane
40 Emission Controls. *Environ. Resour. Econ.*, **66**, 45–63, doi:10.1007/s10640-015-9937-6.
41 <https://doi.org/10.1007/s10640-015-9937-6>.
- 42 Saunio, M., and Coauthors, 2016: The global methane budget 2000–2012. *ESSD*, **8**, 697–751, doi:10.5194/essd-8-697-
43 2016.
- 44 Saygin, D., M. K. Patel, E. Worrell, C. Tam, and D. J. Gielen, 2011: Potential of best practice technology to improve
45 energy efficiency in the global chemical and petrochemical sector. *Energy*, **36**, 5779–5790,
46 doi:10.1016/j.energy.2011.05.019.
- 47 Schleussner, C.-F., and Coauthors, 2016: Science and policy characteristics of the Paris Agreement temperature goal.
48 *Nat. Clim. Chang.*, **6**, 827–835, doi:10.1038/nclimate3096.
49 <http://www.nature.com/nclimate/journal/v6/n9/full/nclimate3096.html>.
- 50 Schmidt, M. G. W., H. Held, E. Kriegler, and A. Lorenz, 2013: Climate Policy Under Uncertain and Heterogeneous
51 Climate Damages. *Environ. Resour. Econ.*, **54**, 79–99, doi:10.1007/s10640-012-9582-2.
- 52 Schneider, T., J. Teixeira, C. S. Bretherton, F. Briant, K. G. Pressel, C. Schär, and A. P. Siebesma, 2017: Climate goals
53 and computing the future of clouds. *Nat. Clim. Chang.*, **7**, 3–5, doi:10.1038/nclimate3190.
- 54 Schneider von Deimling, T., M. Meinshausen, A. Levermann, V. Huber, K. Frieler, D. M. Lawrence, and V. Brovkin,
55 2012: Estimating the near-surface permafrost-carbon feedback on global warming. *Biogeosciences*, **9**, 649–665,
56 doi:10.5194/bg-9-649-2012. <http://www.biogeosciences.net/9/649/2012/> (Accessed July 11, 2017).
- 57 Shah, N., M. Wei, V. Letschert, and A. Phadke, 2015: *Benefits of Leapfrogging to Superefficiency and Low Global
58 Warming Potential Refrigerants in Room Air Conditioning*. Berkeley, US, 58 pp.
59 https://eetd.lbl.gov/sites/all/files/lbnl-1003671_0.pdf.
- 60 Sherwood, S. C., S. Bony, and J.-L. Dufresne, 2014: Spread in model climate sensitivity traced to atmospheric
61 convective mixing. *Nature*, **505**, 37–42. <http://dx.doi.org/10.1038/nature12829>.
- 62 Shindell, D., and Coauthors, 2012: Simultaneously Mitigating Near-Term Climate Change and Improving Human
63 Health and Food Security. *Science (80-)*, **335**, 183–189, doi:10.1126/science.1210026.

- 1 —, and Coauthors, 2017a: A climate policy pathway for near- and long-term benefits. *Science* (80-.), **356**,
2 <http://science.sciencemag.org/content/356/6337/493> (Accessed July 21, 2017).
- 3 Shindell, D. T., 2014: Inhomogeneous forcing and transient climate sensitivity. *Nat. Clim. Chang.*, **4**, 18–21,
4 doi:10.1038/NCLIMATE2136.
- 5 Shindell, D. T., 2015: The social cost of atmospheric release. *Clim. Change*, **130**, 313–326, doi:10.1007/s10584-015-
6 1343-0. <http://link.springer.com/10.1007/s10584-015-1343-0> (Accessed July 22, 2017).
- 7 —, 2016: Crop yield changes induced by emissions of individual climate-altering pollutants. *Earth's Futur.*, **4**, 373–
8 380.
- 9 —, G. Faluvegi, L. Rotstayn, and G. Milly, 2015: Spatial patterns of radiative forcing and surface temperature
10 response. *J. Geophys. Res. Atmos.*, **120**, 5385–5403, doi:10.1002/2014JD022752.
- 11 Shindell, D. T., J. S. Fuglestedt, and W. J. Collins, 2017b: The social cost of methane: theory and applications.
12 *Faraday Discuss.*, doi:10.1039/C7FD00009J. <http://dx.doi.org/10.1039/C7FD00009J>.
- 13 Shukla, P. R., and V. Chaturvedi, 2012: Low carbon and clean energy scenarios for India: Analysis of targets approach.
14 *Energy Econ.*, **34**, S487–S495, doi:10.1016/j.eneco.2012.05.002.
15 <http://linkinghub.elsevier.com/retrieve/pii/S0140988312001028> (Accessed July 18, 2017).
- 16 Sims, R., R. Schaeffer, and E. Al., 2014: Transport. *Climate Change 2014: Mitigation of Climate Change. Contribution*
17 *of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 599–
18 670.
- 19 van Sluisveld, M. A. E., and Coauthors, 2015: Comparing future patterns of energy system change in 2 °C scenarios
20 with historically observed rates of change. *Glob. Environ. Chang.*, **35**, 436–449,
21 doi:10.1016/j.gloenvcha.2015.09.019. <http://linkinghub.elsevier.com/retrieve/pii/S095937801530056X> (Accessed
22 July 14, 2017).
- 23 Smith, P., 2016: Soil carbon sequestration and biochar as negative emission technologies. *Glob. Chang. Biol.*, **22**,
24 1315–1324, doi:10.1111/gcb.13178. <http://onlinelibrary.wiley.com/doi/10.1111/gcb.13178/abstract> (Accessed
25 August 15, 2016).
- 26 —, and M. et al. Bustamante, 2014: Agriculture, Forestry and Other Land Use (AFOLU). *Climate Change 2014:*
27 *Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the*
28 *Intergovernmental Panel on Climate Change*, 811–922.
- 29 —, and Coauthors, 2013: How much land-based greenhouse gas mitigation can be achieved without compromising
30 food security and environmental goals? *Glob. Chang. Biol.*, **19**, 2285–2302, doi:10.1111/gcb.12160.
31 <http://doi.wiley.com/10.1111/gcb.12160> (Accessed July 10, 2017).
- 32 —, and Coauthors, 2015: Biophysical and economic limits to negative CO₂ emissions. *Nat. Clim. Chang.*, **6**, 42–50,
33 doi:10.1038/nclimate2870. <http://www.nature.com/doi/10.1038/nclimate2870> (Accessed July 23, 2017).
- 34 —, and Coauthors, 2016: Biophysical and economic limits to negative CO₂ emissions. *Nat. Clim. Chang.*, **6**, 42–50,
35 doi:10.1038/nclimate2870.
- 36 Smith, S. M., J. A. Lowe, N. H. A. Bowerman, L. K. Gohar, C. Huntingford, and M. R. Allen, 2012: Equivalence of
37 greenhouse-gas emissions for peak temperature limits. *Nat. Clim. Chang.*, **2**, 535–538, doi:10.1038/nclimate1496.
38 <http://www.nature.com/nclimate/journal/v2/n7/full/nclimate1496.html>.
- 39 Sorrell, S., and J. Sijm, 2003: Carbon Trading in the Policy Mix. *Oxford Rev. Econ. Policy*, **19**, 420–437,
40 doi:10.1093/oxrep/19.3.420. <https://academic.oup.com/oxrep/article-lookup/doi/10.1093/oxrep/19.3.420>
41 (Accessed July 6, 2017).
- 42 von Stechow, C., and Coauthors, 2015: Integrating Global Climate Change Mitigation Goals with Other Sustainability
43 Objectives: A Synthesis. *Annu. Rev. Environ. Resour.*, **40**, 363–394, doi:10.1146/annurev-environ-021113-
44 095626.
- 45 —, and Coauthors, 2016: 2 °C and SDGs: united they stand, divided they fall? *Environ. Res. Lett.*, **11**, 34022,
46 doi:10.1088/1748-9326/11/3/034022.
- 47 Steinacher, M., F. Joos, and T. F. Stocker, 2013: Allowable carbon emissions lowered by multiple climate targets.
48 *Nature*, **499**, 197–201, doi:10.1038/nature12269. <http://www.nature.com/doi/10.1038/nature12269>
49 (Accessed July 23, 2017).
- 50 De Stercke, S., 2014: *Dynamics of Energy Systems: a Useful Perspective*. Laxenburg, Austria,
51 <http://tntcat.iiasa.ac.at/PFUDB/>.
- 52 Stern, N., 2007: *The economics of climate change : the Stern review*. Cambridge University Press, 692 pp.
- 53 Stern, N., 2013: The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross
54 Underestimation of Risk onto Already Narrow Science Models. *J. Econ. Lit.*, **51**, 838–859,
55 doi:10.1257/jel.51.3.838. <http://pubs.aeaweb.org/doi/abs/10.1257/jel.51.3.838>.
- 56 Stern, N., 2016: Current climate models are grossly misleading. *Nature*, **530**, 407–409, doi:10.1038/530407a.
- 57 Stern, N. H., and J. Rydge, 2012: The new industrial revolution and international agreement on climate change. *Econ.*
58 *Energy Environ. policy*, **1**, 1–19.
- 59 Stevanović, M., and Coauthors, 2017: Mitigation Strategies for Greenhouse Gas Emissions from Agriculture and Land-
60 Use Change: Consequences for Food Prices. *Environ. Sci. Technol.*, **51**, 365–374, doi:10.1021/acs.est.6b04291.
61 <http://pubs.acs.org/doi/abs/10.1021/acs.est.6b04291> (Accessed July 10, 2017).
- 62 Stiglitz, J. E., and N. H. Stern, 2017: *Report of the High-Level Commission on Carbon Prices*. 61 pp.
- 63 Stocker, T. F., and Coauthors, 2013: Technical Summary. *Climate Change 2013: The Physical Science Basis*.

- 1 *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*
2 *Change*, 33–115.
- 3 Su, X., and Coauthors, 2017: Emission pathways to achieve 2.0°C and 1.5°C climate targets. *Earth's Futur.*,
4 doi:10.1002/2016EF000492. <http://doi.wiley.com/10.1002/2016EF000492> (Accessed July 9, 2017).
- 5 Summers, L. H., 2016: The Age of Secular Stagnation: What It Is and What to Do About It. *Foreign Aff.*.
- 6 Sussams, L., and J. Leaton, 2017: *Expect the Unexpected - The Disruptive Power of Low-carbon Technology*. London,
7 UK, 52 pp.
- 8 Szulcowski, M. L., C. W. MacMinn, and R. Juanes, 2014: Theoretical analysis of how pressure buildup and CO₂
9 migration can both constrain storage capacity in deep saline aquifers. *Int. J. Greenh. Gas Control*, **23**, 113–118,
10 doi:10.1016/j.ijggc.2014.02.006.
- 11 Tachiiri, K., T. Hajima, and M. Kawamiya, 2015: Increase of uncertainty in transient climate response to cumulative
12 carbon emissions after stabilization of atmospheric CO₂ concentration. *Environ. Res. Lett.*, **10**, 125018,
13 doi:10.1088/1748-9326/10/12/125018.
- 14 Tan, I., T. Storelvmo, and M. D. Zelinka, 2016: Observational constraints on mixed-phase clouds imply higher climate
15 sensitivity. *Science (80-.)*, **352**. <http://science.sciencemag.org/content/352/6282/224> (Accessed April 5, 2017).
- 16 Tavoni, M., and R. S. J. Tol, 2010: Counting only the hits? The risk of underestimating the costs of stringent climate
17 policy. *Clim. Change*, **100**, 769–778, doi:10.1007/s10584-010-9867-9.
- 18 —, E. De Cian, G. Luderer, J. C. Steckel, and H. Waisman, 2012: The value of technology and of its evolution
19 towards a low carbon economy. *Clim. Change*, **114**, 39–57, doi:10.1007/s10584-011-0294-3.
20 <http://link.springer.com/10.1007/s10584-011-0294-3> (Accessed June 20, 2017).
- 21 —, E. Kriegler, T. Aboumahboub, K. Calvin, G. De Maere, and M. Wise, 2013: The Distribution of the Major
22 Economies' Effort in the Durban Platform Scenarios. *Clim. Chang. Econ.*, **4**, 1–25,
23 doi:10.1142/S2010007814920018.
- 24 —, and Coauthors, 2014: Post-2020 climate agreements in the major economies assessed in the light of global
25 models. *Nat. Clim. Chang.*, **5**, 119–126, doi:10.1038/nclimate2475.
26 <http://www.nature.com/doi/10.1038/nclimate2475> <http://dx.doi.org/10.1038/nclimate2475>.
- 27 Thomson, A. M., and Coauthors, 2011: RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Clim. Change*,
28 **109**, 77–94, doi:10.1007/s10584-011-0151-4.
- 29 Thornton, P. E., and Coauthors, 2017: Biospheric feedback effects in a synchronously coupled model of human and
30 Earth systems. *Nat. Clim. Chang.*, **7**, 496–500, doi:10.1038/nclimate3310.
31 <https://www.nature.com/nclimate/journal/v7/n7/pdf/nclimate3310.pdf> (Accessed July 11, 2017).
- 32 Tokarska, K. B., N. P. Gillett, A. J. Weaver, V. K. Arora, and M. Eby, 2016: The climate response to five trillion tonnes
33 of carbon. *Nat. Clim. Chang.*, **6**, 851–855, doi:10.1038/nclimate3036.
- 34 Tol, R. S. J., 1999: Spatial and {Temporal} {Efficiency} in {Climate} {Policy}: {Applications} of {FUND}. *Environ.*
35 *Resour. Econ.*, 33–49.
- 36 Torvanger, A., A.-A. Grimstad, E. Lindeberg, N. Rive, K. Rypdal, R. B. Skeie, J. Fuglestedt, and P. Tollefsen, 2012:
37 Quality of geological CO₂ storage to avoid jeopardizing climate targets. *Clim. Change*, **114**, 245–260,
38 doi:10.1007/s10584-012-0447-z. <https://doi.org/10.1007/s10584-012-0447-z>.
- 39 Trutnevyte, E., J. Barton, Á. O'Grady, D. Ogunkunle, D. Pudjianto, and E. Robertson, 2014: Linking a storyline with
40 multiple models: A cross-scale study of the UK power system transition. *Technol. Forecast. Soc. Change*, **89**, 26–
41 42, doi:10.1016/j.techfore.2014.08.018. <http://linkinghub.elsevier.com/retrieve/pii/S0040162514002571>
42 (Accessed July 11, 2017).
- 43 Tsigaridis, K., M. Krol, F. J. Dentener, Y. Balkanski, J. Lathè Ere, S. Metzger, D. A. Hauglustaine, and M. Kanakidou,
44 2006: Change in global aerosol composition since preindustrial times. *Atmos. Chem. Phys. Atmos. Chem. Phys.*,
45 **6**, 5143–5162.
- 46 Turnheim, B., F. Berkhout, F. W. Geels, A. Hof, A. Mcmeekin, B. Nykvist, and D. P. van Vuuren, 2015: Evaluating
47 sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Glob.*
48 *Environ. Chang.*, **35**, 239–253, doi:10.1016/j.gloenvcha.2015.08.010.
49 <http://linkinghub.elsevier.com/retrieve/pii/S0959378015300315> (Accessed July 11, 2017).
- 50 UNEP, 2016: *The Emissions Gap Report 2016*. Nairobi, Kenya, 1-85 pp.
- 51 UNFCCC Secretariat, 2015: *Synthesis Report on the Aggregate Effect of the Intended Nationally Determined*
52 *Contributions*. Bonn, Germany, 66 pp.
- 53 —, 2016: *Aggregate effect of the intended nationally determined contributions: an update*. Bonn, Germany, 75 pp.
- 54 UNIDO, 2010: *Carbon Capture and Storage in Industrial Applications: Technology Synthesis Report*.
55 <http://cdn.globalccsinstitute.com/sites/default/files/publications/15661/carbon-capture-and-storage-industrial-applications-technology-synthesis-report.pdf>.
- 56 Vandyck, T., K. Keramidis, B. Saveyn, A. Kitous, and Z. Vrontisi, 2016: A global stocktake of the Paris pledges:
57 Implications for energy systems and economy. *Glob. Environ. Chang.*, **41**, 46–63,
58 doi:10.1016/j.gloenvcha.2016.08.006. <http://www.sciencedirect.com/science/article/pii/S095937801630142X>
59 (Accessed April 6, 2017).
- 60 Vangkilde-Pedersen, T., and Coauthors, 2009: Assessing European capacity for geological storage of carbon dioxide-
61 the EU GeoCapacity project. *Energy Procedia*, **1**, 2663–2670, doi:10.1016/j.egypro.2009.02.034.
- 62 Velders, G. J. M., D. W. Fahey, J. S. Daniel, S. O. Andersen, and M. McFarland, 2015: Future atmospheric abundances

- 1 and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. *Atmos. Environ.*,
2 **123**, 200–209, doi:10.1016/j.atmosenv.2015.10.071. <http://dx.doi.org/10.1016/j.atmosenv.2015.10.071>.
- 3 Verbong, G. P. J., and F. W. Geels, 2010: Exploring sustainability transitions in the electricity sector with socio-
4 technical pathways. *Technol. Forecast. Soc. Change*, **77**, 1214–1221, doi:10.1016/j.techfore.2010.04.008.
5 <http://linkinghub.elsevier.com/retrieve/pii/S0040162510000752> (Accessed July 11, 2017).
- 6 Vögele, S., P. Hansen, W.-R. Poganietz, S. Prehofer, and W. Weimer-Jehle, 2017: Building scenarios for energy
7 consumption of private households in Germany using a multi-level cross-impact balance approach. *Energy*, **120**,
8 937–946, doi:10.1016/j.energy.2016.12.001.
9 <http://www.sciencedirect.com/science/article/pii/S0360544216318059> (Accessed July 11, 2017).
- 10 van Vuuren, D. P., and E. Stehfest, 2013: If climate action becomes urgent: the importance of response times for
11 various climate strategies. *Clim. Change*, **121**, 473–486, doi:10.1007/s10584-013-0769-5.
12 <http://link.springer.com/10.1007/s10584-013-0769-5> (Accessed July 14, 2017).
- 13 ———, and Coauthors, 2011a: RCP2.6: Exploring the possibility to keep global mean temperature increase below 2°C.
14 *Clim. Change*, **109**, 95–116, doi:10.1007/s10584-011-0152-3. [http://link.springer.com/10.1007/s10584-011-0152-](http://link.springer.com/10.1007/s10584-011-0152-3)
15 [3](http://link.springer.com/10.1007/s10584-011-0152-3) (Accessed April 6, 2017).
- 16 ———, and Coauthors, 2011b: The representative concentration pathways: An overview. *Clim. Change*, **109**, 5–31,
17 doi:10.1007/s10584-011-0148-z.
- 18 van Vuuren, D. P., and Coauthors, 2012: A comprehensive view on climate change: coupling of earth system and
19 integrated assessment models. *Environ. Res. Lett.*, **7**, 24012, doi:10.1088/1748-9326/7/2/024012.
20 <http://stacks.iop.org/1748-9326/7/i=2/a=024012?key=crossref.cbe94a31d255dec301e0d50c86a36858> (Accessed
21 July 11, 2017).
- 22 van Vuuren, D. P., and Coauthors, 2016: Carbon budgets and energy transition pathways. *Environ. Res. Lett.*, **11**,
23 75002, doi:10.1088/1748-9326/11/7/075002.
- 24 ———, and Coauthors, 2017: Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm.
25 *Glob. Environ. Chang.*, **42**, 237–250, doi:10.1016/j.gloenvcha.2016.05.008.
26 <http://dx.doi.org/10.1016/j.gloenvcha.2016.05.008>.
- 27 Walsh, B., P. Ciaia, I. A. Janssens, J. Peñuelas, K. Riahi, F. Rydzak, D. P. Van Vuuren, and M. Obersteiner, 2017:
28 Pathways for balancing CO₂ emissions and sinks. *Nat. Commun.*, **8**, doi:10.1038/ncomms14856.
29 <https://www.nature.com/articles/ncomms14856.pdf> (Accessed July 9, 2017).
- 30 Walsh, M. J., and Coauthors, 2016: Algal food and fuel coproduction can mitigate greenhouse gas emissions while
31 improving land and water-use efficiency. *Environ. Res. Lett.*, **11**, 114006. [http://stacks.iop.org/1748-](http://stacks.iop.org/1748-9326/11/i=11/a=114006)
32 [9326/11/i=11/a=114006](http://stacks.iop.org/1748-9326/11/i=11/a=114006).
- 33 Warwick, P. D., M. K. Verma, P. A. Freeman, M. D. Corum, and S. H. Hickman, 2014: U.S. geological survey carbon
34 sequestration - geologic research and assessments. *Energy Procedia*, **63**, 5305–5309,
35 doi:10.1016/j.egypro.2014.11.561.
- 36 Webster, M., L. Jakobovits, and J. Norton, 2008: Learning about climate change and implications for near-term policy.
37 *Clim. Change*, **89**, 67–85, doi:10.1007/s10584-008-9406-0. <http://link.springer.com/10.1007/s10584-008-9406-0>
38 (Accessed July 21, 2017).
- 39 Wei, N., X. Li, Y. Wang, R. T. Dahowski, C. L. Davidson, and G. S. Bromhal, 2013: A preliminary sub-basin scale
40 evaluation framework of site suitability for onshore aquifer-based CO₂ storage in China. *Int. J. Greenh. Gas*
41 *Control*, **12**, 231–246, doi:10.1016/j.ijggc.2012.10.012.
- 42 Weindl, I., and Coauthors, Livestock and human use of land: productivity trends and 1 dietary choices as drivers of
43 future land and carbon dynamics. *Glob. Planet. Change.*,
44 ———, H. Lotze-Campen, A. Popp, C. Müller, P. Havlík, M. Herrero, C. Schmitz, and S. Rolinski, 2015: Livestock in a
45 changing climate: production system transitions as an adaptation strategy for agriculture. *Environ. Res. Lett.*, **10**,
46 94021, doi:10.1088/1748-9326/10/9/094021. [http://stacks.iop.org/1748-](http://stacks.iop.org/1748-9326/10/i=9/a=094021?key=crossref.35f5e9a79c87f6c983a06ce0d796634c)
47 [9326/10/i=9/a=094021?key=crossref.35f5e9a79c87f6c983a06ce0d796634c](http://stacks.iop.org/1748-9326/10/i=9/a=094021?key=crossref.35f5e9a79c87f6c983a06ce0d796634c) (Accessed July 17, 2017).
- 48 West, J. J., and Coauthors, 2013: Co-benefits of mitigating global greenhouse gas emissions for future air quality and
49 human health. *Nat. Clim. Chang.*, **3**, 885–889, doi:10.1038/nclimate2009.
50 <http://www.nature.com/doi/10.1038/nclimate2009> (Accessed April 5, 2017).
- 51 Weyant, J., 2017: Some Contributions of Integrated Assessment Models of Global Climate Change. *Rev. Environ.*
52 *Econ. Policy*, **11**, 115–137, doi:10.1093/reep/rew018. <https://academic.oup.com/reep/article/3066306/Some>.
- 53 Weyant, J. P., F. C. de la Chesnaye, and G. J. Blanford, 2006: Overview of EMF-21: Multigas Mitigation and Climate
54 Policy. *Energy J.*, **SI2006**, doi:10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI3-1.
- 55 Wigley, T. M. L., R. Richels, and J. Edmonds, 2007: Overshoot Pathways to CO₂ stabilization in a multi-gas context.
56 *Human Induced Climate Change: An Interdisciplinary Perspective*, M.E. Schlesinger, H.S. Khesghi, J. Smith,
57 F.C. De La Chesnaye, J.M. Reilly, T. Wilson, and C. Kolstad, Eds., Cambridge University Press, Cambridge, 84–
58 92.
- 59 Wilson, C., A. Grubler, K. S. Gallagher, and G. F. Nemet, 2012: Marginalization of end-use technologies in energy
60 innovation for climate protection. *Nat. Clim. Chang.*, **2**, doi:10.1038/NCLIMATE1576.
61 <https://www.nature.com/nclimate/journal/v2/n11/pdf/nclimate1576.pdf> (Accessed July 11, 2017).
- 62 ———, T. Hargreaves, and R. Hauxwell-Baldwin, 2015: Smart homes and their users: a systematic analysis and key
63 challenges. *Pers. Ubiquitous Comput.*, **19**, 463–476, doi:10.1007/s00779-014-0813-0.

- 1 <http://link.springer.com/10.1007/s00779-014-0813-0> (Accessed July 13, 2017).
- 2 Wise, M., K. Calvin, P. Kyle, P. Luckow, and J. Edmonds, 2014: Economic and physical modeling of land use in
3 GCAM 3.0 and an application to agricultural productivity, land, and terrestrial carbon. *Clim. Chang. Econ.*, **5**,
4 1450003, doi:10.1142/S2010007814500031.
5 <http://www.worldscientific.com/doi/abs/10.1142/S2010007814500031> (Accessed July 10, 2017).
- 6 Woodcock, J., and Coauthors, 2009: Public health benefits of strategies to reduce greenhouse-gas emissions: urban land
7 transport. *Lancet*, **374**, 1930–1943, doi:10.1016/S0140-6736(09)61714-1.
8 <http://www.ncbi.nlm.nih.gov/pubmed/19942277> (Accessed July 13, 2017).
- 9 World Bank, Ecofys, and Vivid Economics, 2016: *State and Trends of Carbon Pricing 2016*. World Bank, Washington
10 D.C., USA, <https://www.openknowledge.worldbank.org/handle/10986/25160> (Accessed July 6, 2017).
- 11 Yeh, S., G. S. Mishra, L. Fulton, P. Kyle, D. L. McCollum, J. Miller, P. Cazzola, and J. Teter, 2016: Detailed
12 assessment of global transport-energy models' structures and projections. *Transp. Res. Part D Transp. Environ.*,
13 doi:10.1016/j.trd.2016.11.001. <http://linkinghub.elsevier.com/retrieve/pii/S1361920916301651> (Accessed July
14 18, 2017).
- 15 Zachmann, G., and C. Von Hirschhausen, 2008: First evidence of asymmetric cost pass-through of EU emissions
16 allowances: Examining wholesale electricity prices in Germany. *Econ. Lett.*,
17 <http://www.sciencedirect.com/science/article/pii/S0165176507003400> (Accessed July 6, 2017).
- 18 Zeman, F., and K. Lackner, 2004: Capturing carbon dioxide directly from the atmosphere. *World Resour. Rev.*, **16**,
19 157–172. http://wordpress.ei.columbia.edu/lenfest/files/2012/11/ZEMAN_LACKNER_2004.pdf (Accessed May
20 11, 2015).
- 21 Zeman, F. S., and D. W. Keith, 2008: Carbon Neutral Hydrocarbons. *Philos. Trans. R. Soc. a-Mathematical Phys. Eng.*
22 *Sci.*, **366**, 3901–3918, doi:10.1098/rsta.2008.0143.
- 23 Zhai, C., J. H. Jiang, and H. Su, 2015: Long-term cloud change imprinted in seasonal cloud variation: More evidence of
24 high climate sensitivity. *Geophys. Res. Lett.*, **42**, 8729–8737, doi:10.1002/2015GL065911.
25 <http://doi.wiley.com/10.1002/2015GL065911> (Accessed April 5, 2017).
- 26 Zickfeld, K., and T. Herrington, 2015: The UVic Earth system climate model: model description, climatology, and
27 applications to past, present and future climates. *Atmos.-Ocean*, **39**, L05703, doi:10.1088/1748-
28 9326/10/3/031001. <http://iopscience.iop.org/article/10.1088/1748-9326/10/3/031001/meta> (Accessed April 4,
29 2017).
- 30 Zickfeld, K., V. K. Arora, and N. P. Gillett, 2012: Is the climate response to CO2 emissions path dependent? *Geophys.*
31 *Res. Lett.*, **39**, n/a--n/a, doi:10.1029/2011GL050205.
- 32 Zickfeld, K., A. H. MacDougall, and H. D. Matthews, 2016: On the proportionality between global temperature change
33 and cumulative CO2 emissions during periods of net negative CO2 emissions. *Environ. Res. Lett.*, **11**, 55006,
34 doi:10.1088/1748-9326/11/5/055006. [http://stacks.iop.org/1748-
35 9326/11/i=5/a=055006?key=crossref.636dc44f6dba4b8a51aeff076afe0be1](http://stacks.iop.org/1748-9326/11/i=5/a=055006?key=crossref.636dc44f6dba4b8a51aeff076afe0be1).
- 36