

## WG III contribution to the Sixth Assessment Report

### List of corrigenda to be implemented

The corrigenda listed below will be implemented in the Chapter during copy-editing.

### CHAPTER 3

Document (Chapter, Annex, Supp. Material)	Page (Based on the final pdf FGD version)	Line	Detailed information on correction to make
Chapter 3	93	Fig 1, CWG Box 1	Missing figure (legend is present). CWG Box to also be added to chapter ToC
Chapter 3	88	41-43	Replace: Equitable burden sharing compliant with the Paris Agreement leads to negative carbon allowances for developed countries as well as China by mid-century (van den Berg et al. 2020), more stringent than cost-optimal pathways  With: Some interpretations of equitable burden sharing compliant with the Paris Agreement leads to negative carbon allowances for developed countries and some developing countries by mid-century (van den Berg et al. 2020), more stringent than cost-optimal pathways
Chapter 3	6	42	Replace: around 199 (56-482) million ha in 2100 in pathways  With: around 199 (56-482) million ha in 2050 in pathways
Chapter 3	6	4	Replace: it is achieved around 10-20 years later than  With: it is achieved around 10-40 years later than
Chapter 3	26	52	Replace: it is achieved around 10-20 years later than  With: it is achieved around 10-40 years later than
Chapter 3	Front	10	Replace: Detlef van Vuuren  With: Detlef P. van Vuuren

Chapter 3	Front	8	Replace: Glen Peters  With: Glen P. Peters
Chapter 3	53	1	Replace: "Table 3.4: Energy, emissions and CDR characteristics of the pathways by climate category for 2030, 2050, 2100. Source: AR6 scenarios database"  With: "Table 3.4: Energy and emissions characteristics of the pathways by climate category for 2030, 2050, 2100. Source: AR6 scenarios database"
Chapter 3	53	2	Table 3.4  A new version will be updated with the following changes: 1. Change SSP2-2.6 to SSP1-2.6 in row C3, column 1, sub column 3 2. Title of third row to be changed from: "Co2 intensity of Primary Energy Index 2020 = 100" to "Energy & Industrial Processes variable 2020 = 100" 3. Total CDR column to be removed altogether
Chapter 3	53	2	Table 3.4 Old Footnotes 0-2 updated in response to Gov comments in the SPM Table 1.
Chapter 3	17	17	Table 3.1 Change SSP2-2.6 to SSP1-2.6
Chapter 3	17	17	Table 3.1 Change header column "WGIII IP" to "WGIII IP/IMP"
Chapter 3	55	19	Fig 3.21 (left panel) –updated Should be the same as SPM Fig 5 lower right panel
Chapter 3	67	27	Table 3.5 Total CDR row of the table should no longer be included (delete) Additionally, add footnote: ""Cumulative CDR from AFOLU cannot be quantified precisely because models use different reporting methodologies that in some cases combine gross emissions and removals, and use different baselines."
Chapter 3	82	1	Fig 3.31 - updated A new figure to replace existing one
Chapter 3	43	4	are associated with net global GHG emissions of 40 (32–55) GtCO <sub>2</sub> -eq yr <sup>-1</sup> by 2030 and 20 (13-26) change to: are associated with net global GHG emissions of 44 (32–55) GtCO <sub>2</sub> -eq yr <sup>-1</sup> by 2030 and 20 (13-26)
Chapter 3	48	1	Fig 3.16 - updated A new figure to replace existing one
Chapter 3	22	1	Fig 3.6 - updated A new figure to replace existing one

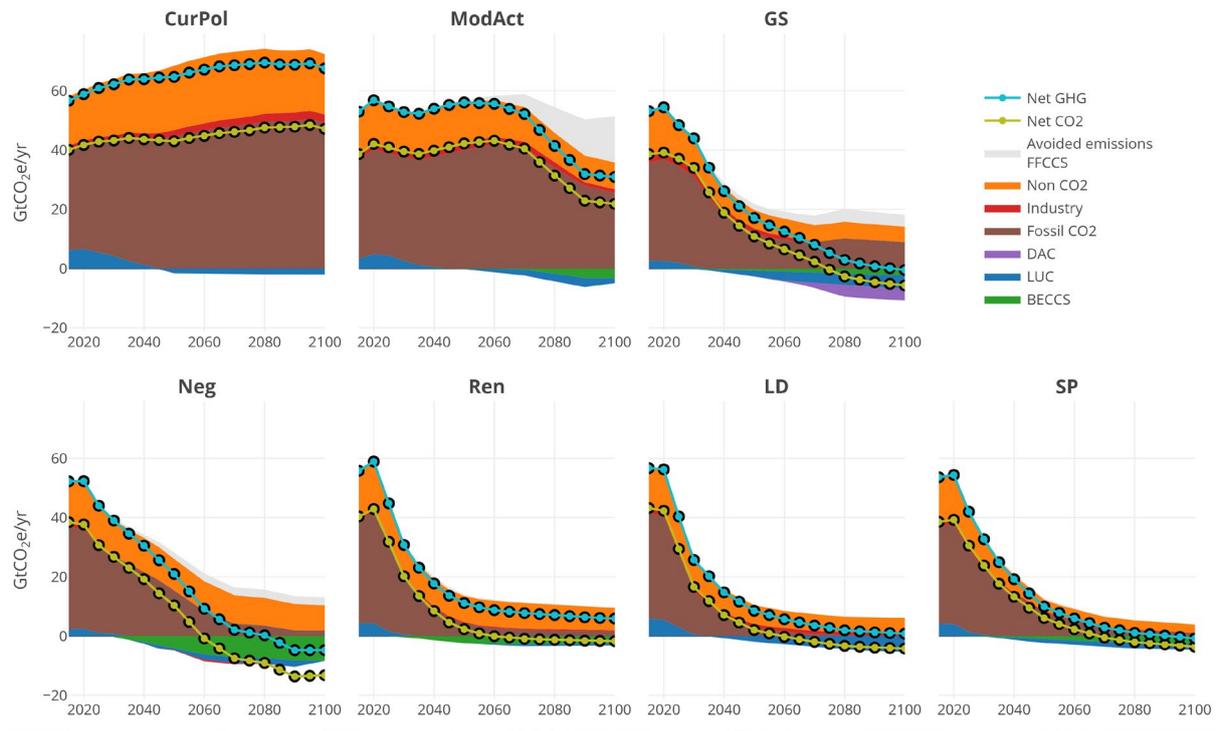
Chapter 3	23	2	Fig 3.7 - updated A new figure to replace existing one
Chapter 3	28	1	Fig 3.10 - updated A new figure to replace existing one
Chapter 3	42	30	Fig 3.14 - updated A new figure to replace existing one
Chapter 3	75	23	Table 3.6 – updated A new figure to replace existing one
Chapter 3	4	16	2.4°C change to: 2.2°C
Chapter 3	4	15	52-60 GtCO <sub>2</sub> -eq yr <sup>-1</sup> by 2030 and to 46-67 change to 54-61 GtCO <sub>2</sub> -eq yr <sup>-1</sup> by 2030 and to 47-67
Chapter 3	73	19-22	Replace with: To still have a likely chance to stay below 2°C, the global post-2030 GHG emission reduction rates would need to be abruptly raised in 2030 from 0-0.7 GtCO <sub>2</sub> -eq yr <sup>-1</sup> to an average of 1.4-2.0 GtCO <sub>2</sub> -eq yr <sup>-1</sup> during the period 2030-2050 (Figure 3.30c), around 70% of that in immediate mitigation pathways confirming findings in the literature (Winning et al. 2019).
Chapter 3	69	1	Replace: reductions would need to abruptly increase after 2030 to an annual average rate of 1.3-2.1 GtCO <sub>2</sub> -eq during the period 2030-2050,  With: reductions would need to abruptly increase after 2030 to an annual average rate of 1.4-2.0 GtCO <sub>2</sub> -eq during the period 2030-2050,
Chapter 3	72	25-28	Replace: For the 139 scenarios of this kind that are collected in the AR6 scenario database and that still likely limit warming to 2°C, the 2030 emissions range is 52.5 (46.5-56) GtCO <sub>2</sub> -eq (based on native model reporting) and 52.5 (47-56.5) GtCO <sub>2</sub> -eq, respectively (based on harmonized emissions data for climate assessment)  With: For the 139 scenarios of this kind that are collected in the AR6 scenario database and that still likely limit warming to 2°C, the 2030 emissions range is 53 (45-58) GtCO <sub>2</sub> -eq (based on native model reporting) and 52.5 (47-56.5) GtCO <sub>2</sub> -eq, respectively (based on harmonized emissions data for climate assessment)
Chapter 3	72	32-25	Replace: The assessed emission ranges from implementing the unconditional (unconditional and conditional) elements of current NDCs implies an emissions gap to cost-effective mitigation pathways of 20-26 (16-24) GtCO <sub>2</sub> -eq in 2030 for limiting warming to 1.5°C with no or limited overshoot and 10-17 (7-14) GtCO <sub>2</sub> -eq in 2030 for likely limiting warming to 2°C  With: The assessed emission ranges from implementing the unconditional (unconditional and conditional) elements of current NDCs implies an emissions gap to cost-effective mitigation

			pathways of 19-26 (16-23) GtCO <sub>2</sub> -eq in 2030 for limiting warming to 1.5°C with no or limited overshoot and 10-16 (6-14) GtCO <sub>2</sub> -eq in 2030 for likely limiting warming to 2°C
Chapter 3	82	1	Figure 3.31 Change title to "GHG emissions"
Chapter 3	75	23	Table 3.6 – Definition of global indicators in the rows need to be clarified: Change in GHG emissions in ... Change in CO <sub>2</sub> emissions in ... Change in net land use CO <sub>2</sub> emissions in ... Change in CH <sub>4</sub> emissions in ... Change in primary energy from coal ... Change in primary energy from oil ... Change in primary energy from gas ... Change in primary energy from nuclear ... Change in primary energy from modern biomass ... Change in primary energy from coal ... Change in carbon intensity of electricity in ... Change in carbon intensity of non-electric final energy consumption in ...
Chapter 3	4	35	with net global GHG emissions of 30-49 GtCO <sub>2</sub> -eq yr <sup>-1</sup> by 2030 and 13-27 GtCO <sub>2</sub> change to with net global GHG emissions of 32-55 GtCO <sub>2</sub> -eq yr <sup>-1</sup> by 2030 and 14-26 GtCO <sub>2</sub>
Chapter 3	4	36-37	This corresponds to reductions, relative to 2019 levels, of 12-46% by 2030 and 52-77% by 2050. change to This corresponds to reductions, relative to 2019 levels, of 13-45% by 2030 and 52-76% by 2050.
Chapter 3	4	40	reductions of 38–63% by 2030 and 75-98% by 2050 relative to 2019 levels. change to reductions of 34–60% by 2030 and 73-98% by 2050 relative to 2019 levels.
Chapter 3	5	32	890 (640-1160) GtCO <sub>2</sub> in pathways likely limiting warming to 2.0°C. change to 880 (640-1130) GtCO <sub>2</sub> in pathways likely limiting warming to 2.0°C.
Chapter 3	5	37	4-11 GtCO <sub>2</sub> -eq yr <sup>-1</sup> change to 8 (4-12)

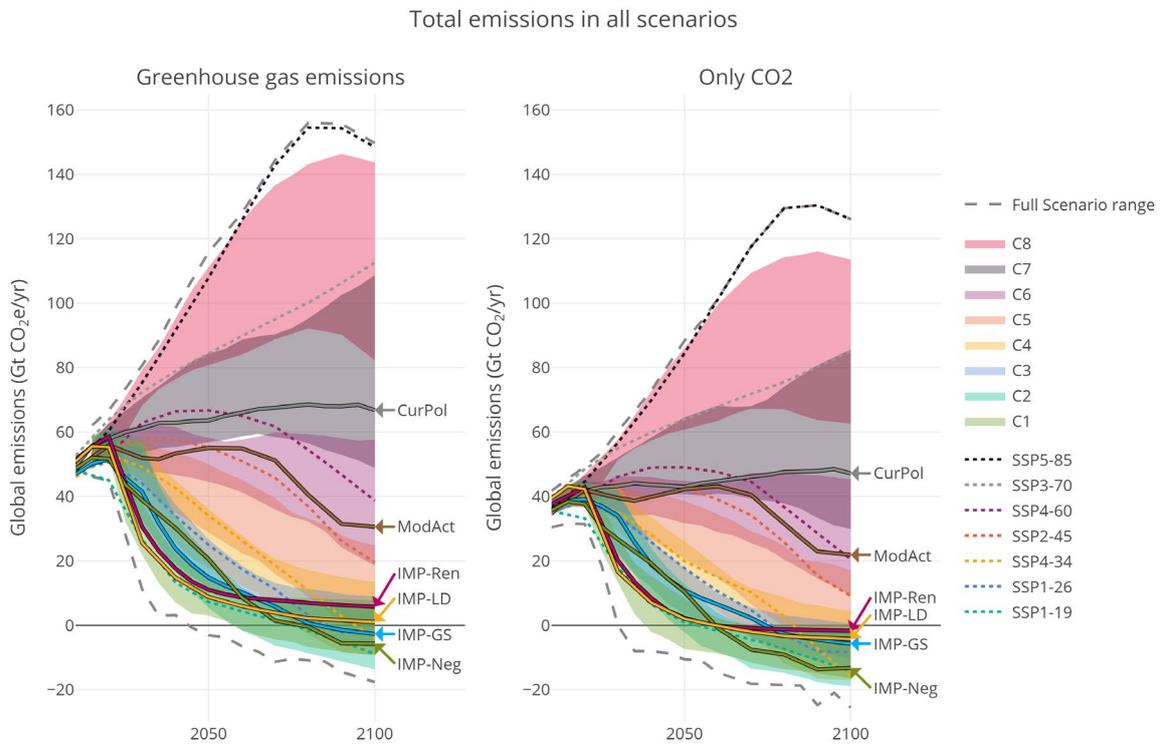
Chapter 3	5	6	Replace: to an average of 1.3-2.1 GtCO <sub>2</sub> -eq per year  With to an average of 1.4-2.0 GtCO <sub>2</sub> -eq per year
Chapter 3	43	9	and 84 (74–98) % in 2050 change to and 84 (73–98) % in 2050
Chapter 3	37	21	net zero around 2060-2100 change to net zero around 2055-2095
Chapter 3	37	24	4-11 GtCO <sub>2</sub> -eq yr-1 change to 4-12 GtCO <sub>2</sub> -eq yr-1
Chapter 3	26	36	to 52-60 GtCO <sub>2</sub> -eq yr-1 by 2030 and to 46-67 change to to 54-60 GtCO <sub>2</sub> -eq yr-1 by 2030 and to 47-67
Chapter 3	26	38	to a median global warming of 2.4°C to 3.5°C by 2100 change to to a median global warming of 2.2°C to 3.5°C by 2100
Chapter 3	29	14	While warming would likely be in the range from 2.2-3.8 °C – warming above 5°C cannot be excluded. change to While warming would more likely than not be in the range from 2.2-3.5 °C – warming up to 5°C cannot be excluded.
Chapter 3	29	6-7	(caption) Global mean temperature outcome of the ensemble of scenarios included in the climate categories C1-C7 (based on RCM calibrated to the WGI assessment, both in terms of future and historic warming). The left panel shows the ranges of scenario uncertainty (shaded area) with the P50 RCM probability (line). The right panel shows the P5 to P95 range of RCM climate uncertainty (C1-C7 is explained in Table 3.1) and the P50 (line) and P66 (dashed line). change to Global mean temperature outcome of the ensemble of scenarios included in the climate categories C1-C8 (based on RCM calibrated to the WGI assessment, both in terms of future and historic warming). The left panel shows the ranges of scenario uncertainty (shaded area) with the P50 RCM probability (line). The right panel shows the P5 to P95 range of combined RCM climate uncertainty (C1-C8 is explained in Table 3.1) and scenario uncertainty, and the P50 (line) and P66 (dashed line).
Chapter 3	29	25	combining scenario and uncertainty change to combining scenario and climate uncertainty
Chapter 3	81	4	Replace: GHG emissions of 47 (38-51) With: global GHG emissions of 48 (38-52)

Chapter 3	5	12-14	<p>Replace: Pathways accelerating actions compared to current NDCs that reduce annual GHG emissions to 47 (38-51) GtCO<sub>2</sub>-eq by 2030, or 3-9 GtCO<sub>2</sub>-eq below projected emissions from fully implementing current NDCs reduce the mitigation challenge for likely limiting warming to 2°C after 2030.</p> <p>With: Pathways accelerating actions compared to NDCs announced prior to COP26 that reduce annual GHG emissions to 48 (38-52) GtCO<sub>2</sub>-eq by 2030, or 2-9 GtCO<sub>2</sub>-eq below projected emissions from fully implementing NDCs announced prior to COP26, reduce the mitigation challenge for likely limiting warming to 2°C after 2030.</p>
Chapter 3	81	7-8	This closes the implementation gap for the NDCs, and in addition falls below the emissions range implied by implementing unconditional and conditional elements of NDCs by 2-9 GtCO <sub>2</sub> -eq.
Chapter 3	40	4-6	<p>Replace: As they need to reach net zero CO<sub>2</sub> only a few years later, with 2030 CO<sub>2</sub> emission levels being around twice as high, they imply post-2030 CO<sub>2</sub> emissions reduction rates that are almost double that of pathways limiting warming to 1.5°C with no or limited overshoot</p> <p>With: As they need to reach net zero CO<sub>2</sub> only a few years later, from 2030 CO<sub>2</sub> emission levels that are about as high as 2020 levels, they imply post-2030 CO<sub>2</sub> emissions reduction rates that are substantially higher (by around 30%) than in pathways limiting warming to 1.5°C with no or limited overshoot</p>
Chapter 3	40	Footnote 6	<p>Replace Pathways that follow emission levels projected from the implementation of current NDCs until 2030 and that still likely limit warming to 2°C reach net zero CO<sub>2</sub> emissions during 2065 - 2070 (2060 - ...)</p> <p>With Pathways that follow emission levels projected from the implementation of current NDCs until 2030 and that still likely limit warming to 2°C reach net zero CO<sub>2</sub> emissions during 2065 - 2070 (2060 - 2100)</p>
Chapter 3	41	11-13	<p>Replace: the time lag between reaching net zero CO<sub>2</sub> and net zero GHG is 11-14 (6-40) years and the amount of net negative CO<sub>2</sub> emissions deployed to balance non-CO<sub>2</sub> emissions at the time of net zero is -6 to -7 (-10 to -4) GtCO<sub>2</sub></p> <p>With: the time lag between reaching net zero CO<sub>2</sub> and net zero GHG is 12-14 (7-39) years and the amount of net negative CO<sub>2</sub> emissions deployed to balance non-CO<sub>2</sub> emissions at the time of net zero GHG is around -7 (-10 to -4) GtCO<sub>2</sub></p>
Chapter 3	39	13	Cross-chapter box 3 Figure 1 to be updated to accommodate minor revisions to GHG emissions data shown in the left column.

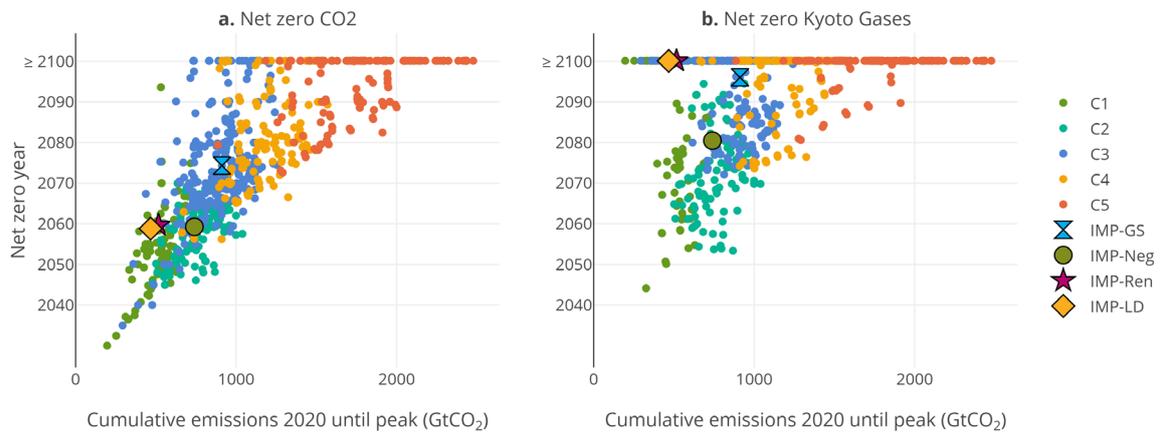
**Corrected Fig 3.7**



**Corrected Fig 3.10**

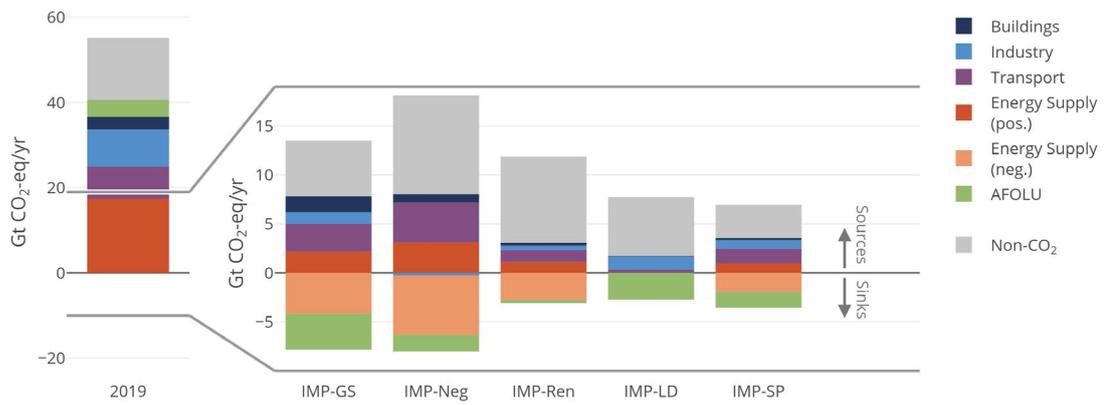


**Corrected Fig 3.14**



**Corrected Fig 3.16b**

**b. IMP characteristics: CO<sub>2</sub> emissions at net-zero year**



# Chapter 3: Mitigation Pathways Compatible with Long-Term Goals

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## 1 **Executive summary**

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

13  
14 **Pathways consistent with the implementation and extrapolation of countries' current policies**  
15 **see GHG emissions reaching 52-60 GtCO<sub>2</sub>-eq yr<sup>-1</sup> by 2030 and to 46-67 GtCO<sub>2</sub>-eq yr<sup>-1</sup> by 2050,**  
16 **leading to a median global warming of 2.4°C to 3.5°C by 2100 (*medium confidence*).** These  
17 pathways consider policies at the time that they were developed. The Shared Socioeconomic  
18 Pathways (SSPs) permit a more systematic assessment of future GHG emissions and their  
19 uncertainties than was possible in AR5. The main emissions drivers include growth in population,  
20 reaching 8.5-9.7 billion by 2050, and an increase in global GDP of 2.7-4.1% per year between 2015  
21 and 2050. Final energy demand in the absence of any new climate policies is projected to grow to  
22 around 480 to 750 EJ yr<sup>-1</sup> in 2050 (compared to around 390 EJ in 2015). (*medium confidence*) The  
23 highest emissions scenarios in the literature result in global warming of >5°C by 2100, based on  
24 assumptions of rapid economic growth and pervasive climate policy failures. (*high confidence*). {3.3}

25  
26 **Many pathways in the literature show how to likely limit global warming compared to**  
27 **preindustrial times to 2°C with no overshoot or to 1.5°C with limited overshoot. The likelihood**  
28 **of limiting warming to 1.5°C with no or limited overshoot has dropped in AR6 compared to**  
29 **SR1.5 because global GHG emissions have risen since the time SR1.5 was published, leading to**  
30 **higher near-term emissions (2030) and higher cumulative CO<sub>2</sub> emissions until the time of net**  
31 **zero (*medium confidence*).** Only a small number of published pathways limit global warming to  
32 1.5°C without overshoot over the course of the 21<sup>st</sup> century. {3.3, Annex III.II.3}

33  
34 **Cost-effective mitigation pathways assuming immediate actions to likely limit warming to 2°C**  
35 **are associated with net global GHG emissions of 30-49 GtCO<sub>2</sub>-eq yr<sup>-1</sup> by 2030 and 13-27 GtCO<sub>2</sub>-**  
36 **eq yr<sup>-1</sup> by 2050 (*medium confidence*).** This corresponds to reductions, relative to 2019 levels, of 12-  
37 46% by 2030 and 52-77% by 2050. Pathways that limit global warming to below 1.5°C with no or  
38 limited overshoot require a further acceleration in the pace of the transformation, with net GHG  
39 emissions typically around 21-36 GtCO<sub>2</sub>-eq yr<sup>-1</sup> by 2030 and 1-15 GtCO<sub>2</sub>-eq yr<sup>-1</sup> by 2050; thus  
40 reductions of 38–63% by 2030 and 75-98% by 2050 relative to 2019 levels. {3.3}

41 **Pathways following current NDCs<sup>1</sup> until 2030 reach annual emissions of 47-57 GtCO<sub>2</sub>-eq by**  
42 **2030, thereby making it impossible to limit warming to 1.5°C with no or limited overshoot and**  
43 **strongly increasing the challenge to likely limit warming to 2°C (*high confidence*).** A high

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FOOTNOTE <sup>1</sup> Current NDCs refers to the most recent nationally determined contributions submitted to the UNFCCC as well as those publicly announced with sufficient detail on targets, but not yet submitted, up to 11 October 2021, and reflected in studies published up to 11 October 2021.

1 overshoot of 1.5°C increases the risks from climate impacts and increases the dependence on large  
2 scale carbon dioxide removal from the atmosphere. A future consistent with current NDCs implies  
3 higher fossil fuel deployment and lower reliance on low carbon alternatives until 2030, compared to  
4 mitigation pathways with immediate action to likely limit warming to 2°C and below. To likely limit  
5 warming to 2°C after following the NDCs to 2030, the pace of global GHG emission reductions  
6 would need to accelerate quite rapidly from 2030 onward: to an average of 1.3-2.1 GtCO<sub>2</sub>-eq per year  
7 between 2030 and 2050, which is similar to global CO<sub>2</sub> emission reductions in 2020 due to the  
8 COVID-19 pandemic, and around 70% faster than in immediate action pathways likely limiting  
9 warming to 2°C. Accelerating emission reductions after following an NDC pathway to 2030 would be  
10 particularly challenging because of the continued build-up of fossil fuel infrastructure that would be  
11 expected to take place between now and 2030. {3.5, 4.2}

12 **Pathways accelerating actions compared to current NDCs that reduce annual GHG emissions to**  
13 **47 (38-51) GtCO<sub>2</sub>-eq by 2030, or 3-9 GtCO<sub>2</sub>-eq below projected emissions from fully**  
14 **implementing current NDCs reduce the mitigation challenge for likely limiting warming to 2°C**  
15 **after 2030. (*medium confidence*).** The accelerated action pathways are characterized by a global, but  
16 regionally differentiated, roll-out of regulatory and pricing policies. Compared to NDCs, they see less  
17 fossil fuels and more low-carbon fuels until 2030, and narrow, but do not close the gap to pathways  
18 assuming immediate global action using all available least-cost abatement options. All delayed or  
19 accelerated action pathways likely limiting warming to below 2°C converge to a global mitigation  
20 regime at some point after 2030 by putting a significant value on reducing carbon and other GHG  
21 emissions in all sectors and regions. {3.5}

22 **Mitigation pathways limiting warming to 1.5°C with no or limited overshoot reach 50%**  
23 **reductions of CO<sub>2</sub> in the 2030s, relative to 2019, then reduce emissions further to reach net zero**  
24 **CO<sub>2</sub> emissions in the 2050s. Pathways likely limiting warming to 2°C reach 50% reductions in**  
25 **the 2040s and net zero CO<sub>2</sub> by 2070s (*medium confidence*).** {3.3, Cross-Chapter Box 3 in Chapter  
26 3}

27  
28 **Peak warming in mitigation pathways is determined by the cumulative net CO<sub>2</sub> emissions until**  
29 **the time of net zero CO<sub>2</sub> and the warming contribution of other GHGs and climate forcers at**  
30 **that time (*high confidence*).** Cumulative net CO<sub>2</sub> emissions from 2020 to the time of net zero CO<sub>2</sub>  
31 are 510 (330-710) GtCO<sub>2</sub> in pathways that limit warming to 1.5°C with no or limited overshoot and  
32 890 (640-1160) GtCO<sub>2</sub> in pathways likely limiting warming to 2.0°C. These estimates are consistent  
33 with the assessment of remaining carbon budgets by WGI after adjusting for differences in peak  
34 warming levels. {3.3, Box 3.4}

35 **Rapid reductions in non-CO<sub>2</sub> GHGs, particularly methane, would lower the level of peak**  
36 **warming (*high confidence*).** Residual non-CO<sub>2</sub> emissions at the time of reaching net zero CO<sub>2</sub> range  
37 between 4-11 GtCO<sub>2</sub>-eq yr<sup>-1</sup> in pathways likely limiting warming to 2.0°C or below. Methane (CH<sub>4</sub>)  
38 is reduced by around 20% (1-46%) in 2030 and almost 50% (26-64%) in 2050, relative to 2019.  
39 Methane emission reductions in pathways limiting warming to 1.5°C with no or limited overshoot are  
40 substantially higher by 2030, 33% (19-57%), but only moderately so by 2050, 50% (33-69%).  
41 Methane emissions reductions are thus attainable at relatively lower GHG prices but are at the same  
42 time limited in scope in most 1.5-2°C pathways. Deeper methane emissions reductions by 2050 could  
43 further constrain the peak warming. N<sub>2</sub>O emissions are reduced too, but similar to CH<sub>4</sub>, emission  
44 reductions saturate for more stringent climate goals. In the mitigation pathways, the emissions of  
45 cooling aerosols are reduced due to reduced use of fossil fuels. The overall impact on non-CO<sub>2</sub>-related  
46 warming combines these factors. {3.3}

1 **Net zero GHG emissions imply net negative CO<sub>2</sub> emissions at a level compensating residual non-**  
2 **CO<sub>2</sub> emissions. Only 30% of the pathways likely limiting warming to 2°C or below reach net**  
3 **zero GHG emissions in the 21<sup>st</sup> century. (*high confidence*).** In those pathways reaching net zero  
4 GHGs, it is achieved around 10-20 years later than for net zero CO<sub>2</sub>. (*medium confidence*). The  
5 reported quantity of residual non-CO<sub>2</sub> emissions depends on accounting: the choice of GHG metric.  
6 Reaching and sustaining global net zero GHG emissions, measured in terms of GWP-100, results in a  
7 gradual decline of temperature. (*high confidence*) {3.3, Cross-Chapter Box 3 in Chapter 3, Cross-  
8 Chapter Box 2 in Chapter 2}

9  
10 **Pathways likely limiting warming to 2°C and below exhibit substantial reductions in emissions**  
11 **from all sectors (*high confidence*).** Projected CO<sub>2</sub> emissions reductions between 2019 and 2050 in  
12 1.5°C pathways with no or limited overshoot are around 77% (31-96%) for energy demand, 115% for  
13 energy supply (90 to 167%), and 148% for AFOLU (94 to 387%). In pathways likely limiting  
14 warming to 2°C, projected CO<sub>2</sub> emissions are reduced between 2019 and 2050 by around 49% for  
15 energy demand, 97% for energy supply, and 136% for AFOLU. (*medium confidence*) {3.4}

16  
17 **Delaying or sacrificing emissions reductions in one sector or region involves compensating**  
18 **reductions in other sectors or regions if warming is to be limited (*high confidence*).** Mitigation  
19 pathways show differences in the timing of decarbonization and when net zero CO<sub>2</sub> emissions are  
20 achieved across sectors and regions. At the time of global net zero CO<sub>2</sub> emissions, emissions in some  
21 sectors and regions are positive while others are negative; the ordering depends on the mitigation  
22 options available, the cost of those options, and the policies implemented. In cost-effective mitigation  
23 pathways, the energy supply sector typically reaches net zero CO<sub>2</sub> before the economy as a whole,  
24 while the demand sectors reach net zero CO<sub>2</sub> later, if ever (*high confidence*). {3.4}

25  
26 **Pathways likely limiting warming to 2°C and below involve substantial reductions in fossil fuel**  
27 **consumption and a near elimination of the use of coal without CCS (*high confidence*).** These  
28 pathways show an increase in low carbon energy, with 88% (69-97%) of primary energy coming from  
29 these sources by 2100. {3.4}

30  
31 **Stringent emissions reductions at the level required for 2°C and below are achieved through**  
32 **increased direct electrification of buildings, transport, and industry, resulting in increased**  
33 **electricity generation in all pathways (*high confidence*).** Nearly all electricity in pathways likely  
34 limiting warming to 2°C or below is from low or no carbon technologies, with different shares of  
35 nuclear, biomass, non-biomass renewables, and fossil CCS across pathways. {3.4}

36  
37 **The measures required to likely limit warming to 2°C or below can result in large scale**  
38 **transformation of the land surface (*high confidence*).** Pathways likely limiting warming to 2°C or  
39 below are projected to reach net zero CO<sub>2</sub> emissions in the AFOLU sector between 2020s and 2070,  
40 with an increase of forest cover of about 322 million ha (-67 to 890 million ha) in 2050 in pathways  
41 limiting warming to 1.5°C with no or limited overshoot. Cropland area to supply biomass for  
42 bioenergy (including BECCS) is around 199 (56-482) million ha in 2100 in pathways limiting  
43 warming to 1.5°C with no or limited overshoot. The use of bioenergy can lead to either increased or  
44 reduced emissions, depending on the scale of deployment, conversion technology, fuel displaced, and  
45 how/where the biomass is produced (*high confidence*). {3.4}

46  
47 **Anthropogenic land CO<sub>2</sub> emissions and removals in IAM pathways cannot be directly compared**  
48 **with those reported in national GHG inventories (*high confidence*).** Methodologies enabling a  
49 more like-for-like comparison between models' and countries' approaches would support more  
50 accurate assessment of the collective progress achieved under the Paris Agreement. {3.4, 7.2.2.5}

1  
2 **Pathways that likely limiting warming to 2°C or below involve some amount of CDR to**  
3 **compensate for residual GHG emissions remaining after substantial direct emissions reductions**  
4 **in all sectors and regions (*high confidence*).** CDR deployment in pathways serves multiple  
5 purposes: accelerating the pace of emissions reductions, offsetting residual emissions, and creating the  
6 option for net negative CO<sub>2</sub> emissions in case temperature reductions need to be achieved in the long  
7 term (*high confidence*). CDR options in the pathways are mostly limited to BECCS, afforestation and  
8 DACCS. CDR through some measures in AFOLU can be maintained for decades but not in the very  
9 long term because these sinks will ultimately saturate (*high confidence*). {3.4}

10  
11 **Mitigation pathways show reductions in energy demand relative to reference scenarios, through**  
12 **a diverse set of demand-side interventions (*high confidence*).** Bottom-up and non-IAM studies  
13 show significant potential for demand-side mitigation. A stronger emphasis on demand-side  
14 mitigation implies less dependence on CDR and, consequently, reduced pressure on land and  
15 biodiversity. {3.4, 3.7}

16  
17 **Limiting warming requires shifting energy investments away from fossil-fuels and towards low-**  
18 **carbon technologies (*high confidence*).** The bulk of investments are needed in medium- and low-  
19 income regions. Investment needs in the electricity sector are on average 2.3 trillion USD<sub>2015</sub> yr<sup>-1</sup>  
20 over 2023-2052 for pathways limiting temperature to 1.5°C with no or limited overshoot, and 1.7  
21 trillion USD<sub>2015</sub> yr<sup>-1</sup> for pathways likely limiting warming to 2°C. {3.6.1}

22  
23 **Pathways likely avoiding overshoot of 2°C warming require more rapid near-term**  
24 **transformations and are associated with higher up-front transition costs, but meanwhile bring**  
25 **long-term gains for the economy as well as earlier benefits in avoided climate change impacts**  
26 **(*high confidence*).** This conclusion is independent of the discount rate applied, though the modelled  
27 cost-optimal balance of mitigation action over time does depend on the discount rate. Lower discount  
28 rates favour earlier mitigation, reducing reliance on CDR and temperature overshoot. {3.6.1, 3.8}

29  
30 **Mitigation pathways likely limiting warming to 2°C entail losses in global GDP with respect to**  
31 **reference scenarios of between 1.3% and 2.7% in 2050; and in pathways limiting warming to**  
32 **1.5°C with no or limited overshoot, losses are between 2.6% and 4.2%. Yet, these estimates do**  
33 **not account for the economic benefits of avoided climate change impacts (*medium confidence*).**  
34 In mitigation pathways likely limiting warming to 2°C, marginal abatement costs of carbon are about  
35 90 (60-120) USD<sub>2015</sub>/tCO<sub>2</sub> in 2030 and about 210 (140-340) USD<sub>2015</sub>/tCO<sub>2</sub> in 2050; in pathways  
36 that limit warming to 1.5°C with no or limited overshoot, they are about 220 (170-290)  
37 USD<sub>2015</sub>/tCO<sub>2</sub> in 2030 and about 630 (430-990) USD<sub>2015</sub>/tCO<sub>2</sub> in 2050<sup>2</sup>. {3.6.1}

38  
39 **The global benefits of pathways likely limiting warming to 2°C outweigh global mitigation costs**  
40 **over the 21<sup>st</sup> century, if aggregated economic impacts of climate change are at the moderate to**  
41 **high end of the assessed range, and a weight consistent with economic theory is given to**  
42 **economic impacts over the long-term. This holds true even without accounting for benefits in**  
43 **other sustainable development dimensions or non-market damages from climate change**  
44 **(*medium confidence*).** The aggregate global economic repercussions of mitigation pathways include  
45 the macroeconomic impacts of investments in low-carbon solutions and structural changes away from  
46 emitting activities, co-benefits and adverse side effects of mitigation, (avoided) climate change  
47 impacts, and (reduced) adaptation costs. Existing quantifications of global aggregate economic

---

FOOTNOTE<sup>2</sup> Numbers in parenthesis represent the interquartile range of the scenario samples.

1 impacts show a strong dependence on socioeconomic development conditions, as these shape  
2 exposure and vulnerability and adaptation opportunities and responses. (Avoided) impacts for poorer  
3 households and poorer countries represent a smaller share in aggregate economic quantifications  
4 expressed in GDP or monetary terms, whereas their well-being and welfare effects are comparatively  
5 larger. When aggregate economic benefits from avoided climate change impacts are accounted for,  
6 mitigation is a welfare-enhancing strategy. (*high confidence*) {3.6.2}

7  
8 **The economic benefits on human health from air quality improvement arising from mitigation**  
9 **action can be of the same order of magnitude as mitigation costs, and potentially even larger**  
10 **(*medium confidence*).** {3.6.3}

11  
12 **Differences between aggregate employment in mitigation pathways compared to reference**  
13 **scenarios are relatively small, although there may be substantial reallocations across sectors,**  
14 **with job creation in some sectors and job losses in others.** The net employment effect (and its sign)  
15 depends on scenario assumptions, modelling framework, and modelled policy design. Mitigation has  
16 implications for employment through multiple channels, each of which impacts geographies, sectors  
17 and skill categories differently. (*medium confidence*) {3.6.4}

18  
19 **The economic repercussions of mitigation vary widely across regions and households, depending**  
20 **on policy design and level of international cooperation (*high confidence*).** Delayed global  
21 cooperation increases policy costs across regions, especially in those that are relatively carbon  
22 intensive at present (*high confidence*). Pathways with uniform carbon values show higher mitigation  
23 costs in more carbon-intensive regions, in fossil-fuels exporting regions and in poorer regions (*high*  
24 *confidence*). Aggregate quantifications expressed in GDP or monetary terms undervalue the economic  
25 effects on households in poorer countries; the actual effects on welfare and well-being are  
26 comparatively larger (*high confidence*). Mitigation at the speed and scale required to likely limit  
27 warming to 2°C or below implies deep economic and structural changes, thereby raising multiple  
28 types of distributional concerns across regions, income classes and sectors (*high confidence*). {3.6.1,  
29 3.6.4}

30  
31 **The timing of mitigation actions and their effectiveness will have significant consequences for**  
32 **broader sustainable development outcomes in the longer term (*high confidence*).** Ambitious  
33 mitigation can be considered a precondition for achieving the Sustainable Development Goals,  
34 especially for vulnerable populations and ecosystems with little capacity to adapt to climate impacts.  
35 Dimensions with anticipated co-benefits include health, especially regarding air pollution, clean  
36 energy access and water availability. Dimensions with potential trade-offs include food, employment,  
37 water stress, and biodiversity, which come under pressure from large-scale CDR deployment, energy  
38 affordability/access, and mineral resource extraction. (*high confidence*) {3.7}

39  
40 **Many of the potential trade-offs of mitigation measures for other sustainable development**  
41 **outcomes depend on policy design and can thus be compensated or avoided with additional**  
42 **policies and investments or through policies that integrate mitigation with other SDGs (*high***  
43 ***confidence*).** Targeted SDG policies and investments, for example in the areas of healthy nutrition,  
44 sustainable consumption and production, and international collaboration, can support climate change  
45 mitigation policies and resolve or alleviate trade-offs. Trade-offs can be addressed by complementary  
46 policies and investments, as well as through the design of cross-sectoral policies integrating  
47 mitigation with the Sustainable Development Goals of health, nutrition, sustainable consumption and  
48 production, equity and biodiversity. {3.7}

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

7  
8 **Different mitigation pathways are associated with different feasibility challenges, though**  
9 **appropriate enabling conditions can reduce these challenges.** Feasibility challenges are transient  
10 and concentrated in the next two to three decades (*high confidence*). They are multi-dimensional,  
11 context-dependent and malleable to policy, technological and societal trends. {3.8}

12  
13 **Mitigation pathways are associated with significant institutional and economic feasibility**  
14 **challenges rather than technological and geophysical.** The rapid pace of technological  
15 development and deployment in mitigation pathways is not incompatible with historical records.  
16 Institutional capacity is rather a key limiting factor for a successful transition. Emerging economies  
17 appear to have highest feasibility challenges in the short to medium term. {3.8}

18  
19 **Pathways relying on a broad portfolio of mitigation strategies are more robust and resilient**  
20 **(*high confidence*).** Portfolios of technological solutions reduce the feasibility risks associated with the  
21 low carbon transition. {3.8}

1  
2

## 3.1 Introduction

### 3.1.1 Assessment of mitigation pathways and their compatibility with long-term goals

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

Stabilizing global average temperature change requires to reduce CO<sub>2</sub> emissions to net zero. Thus, a central cross-cutting topic within the Chapter is the timing of reaching net zero CO<sub>2</sub> emissions and how a “balance between anthropogenic emissions by sources and removals by sinks” could be achieved across time and space. This includes particularly the increasing body of literature since the IPCC Special Report on Global Warming of 1.5°C (SR1.5) which focuses on net zero CO<sub>2</sub> emissions pathways that avoid temperature overshoot and hence do not rely on net negative CO<sub>2</sub> emissions. The chapter conducts a systematic assessment of the associated economic costs as well as the benefits of mitigation for other societal objectives, such as the Sustainable Development Goals (SDGs). In addition, the Chapter builds on SR1.5 and introduces a new conceptual framing for the assessment of possible social, economic, technical, political, and geophysical “feasibility” concerns of alternative pathways, including the enabling conditions that would need to fall into place so that stringent climate goals become attainable.

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

44

### 3.1.2 Linkages to other Chapters in the Report

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

49

1  
2 Within the overall framing of the AR6 report, Chapter 3 and Chapter 4 provide important  
3 complementary views of the required systems transitions across different temporal and spatial scales.  
4 While Chapter 3 focuses on the questions concerning the implications of the long-term objectives for  
5 the medium-to-near-term transformations, Chapter 4 comes from the other direction, and focuses on  
6 current near-term trends and policies (such as the Nationally Determined Contributions - NDCs) and  
7 their consequences with regards to GHG emissions. The latter chapter naturally focuses thus much  
8 more on the regional and national dimensions, and the heterogeneity of current and planned policies.  
9 Bringing together the information from these two chapters enables the assessment of whether current  
10 and planned actions are consistent with the required systems changes for the long-term objectives of  
11 the Paris Agreement.

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

17  
18 Linkages to other chapters exist also on the topic of feasibility, which are informed by the policy, the  
19 sectoral and the demand chapters, the technology and finance chapters, as well as Chapter 4 on  
20 national circumstances.

21  
22 Close collaboration with WGI permitted the use of AR6-calibrated emulators, which assure full  
23 consistency across the different working groups. Linkages to WGII concern the assessment of macro-  
24 economic benefits of avoided impacts that are put into the context of mitigation costs as well as co-  
25 benefits and trade-offs for sustainable development.

### 26 27 **3.1.3 Complementary use of large scenario ensembles and a limited set of Illustrative** 28 **Mitigation Pathways (IMPs)**

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

31  
32 For a comprehensive assessment, a large ensemble of scenarios is collected and made available  
33 through an interactive [AR6 scenario database](#). The collected information is shared across the chapters  
34 of AR6 and includes more than 3000 different pathways from a diverse set of studies. After an initial  
35 screening and quality control, scenarios were further vetted to assess if they sufficiently represented  
36 historical trends (Annex III). Subsequently, the climate consequences of each scenario were assessed  
37 using the climate emulator (leading to further classification). The assessment in Chapter 3 is however  
38 not limited to the scenarios from the database, and wherever necessary other literature sources are also  
39 assessed in order to bring together multiple lines of evidence.

40  
41 In parallel, based on the overall AR6 assessment seven illustrative pathways (IP) were defined  
42 representing critical mitigation strategies discussed in the assessment. The seven pathways are  
43 composed of two sets: (i) one set of five Illustrative Mitigation Pathways (IMPs) and (ii) one set of  
44 two reference pathways illustrative for high emissions. The IMPs are on the one hand representative  
45 of the scenario space but help in addition to communicate archetypes of distinctly different systems  
46 transformations and related policy choices. Subsequently, seven scenarios were selected from the full  
47 database that fitted these storylines of each IP best. For these scenarios are more strict vetting criteria  
48 were applied. The selection was done by first applying specific filters based on the storyline followed  
49 by a final selection (see Box 3.1 and Figure 3.5 a).

**START BOX HERE****Box 3.1 Illustrative Mitigation Pathways**

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

**END BOX HERE****3.2 What are mitigation pathways compatible with long-term goals?****3.2.1 Scenarios and emission pathways**

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

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

**3.2.1.1 Reference scenarios**

It is common to define a reference scenario (also called a baseline scenario). Depending on the research question, a reference scenario could be defined in different ways (Grant et al. 2020): 1) a hypothetical world with no climate policies or climate impacts (Kriegler et al. 2014b), 2) assuming current policies or pledged policies are implemented (Roelfsema et al. 2020), or 3) a mitigation scenario to compare sensitivity with other mitigation scenarios (Kriegler et al. 2014a; Sognaes et al. 2021).

1 No-climate-policy reference scenarios have often been to compare with mitigation scenarios (Clarke  
2 et al. 2014). A no-climate-policy scenario assumes that no future climate policies are implemented,  
3 beyond what is in the model calibration, effectively implying that the carbon price is zero. No-  
4 climate-policy reference scenarios have a broad range depending on socioeconomic assumptions and  
5 model characteristics, and consequently are important when assessing mitigation costs (Riahi et al.  
6 2017; Rogelj et al. 2018b). As countries move forward with climate policies of varying stringency,  
7 no-climate-policy baselines are becoming increasingly hypothetical (Hausfather and Peters 2020).  
8 Studies clearly show current policies are having an effect, particularly when combined with the  
9 declining costs of low carbon technologies (IEA 2020a; UNEP 2020; Roelfsema et al. 2020; Sognaes  
10 et al. 2021), and, consequently, realised trajectories begin to differ from earlier no-climate-policy  
11 scenarios (Burgess et al. 2020). High-end emission scenarios, such as RCP8.5 and SSP5-8.5, are  
12 becoming less likely with climate policy and technology change (see Box 3.3), but high-end  
13 concentration and warming levels may still be reached with the inclusion of strong carbon or climate  
14 feedbacks (Pedersen et al. 2020; Hausfather and Peters 2020).

### 15 **3.2.1.2 Mitigation scenarios**

16 Mitigation scenarios explore different strategies to meet climate goals and are typically derived from  
17 reference scenarios by adding climate or other policies. Mitigation pathways are often developed to  
18 meet a predefined level of climate change, often referred to as a backcast. There are relatively few  
19 IAMs that include an endogenous climate model or emulator due to the added computational  
20 complexity, though exceptions do exist. In practice, models implement climate constraints by either  
21 iterating carbon price assumptions (Strefler et al. 2021b) or by adopting an associated carbon budget  
22 (Riahi et al. 2021). In both cases, other GHGs are typically controlled by CO<sub>2</sub>-equivalent pricing. A  
23 large part of the AR5 literature has focused on forcing pathways towards a target at the end of the  
24 century (van Vuuren et al. 2007, 2011; Clarke et al. 2009; Blanford et al. 2014; Riahi et al. 2017),  
25 featuring a temporary overshoot of the warming and forcing levels (Geden and Lösschel 2017). In  
26 comparison, many recent studies explore mitigation strategies that limit overshoot (Johansson et al.  
27 2020; Riahi et al. 2021). An increasing number of IAM studies also explore climate pathways that  
28 limit adverse side-effects with respect to other societal objectives, such as food security (van Vuuren  
29 et al. 2019; Riahi et al. 2021) or larger sets of sustainability objectives (Soergel et al. 2021a).

### 30 **3.2.2 The utility of Integrated Assessment Models**

31 Integrated Assessment Models (IAMs) are critical for understanding the implications of long-term  
32 climate objectives for the required near-term transition. For doing so, an integrated systems  
33 perspective including the representation of all sectors and GHGs is necessary. IAMs are used to  
34 explore the response of complex systems in a formal and consistent framework. They cover broad  
35 range of modelling frameworks (Keppo et al. 2021). Given the complexity of the systems under  
36 investigation, IAMs necessarily make simplifying assumptions and therefore results need to be  
37 interpreted in the context of these assumptions. IAMs can range from economic models that consider  
38 only carbon dioxide emissions through to detailed process-based representations of the global energy  
39 system, covering separate regions and sectors (such as energy, transport, and land use), all GHG  
40 emissions and air pollutants, interactions with land and water, and a reduced representation of the  
41 climate system. IAMs are generally driven by economics and can have a variety of characteristics  
42 such as partial-, general, or non-equilibrium, myopic or perfect foresight, be based on optimization or  
43 simulation, have exogenous or endogenous technological change, amongst many other characteristics.  
44 IAMs take as input socioeconomic and technical variables and parameters to represent various  
45 systems. There is no unique way to integrate this knowledge into a model, and due to their  
46 complexity, various simplifications and omissions are made for tractability. IAMs therefore have  
47 various advantages and disadvantages which need to be weighed up when interpreting IAM outcomes.  
48 Annex III contains an overview of the different types of models and their key characteristics.  
49

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

10 IAMs have a long history in addressing environmental problems, particularly in the IPCC assessment  
11 process (van Beek et al. 2020). Many policy discussions have been guided by IAM-based  
12 quantifications, such as the required emission reduction rates, net zero years, or technology  
13 deployment rates required to meet certain climate outcomes. This has led to the discussion whether  
14 IAM scenarios have become performative, meaning that they act upon, transform or bring into being  
15 the scenarios they describe (Beck and Mahony 2017, 2018). Transparency of underlying data and  
16 methods is critical for scenario users to understand what drives different scenario results (Robertson  
17 2020). A number of community activities have thus focused on the provision of transparent and  
18 publicly accessible databases of both input and output data (Riahi et al. 2012; Huppmann et al. 2018;  
19 Krey et al. 2019; Daioglou et al. 2020) as well as the provision of open-source code, and increased  
20 documentation (Annex III). Transparency is needed to reveal conditionality of results on specific  
21 choices in terms of assumptions (e.g., discount rates) and model architecture. More detailed  
22 explanations of underlying model dynamics would be critical to increase the understanding of what  
23 drives results (Bistline et al. 2020; Butnar et al. 2020; Robertson 2020).

24 Mitigation scenarios developed for a long-term climate constraint typically focus on cost-effective  
25 mitigation action towards a long-term climate goal. Results from IAM as well as sectoral models  
26 depend on model structure (Mercure et al. 2019), economic assumptions (Emmerling et al. 2019),  
27 technology assumptions (Pye et al. 2018), climate/emissions target formulation (Johansson et al.  
28 2020), and the extent to which pre-existing market distortions are considered (Guivarch et al. 2011).  
29 The vast majority of IAM pathways do not consider climate impacts (Schultes et al. 2021). Equity  
30 hinges upon ethical and normative choices. As most IAM pathways follow the cost-effectiveness  
31 approach, they do not make any additional equity assumptions. Notable exceptions include (Tavoni et  
32 al. 2015; Pan et al. 2017; van den Berg et al. 2020; Bauer et al. 2020). Regional IAM results need thus  
33 to be assessed with care, considering that emissions reductions are happening where it is most cost-  
34 effective, which needs to be separated from the fact who is ultimately paying for the mitigation costs.  
35 Cost-effective pathways can provide a useful benchmark, but may not reflect real-world developments  
36 (Trutnevyte 2016; Calvin et al. 2014a). Different modelling frameworks may lead to different  
37 outcomes (Mercure et al. 2019). Recent studies have shown that other desirable outcomes can evolve  
38 with only minor deviations from cost-effective pathways (Neumann and Brown 2021; Bauer et al.  
39 2020). IAM and sectoral models represent social, political, and institutional factors only in a  
40 rudimentary way. This assessment is thus relying on new methods for the ex-post assessment of  
41 feasibility concerns (Jewell and Cherp 2020; Brutschin et al. 2021). A literature is emerging that  
42 recognises and reflects on the diversity and strengths/weaknesses of model-based scenario analysis  
43 (Keppo et al. 2021).

44 The climate constraint implementation can have a meaningful impact on model results. The literature  
45 so far included many temperature overshoot scenarios with heavy reliance on long-term CDR and net  
46 negative CO<sub>2</sub> emissions to bring back temperatures after the peak (Johansson et al. 2020; Rogelj et al.  
47 2019b). New approaches have been developed to avoid temperature overshoot. The new generation of  
48 scenarios show that CDR is important beyond its ability to reduce temperature, but is essential also for

1 offsetting residual emissions to reach a net zero CO<sub>2</sub> emissions (Rogelj et al. 2019b; Johansson et al.  
2 2020; Riahi et al. 2021; Strefler et al. 2021b).

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

### 24 **3.2.3 The scenario literature and scenario databases**

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

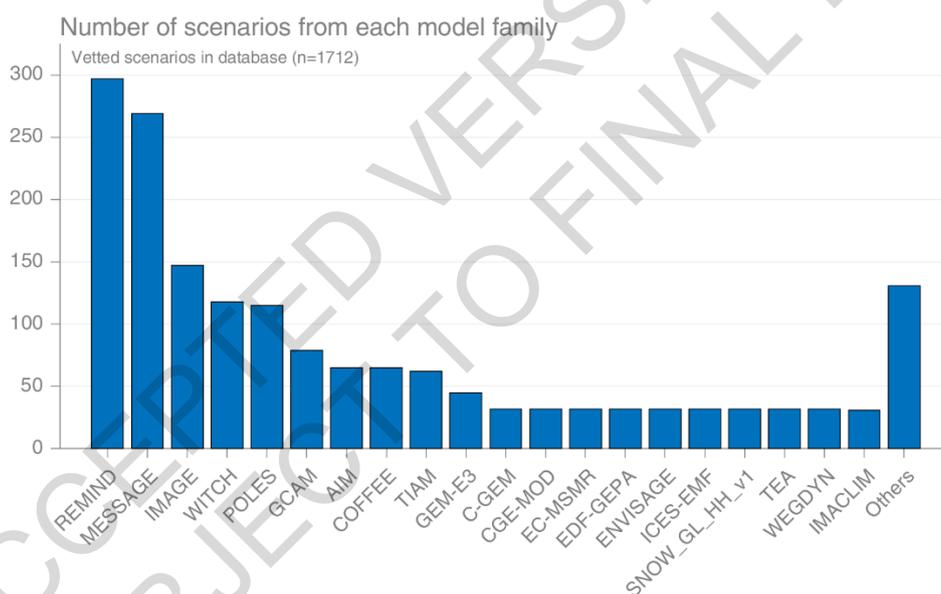
36 One notable development since IPCC AR5 is the Shared Socioeconomic Pathways (SSPs),  
37 conceptually outlined in (Moss et al. 2010) and subsequently developed to support integrated climate  
38 research across the IPCC Working Groups (O'Neill et al. 2014). Initially, a set of SSP narratives were  
39 developed, describing worlds with different challenges to mitigation and adaptation (O'Neill et al.  
40 2017a): SSP1 (sustainability), SSP2 (middle of the road), SSP3 (regional rivalry), SSP4 (inequality)  
41 and SSP5 (rapid growth). The SSPs have now been quantified in terms of energy, land-use change,  
42 and emission pathways (Riahi et al. 2017), for both no-climate-policy reference scenarios and  
43 mitigation scenarios that follow similar radiative forcing pathways as the RCPs assessed in AR5 WGI.  
44 Since then the SSPs have been successfully applied in 1000s of studies (O'Neill et al. 2020b)  
45 including some critiques on the use and application of the SSP framework (Rosen 2021; Pielke and  
46 Ritchie 2021). A selection of the quantified SSPs are used prominently in IPCC AR6 WGI as they  
47 were the basis for most climate modelling since AR5 (O'Neill et al. 2016). Since 2014, when the first  
48 set of SSP data was made available, there has been a divergence between scenario and historic trends

1 (Burgess et al. 2020). As a result, the SSPs require updating (O'Neill et al. 2020b). Most of the  
 2 scenarios in the AR6 database are SSP-based and consider various updates compared to the first  
 3 release (Riahi et al. 2017).

#### 4 **3.2.4 The AR6 scenario database**

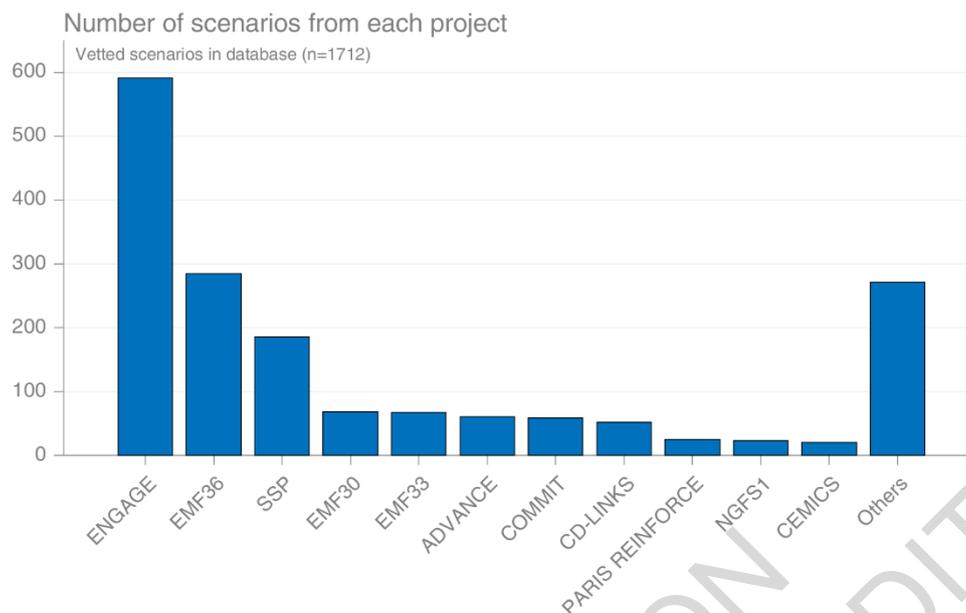
5 To facilitate this assessment, a large ensemble of scenarios has been collected and made available  
 6 through an interactive WGIII AR6 scenario database. The collection of the scenario outputs is  
 7 coordinated by Chapter 3 and expands upon the IPCC SR1.5 scenario explorer (Huppmann et al.  
 8 2018; Rogelj et al. 2018a). A complementary database for national pathways has been established by  
 9 Chapter 4. Annex III contains full details on how the scenario database was compiled.

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



19  
 20 **Figure 3.1 Scenario counts from each model family defined as all versions under the same model's name.**

21



**Figure 3.2 Scenario counts from each named project.**

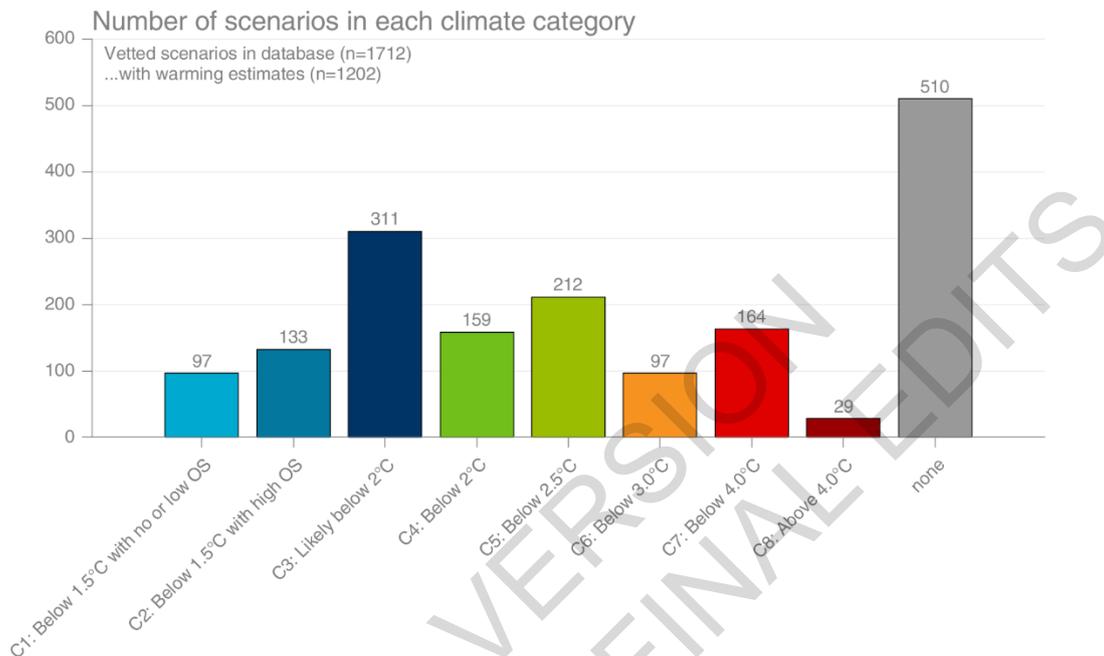
Each scenario with sufficient data is given a temperature classification using climate model emulators. Three emulators were used in the assessment: FAIR (Smith et al. 2018), CICERO-SCM (Skeie et al. 2021), MAGICC (Meinshausen et al. 2020). Only the results of MAGICC are shown in this chapter as it adequately covers the range of outcomes. The emulators are calibrated against the behaviour of complex climate models and observation data, consistent with the outcomes of AR6 WGI AR6 (WGI cross-chapter Box 7.1). The climate assessment is a three-step process of harmonization, infilling and a probabilistic climate model emulator run (Annex III.2.5.1). Warming projections until the year 2100 were derived for 1574 scenarios, of which 1202 passed vetting, with the remaining scenarios having insufficient information (Table 3.1 and Figure 3.3). For scenarios that limit warming to 2°C or below, the SR15 classification was adopted in AR6, with more disaggregation provided for higher warming levels (Table 3.1). These choices can be compared with the selection of common global warming levels (GWL) of 1.5°C, 2°C, 3°C and 4°C to classify climate change impacts in the WGII assessment.

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

Description	Subset	WGI SSP	WGIII IP	Scenarios
<b>C1: Below 1.5°C with no or limited overshoot</b>	<1.5°C peak warming with ≥33% chance and < 1.5°C end of century warming with >50% chance	SSP1-1.9 -,	SP, LD, Ren	<b>97</b>
<b>C2: Below 1.5°C with high overshoot</b>	<1.5°C peak warming with <33% chance and < 1.5°C end of century warming with >50% chance			<b>133</b>
<b>C3: Likely below 2°C</b>	<2°C peak warming with >67% chance	SSP2-2.6	GS, Neg	<b>311</b>
<b>C4: Below 2°C</b>	<2°C peak warming with >50% chance			<b>159</b>
<b>C5: Below 2.5°C</b>	<2.5°C peak warming with >50% chance			<b>212</b>

<b>C6: Below 3°C</b>	<3°C peak warming with >50% chance	SSP2-4.5	Mod-Act	<b>97</b>
<b>C7: Below 4°C</b>	<4°C peak warming with >50% chance	SSP3-7.0	Cur-Pol	<b>164</b>
<b>C8: Above 4°C</b>	>4°C peak warming with $\geq$ 50% chance	SSP5-8.5		<b>29</b>

1



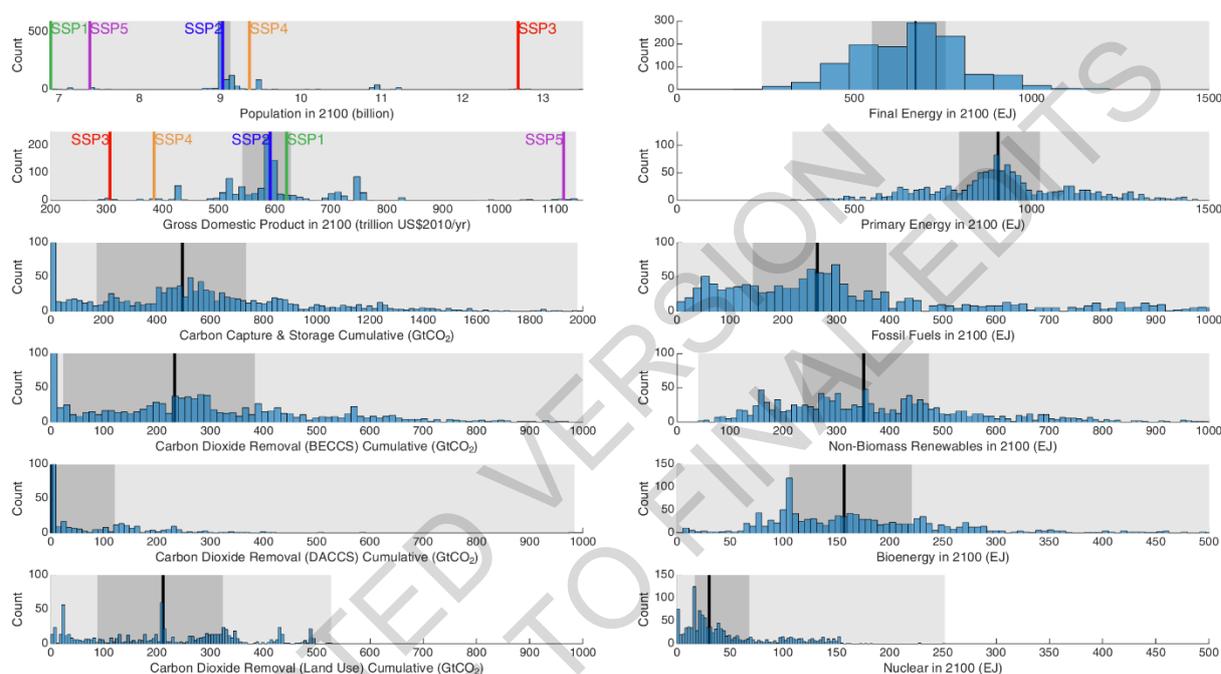
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3 **Figure 3.3 Of the 1686 scenarios that passed vetting, 1202 had sufficient data available to be classified**  
4 **according to temperature, with an uneven distribution across warming levels.**

5 In addition to the temperature classification, each scenario is assigned to one of the following policy  
6 categories: (P0) diagnostic scenarios – 100 of 1686 vetted scenarios; (P1) scenarios with no globally  
7 coordinated policy and either (P1a) no climate mitigation efforts – 119, (P1b) current national  
8 mitigation efforts – 59, (P1c) Nationally Determined Contributions (NDCs) – 110, or (P1d) other non-  
9 standard assumptions – 104; (P2) globally coordinated climate policies with immediate (i.e. before  
10 2030) action – 73, (P2a) without any transfer of emission permits – 435, (P2b) with transfers – 70; or  
11 (P2c) with additional policy assumptions – 55; (P3) globally coordinated climate policies with  
12 delayed (i.e. from 2030 onwards or after 2030) action, preceded by (P3a) no mitigation commitment  
13 or current national policies – 7, (P3b) NDCs – 376, (P3c) NDCs and additional policies – 18 and  
14 (P3d) other non-standard regional assumptions – 0; (P4) Cost-Benefit Analysis (CBA) – 2. The policy  
15 categories were identified using text pattern matching on the scenario metadata and calibrated on the  
16 best-known scenarios from model intercomparisons, with further validation against the related  
17 literature, reported emission and carbon price trajectories, and exchanges with modellers. If the  
18 information available is enough to qualify a policy category number but not sufficient for a  
19 subcategory, then only the number is retained (e.g., P2 instead of P2a/b/c). A suffix added after P0  
20 further qualifies a diagnostic scenario as one of the other policy categories. To demonstrate the  
21 diversity of the scenarios, the vetted scenarios were classified into different categories along the  
22 dimensions of population, GDP, energy, and cumulative emissions (Figure 3.4). The number of  
23 scenarios in each category provides some insight into the current literature, but this does not indicate a  
24 higher probability of that category occurring in reality. For population, the majority of scenarios are  
25 consistent with the SSP2 ‘middle of the road’ category, with very few scenarios exploring the outer

1 extremes. GDP has a slightly larger variation, but overall, most scenarios are around the SSP2  
 2 socioeconomic assumptions. The level of CCS and CDR is expected to change depending on the  
 3 extent of mitigation, but there remains extensive use of both CDR and CCS in scenarios. CDR is  
 4 dominated by bioenergy with CCS (BECCS) and sequestration on land, with relatively few scenarios  
 5 using Direct Air Capture with Carbon Storage (DACCS) and even less with Enhanced Weathering  
 6 and other technologies (not shown). In terms of energy consumption, final energy has a much smaller  
 7 range than primary energy as conversion losses are not included in final energy. Both mitigation and  
 8 reference scenarios are shown, so there is a broad spread in different energy carriers represented in the  
 9 database. Bioenergy has a number of scenarios at around 100EJ, representing a constraint used in  
 10 many model intercomparisons.

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14 **Figure 3.4 Histograms for key categories in the AR6 scenario database. Only scenarios that passed vetting**  
 15 **are shown. For population and GDP, the SSP input data are also shown. The grey shading represents the**  
 16 **0-100% range (light grey), 25-75% range (dark grey), and the median is a black line. The figures with**  
 17 **white areas are outside of the scenario range, but the axis limits are retained to allow comparability with**  
 18 **other categories. Each subfigure potentially has different x- and y-axis limits. Each figure also potentially**  
 19 **contains different numbers of scenarios, depending on what was submitted to the database.**

20

Source: AR6 scenarios database.

### 21 3.2.5 Illustrative Mitigation Pathways

22 Successive IPCC ARs have used scenarios to illustrate key characteristics of possible climate (policy)  
 23 futures. In IPCC AR5 four RCPs made the basis of climate modelling in WGI and WGII, with WGIII  
 24 assessing over 1,000 scenarios spanning those RCPs (Clarke et al. 2014). Of the over 400 hundred  
 25 scenarios assessed in SR15, four scenarios were selected to highlight the trade-off between short-term  
 26 emission reductions and long-term deployment of BECCS (Rogelj et al. 2018a), referred to as  
 27 'Illustrative Pathways'. AR6 WGI and WGII rely on the scenarios selected for CMIP6, called  
 28 ScenarioMIP (O'Neill et al. 2016), to assess warming levels. IPCC AR6 WGIII uses in addition to the  
 29 full set of scenarios also selected Illustrative Mitigation Pathways (IMPs).

30 In WGIII, IMPs were selected to denote the implications of different societal choices for the  
 31 development of future emissions and associated transformations of main GHG emitting sectors (see  
 32 Box 3.1 and Figure 3.5a). The most important function of the IMPs is to illustrate key themes that

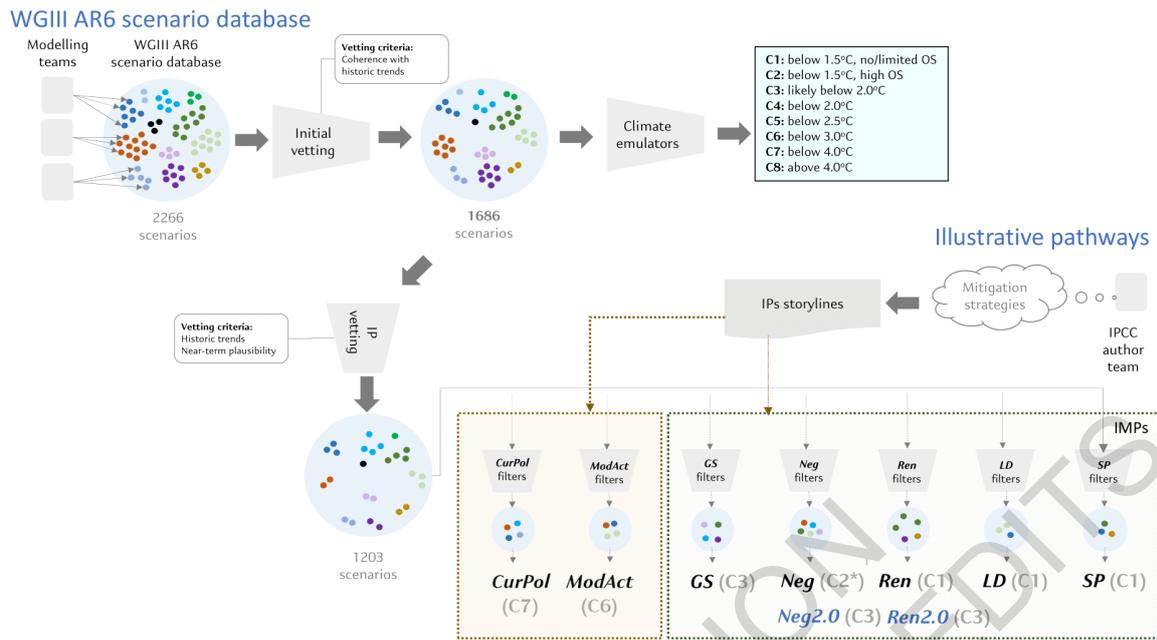
1 form a common thread in the report, both with a storyline and a quantitative illustration. The storyline  
2 describes the key characteristics that define an IMP. The quantitative versions of the IMPs provide  
3 numerical values that are internally consistent and comparable across chapters of the report. The  
4 quantitative IMPs have been selected from the AR6 scenario database. No assessment of the  
5 likelihood of each IMP has been made.

6 The selected scenarios (IPs) are divided into two sets (Figure 3.5 and Figure 3.6): two reference  
7 pathways illustrative of high emissions and five Illustrative Mitigation Pathways (IMPs). The  
8 narratives are explained in full in Annex III. The two reference pathways explore the consequences of  
9 current policies and pledges: Current Policies (*CurPol*) and Moderate Action (*ModAct*). The *CurPol*  
10 pathway explores the consequences of continuing along the path of implemented climate policies in  
11 2020 and only a gradual strengthening after that. The scenario illustrates the outcomes of many  
12 scenarios in the literature that project the outcomes of current policies. The *ModAct* pathway explores  
13 the impact of implementing the Nationally Determined Contributions as formulated in 2020 and some  
14 further strengthening after that. In line with current literature, these two reference pathways lead to an  
15 increase in global mean temperature of more than 2°C (see Section 3.3).

16 The Illustrative Mitigation Pathways properly explore different pathways consistent with meeting the  
17 long-term temperature goals of the Paris Agreement. They represent five different pathways that  
18 emerge from the overall assessment. The IMPs consist of pathways with: gradual strengthening of  
19 current policies (*GS*), extensive use of net negative emissions (*Neg*), renewables (*Ren*), low demand  
20 (*LD*), and shifting pathways (*SP*). Each of these pathways can be implemented with different levels  
21 of ambition. In the IMP framework, *GS* is consistent with staying likely below 2°C (C3), *Neg* shows a  
22 strategy that also stays likely below 2°C level but returns to nearly 1.5°C by the end of the century  
23 (hence indicated as C2\*). The other variants that can limit warming to 1.5°C (C1) were selected. In  
24 addition to these IMPs, sensitivity cases that explore alternative warming levels (C3) for *Neg* and *Ren*  
25 are assessed (*Neg-2.0* and *Ren-2.0*).

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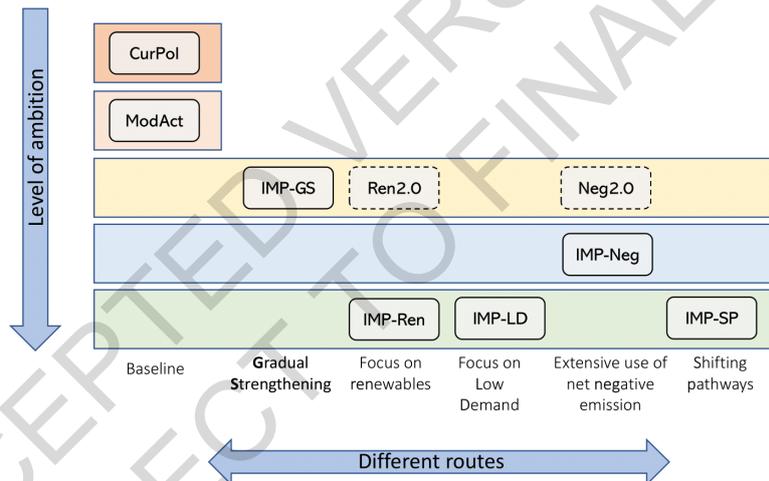
Panel A



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Panel B



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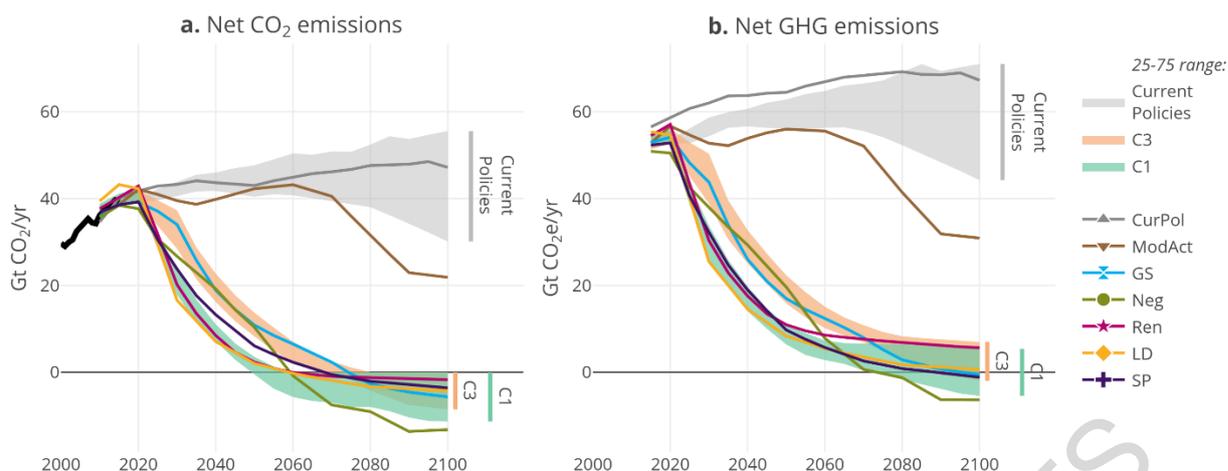
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**Figure 3.5 Panel A: Process for creating the AR6 scenario database and selecting the illustrative (mitigation) pathways.** The compiled scenarios in the AR6 scenarios database were vetted for consistency with historical statistics and subsequently a temperature classification was added using climate model emulators. The illustrative (mitigation) pathways were selected from the full set of pathways based on storylines of critical mitigation strategies that emerged from the assessment. **Panel B: An overview of the Illustrative Pathways selected for use in IPCC AR6 WGIII, consisting of pathways illustrative of higher emissions, Current Policies (CurPol) and Moderate Action (ModAct), and Illustrative Mitigation Pathways (IMPs): gradual strengthening of current policies (GS), extensive use of net negative emissions (Neg), renewables (Ren), low demand (LD), and shifting pathways (SP).**

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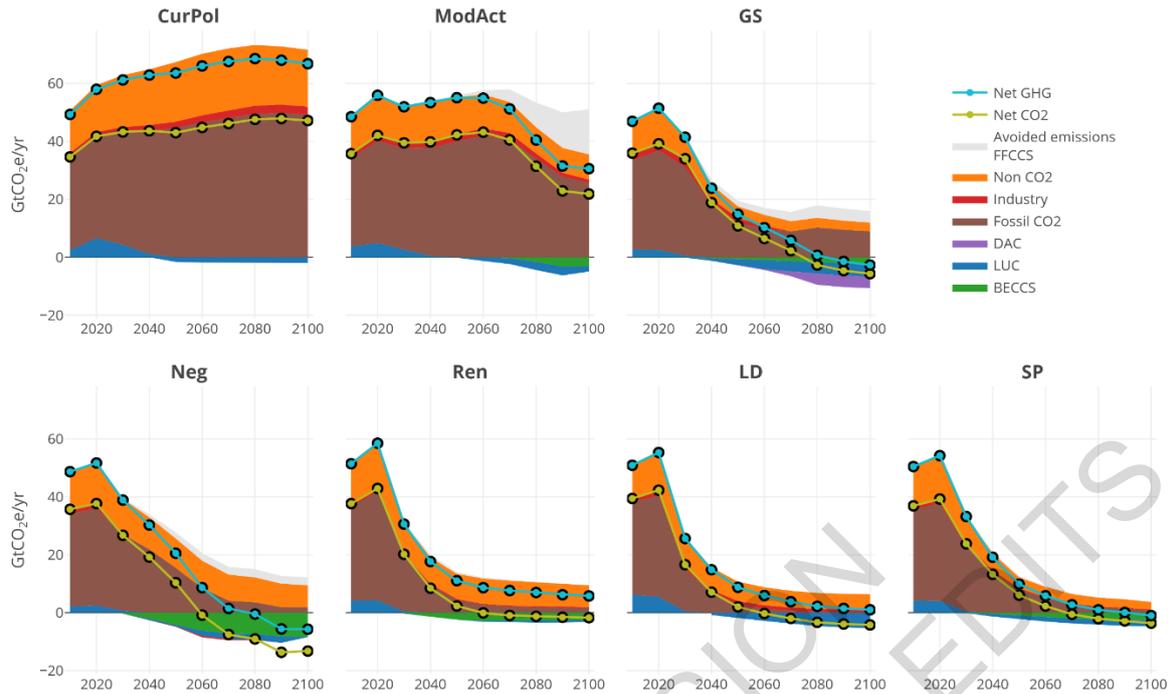


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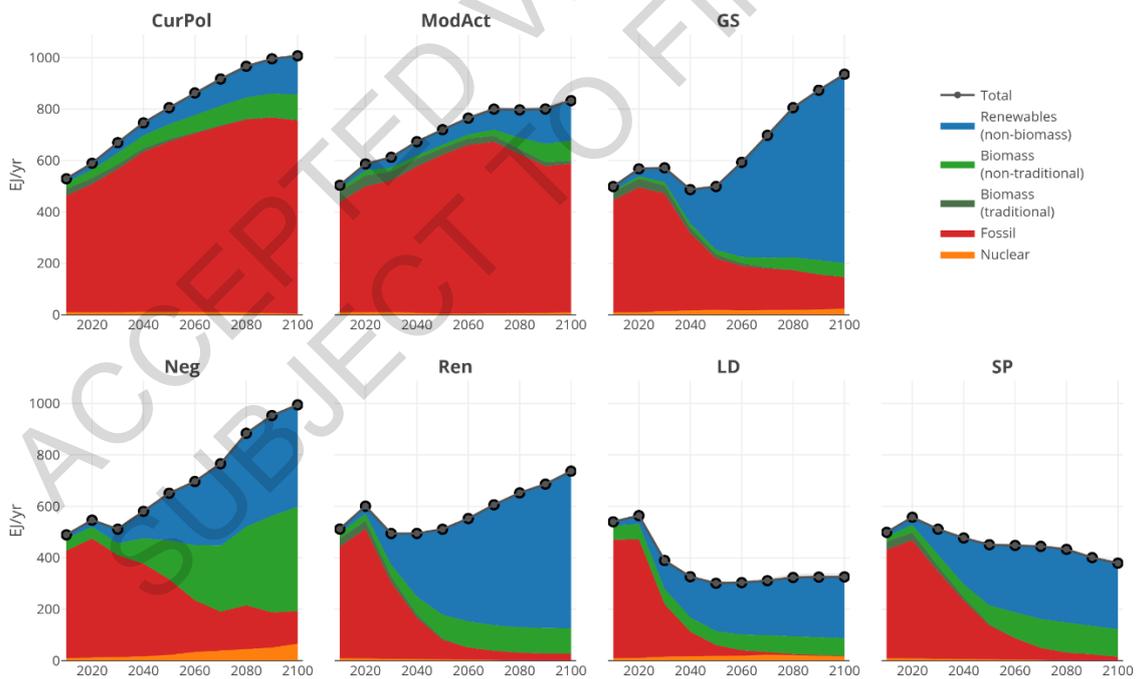
**Figure 3.6 Overview of the net CO<sub>2</sub> emissions and Kyoto GHG emissions for each IMP**

4 The IMPs are selected to have different mitigation strategies, which can be illustrated looking at the  
 5 energy system and emission pathways (Figure 3.7 and Figure 3.8). The mitigation strategies show the  
 6 different options in emission reduction (Figure 3.7). Each panel shows the key characteristics leading  
 7 to total GHG emissions, consisting of residual (gross) emissions (fossil CO<sub>2</sub> emissions, CO<sub>2</sub> emissions  
 8 from industrial processes, and non-CO<sub>2</sub> emissions) and removals (net land-use change, bioenergy with  
 9 carbon capture and storage, and direct air carbon capture and storage), in addition to avoided  
 10 emissions through the use of carbon capture and storage on fossil fuels. The *Neg* and *GS* scenarios  
 11 were shown to illustrate scenarios with a significant role of CDR. The energy supply (Figure 3.8)  
 12 shows the phase-out of fossil fuels in the *LD*, *Ren* and *SP* cases, but a less substantial decrease in the  
 13 *Neg* case. The *GS* case needs to make up its slow start by 1) rapid reductions mid-century and 2)  
 14 massive reliance on net negative emissions by the end of the century. The *CurPol* and *ModAct* cases  
 15 both result in relatively high emissions, showing a slight increase and stabilization compared to  
 16 current emissions, respectively.



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**Figure 3.7** The residual fossil fuel and industry emissions, net land-use change, CDR, and non-CO<sub>2</sub> emissions (using AR6 GWP100) for each of the seven illustrative pathways. Fossil CCS is also shown, though this does not lead to emissions to the atmosphere.



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**Figure 3.8** The energy system in each of the illustrative pathways.

### 3.3 Emission pathways, including socio-economic, carbon budget and climate responses uncertainties

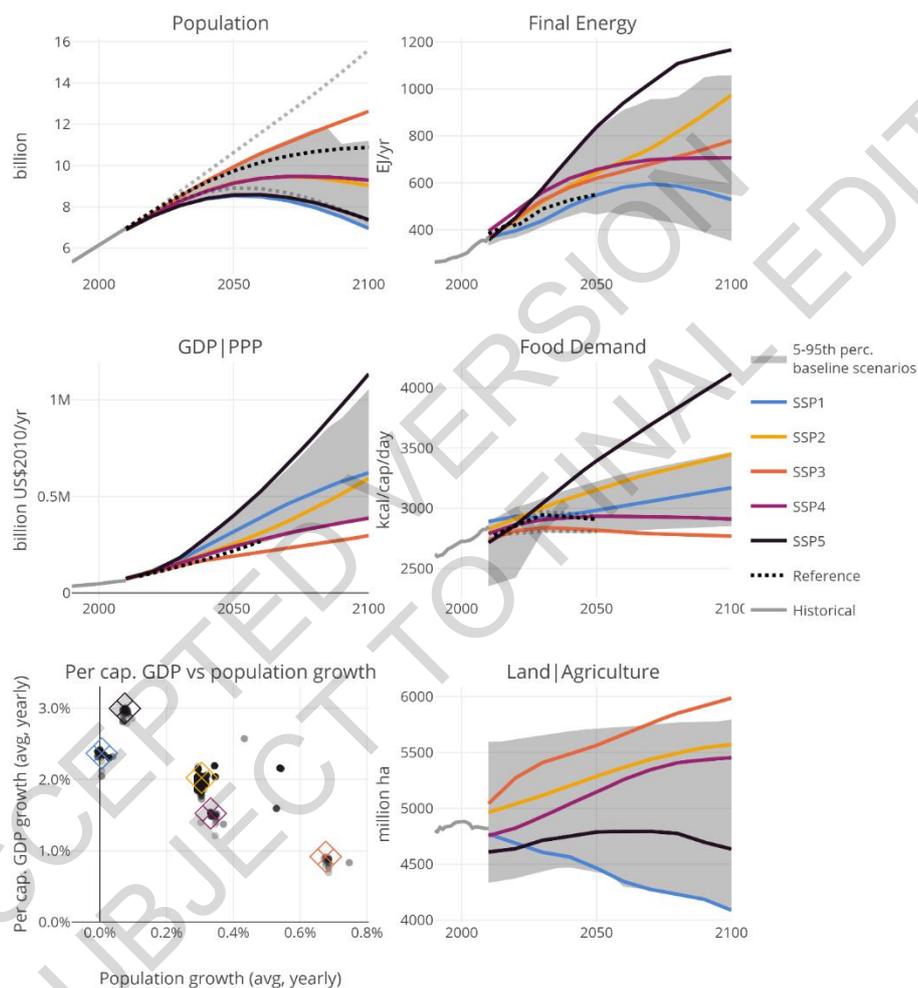
#### 3.3.1 Socio-economic drivers of emissions scenarios

Greenhouse gas emissions mainly originate from the use and transformation of energy, agriculture, land use (change) and industrial activities. The future development of these sources is influenced by trends in socio-economic development, including population, economic activity, technology, politics, lifestyles, and climate policy. Trends for these factors are not independent, and scenarios provide a consistent outlook for these factors together (see Section 3.2). Marangoni et al. (2017) show that in projections, assumptions influencing energy intensity (e.g., structural change, lifestyle and efficiency) and economic growth are the most important determinants of future CO<sub>2</sub> emissions from energy combustion. Other critical factors include technology assumptions, preferences, resource assumptions and policy (van Vuuren et al. 2008). As many of the factors are represented differently in specific models, the model itself is also an important factor – providing a reason for the importance of model diversity (Sognaes et al. 2021). For land use, Stehfest et al. (2019) show that assumptions on population growth are more dominant given that variations in per capita consumption of food are smaller than for energy. Here, we only provide a brief overview of some key drivers. We focus first on so-called reference scenarios (without stringent climate policy) and look at mitigation scenarios in detail later. We use the SSPs to discuss trends in more detail. The SSPs were published in 2017, and by now, some elements will have to be updated (O’Neill et al. 2020b). Still, the ranges represent the full literature relatively well.

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

Economic growth is even more uncertain than the population projections (Figure 3.9). The average growth rate of GDP was about 2.8% per year (constant USD) in the 1990-2019 period (The World Bank 2021). In 2020, the Covid-19 crisis resulted in a considerable drop in GDP (estimated around 4-5%) (IMF 2021). After a recovery period, most economic projections assume growth rates to converge back to previous projections, although at a lower level (IMF 2021; OECD 2021) (see also Box 3.2). In the long-term, assumptions on future growth relate to political stability, the role of the progress of the technology frontier and the degree to which countries can catch up (Johansson et al. 2013). The SSP scenarios cover an extensive range, with low per capita growth in SSP3 and SSP4 (mostly in developing countries) and rapid growth in SSP1 and SSP5. At the same, however, also scenarios outside the range have some plausibility – including the option of economic decline (Kallis et al. 2012) or much faster economic development (Christensen et al. 2018). The OECD long-term projection is at the global level reasonably consistent with SSP2. Equally important economic parameters include income distribution (inequity) and the type of growth (structural change, i.e., services vs manufacturing industries). Some projections (like SSP1) show a considerable convergence of income levels within and across countries, while in other projections, this does not occur (e.g., SSP3). Most scenarios reflect the suggested inverse relationship between the assumed growth rate for income and population growth (Figure 3.9e). SSP1 and SSP5 represent examples of scenarios with relatively low population increase and relatively high-income increase over the century. SSP3

1 represents an example of the opposite – while SSP2 and SSP4 are placed more in the middle. Nearly  
 2 all scenarios assessed here do not account for climate impacts on growth (mostly for methodological  
 3 reasons). As discussed in Section 3.5 these impacts can be considerable. An emerging area of  
 4 literature emphasises the possibility of stabilisation (or even decline) of income levels in developed  
 5 countries, arguing that such a trend would be preferred or even needed for environmental reasons  
 6 (Anderson and Larkin 2013; Kallis et al. 2020; Hickel and Kallis 2020; Keyßer and Lenzen 2021;  
 7 Hickel et al. 2021) (see also Chapter 5). Such scenarios are not common among IAM outcomes, that  
 8 are more commonly based on the idea that decarbonisation can be combined with economic growth  
 9 by a combination of technology, lifestyle and structural economic changes. Still, such scenarios could  
 10 result in a dramatic reduction of energy and resource consumption (see further).



11 **Figure 3.9 Trends in key scenarios characteristics and driving forces as included in the SSP scenarios**  
 12 **(showing 5-95<sup>th</sup> percentiles of the reference scenarios as included in the database in grey shading).**  
 13 **Reference (dotted lines) refers to UN low, medium and high population scenario (UN 2019), OECD Long-**  
 14 **term economic growth scenario (OECD 2021), the scenarios from IEA's World Energy Outlook (IEA**  
 15 **2019), and the scenarios in the FAO assessment (FAO 2018)**  
 16

17 Scenarios show a range of possible energy projections. In the absence of climate policy, most  
 18 scenarios project the final energy demand to continue to grow to around 650-800 EJ yr<sup>-1</sup> in 2100  
 19 (based on the scenario database). Some projections show a very high energy demand up to 1000 EJ yr<sup>-1</sup>  
 20 (comparable to SSP5). The scenario of the IEA lies within the SSP range but near the SSP1  
 21 projection. However, it should be noted that the IEA scenario includes current policies (most  
 22 reference scenarios do not) and many scenarios published before 2021 did not account for the Covid-  
 23 19 crisis. Several researchers discuss the possibility of decoupling material and energy demand from

1 economic growth in the literature, mainly in developed countries (Kemp-Benedict 2018) (decoupling  
2 here refers to either a much slower increase in demand or even a decrease). In the scenario literature,  
3 this is reflected by scenarios with very low demand for final energy based on increased energy  
4 efficiency and less energy-intensive lifestyles (e.g., SSP1 and the LED scenario) (Grubler et al. 2018;  
5 van Vuuren et al. 2018). While these studies show the feasibility of such pathways, their energy  
6 efficiency improvement rates are considerably above the historic range of around 2% (Haberl et al.  
7 2020).

8  
9 (Vrontisi et al. 2018; Roelfsema et al. 2020; Sognaes et al. 2021)(IEA 2021a; Höhne et al.  
10 2021)(Jeffery et al. 2018; Gütschow et al. 2018)(Giarola et al. 2021)(Sognaes et al. 2021)(Höhne et  
11 al. 2021)(Höhne et al. 2021)These scenarios also show clear differences in food consumption and the  
12 amount of land used for agriculture. Food demand in terms of per capita caloric intake is projected to  
13 increase in most scenarios. However, it should be noted that there are large differences in dietary  
14 composition across the scenarios (from more meat-intensive in scenarios like SSP5 to a decrease in  
15 meat consumptions in other scenarios such as SSP1). Land use projections also depend on assumed  
16 changes in yield and the population scenarios. Typically, changes in land use are less drastic than  
17 some other parameters (in fact, the 5-95<sup>th</sup> database range is almost stable). Agriculture land is  
18 projected to increase in SSP3, SSP2, and SSP4 – more-or-less stable in SSP5 and is projected to  
19 decline in SSP1.

### 20 21 **3.3.2 Emission pathways and temperature outcomes**

#### 22 23 **3.3.2.1 Overall mitigation profiles and temperature consequences**

24  
25 Figure 3.10 shows the GHG and CO<sub>2</sub> emission trajectories for different temperature categories as  
26 defined in Section 3.2 (the temperature levels are calculated using simple climate models, consistent  
27 with the outcomes of the recent WGI assessment, Cross-Chapter Box 7.1). It should be noted that  
28 most scenarios currently in the literature do not account for an impact of Covid-19 (see Box 3.2). The  
29 higher categories (C6 and C7) mostly included scenarios with no or modest climate policy. Because  
30 of the progression of climate policy, it is becoming more common that reference scenarios incorporate  
31 implemented climate policies. Modelling studies typically implement current or pledged policies up  
32 until 2030 (Vrontisi et al. 2018; Roelfsema et al. 2020; Sognaes et al. 2021) with some studies  
33 focusing also on the policy development in the long term (IEA 2021a; Höhne et al. 2021). (Jeffery et  
34 al. 2018; Gütschow et al. 2018)Based on the assessment by Chapter 4, reference pathways consistent  
35 with the implementation and extrapolation of current policies are associated with increased GHG  
36 emissions from 59 (53-65) GtCO<sub>2</sub>-eq yr<sup>-1</sup> in 2019 to 52-60 GtCO<sub>2</sub>-eq yr<sup>-1</sup> by 2030 and to 46-67  
37 GtCO<sub>2</sub>-eq yr<sup>-1</sup> by 2050 (see Figure 3.6). Pathways with these near-term emissions characteristics, lead  
38 to a median global warming of 2.4°C to 3.5°C by 2100 (see also further in this section). These  
39 pathways consider policies at the time that they were developed. A recent model comparison that  
40 harmonised socioeconomic, technological, and policy assumptions (Giarola et al. 2021) found a 2.2-  
41 2.9°C median temperature rise in 2100 for current and stated policies, with the results sensitive to the  
42 model used and the method of implementing policies (Sognaes et al. 2021). Scenario inference and  
43 construction methods using similar policy assumptions leads to a median range of 2.9-3.2°C in 2100  
44 for current policies and 2.4-2.9°C in 2100 for 2030 pledges (Höhne et al. 2021). The median spread of  
45 1°C across these studies (2.2-3.2°C) indicates the deep uncertainties involved with modelling  
46 temperature outcomes of 2030 policies through to 2100. (Höhne et al. 2021)

47  
48 The lower categories include increasingly stringent assumed climate policies. For all scenario  
49 categories, except the highest category, emissions peak in the 21st century. For the lowest categories,  
50 the emissions peak is mostly before 2030. In fact, for scenarios in the category that avoids  
51 temperature overshoot for the 1.5°C scenario (C1 category), GHG emissions are reduced already to  
52 almost zero around the middle of the century. Typically, CO<sub>2</sub> emissions reach net zero about 10-20  
53 years before total GHG emissions reach net zero. The main reason is that scenarios reduce non-CO<sub>2</sub>  
54 greenhouse gas emissions less than CO<sub>2</sub> due to a limited mitigation potential (see 3.3.2.2). The figure  
55 also shows that many scenarios in the literature with a temperature outcome below 2 °C show net

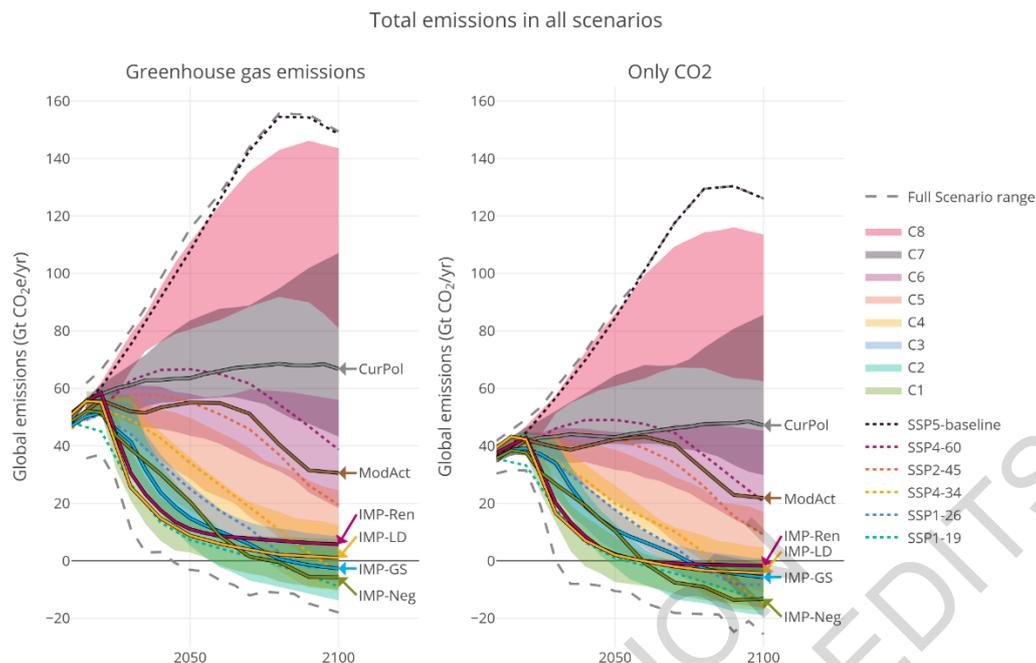
1 negative emissions. There are, however, also exceptions in which more immediate emission  
2 reductions limits the need for CDR. The IMPs illustrate alternative pathways to reach the C1-C3  
3 temperature levels.  
4

#### 5 **START BOX HERE**

#### 6 **Box 3.2 Impact of Covid-19 on long-term emissions**

7  
8  
9 The reduction in CO<sub>2</sub> emissions of the Covid-19 pandemic in 2020 was estimated to be about 6% (see  
10 section 4.2.2.4 and Table S4.2) lower than 2019 levels (BP 2021, Crippa et al. 2021, IEA 2021, Le  
11 Quéré et al. 2021; Friedlingstein et al. 2020; Forster et al. 2020; Liu et al. 2020c). Near-real-time  
12 monitoring estimates show a rebound in emissions levels, meaning 2021 emissions levels are  
13 expected to be higher than 2020 (Le Quéré et al. 2021). The longer-term effects are uncertain but so  
14 far do not indicate a clear structural change for climate policy related to the pandemic. The increase in  
15 renewable shares in 2020 could stimulate a further transition, but slow economic growth can also slow  
16 down (renewable) energy investments. Also, lifestyle changes during the crisis can still develop in  
17 different directions (working from home, but maybe also living further away from work). Without a  
18 major intervention, most long-term scenarios project that emission will start to follow a similar  
19 pathway as earlier projections (although at a reduced level) (IEA 2020b; Kikstra et al. 2021a;  
20 Rochedo et al. 2021). If emissions reductions are limited to only a short time, the adjustment of  
21 pathways will lead to negligible outcomes in the order of 0.01K (Forster et al. 2020; Jones et al.  
22 2021). At the same time, however, the large amount of investments pledged in the recovery packages  
23 could provide a unique opportunity to determine the long-term development of infrastructure, energy  
24 systems and land use (Hepburn et al. 2020; Pianta et al. 2021; Andrijevic et al. 2020b). Near-term  
25 alternative recovery pathways have been shown to have the potential to influence carbon price  
26 pathways, and energy investments and electrification requirements under stringent mitigation targets  
27 (Kikstra et al. 2021a; Rochedo et al. 2021; Bertram et al. 2021; Pollitt et al. 2021; Shan et al. 2021).  
28 Most studies suggest a noticeable reduction in 2030 emissions. However, much further reductions  
29 would be needed to reach the emission levels consistent with mitigation scenarios that would likely  
30 stay below 2°C or lower (see Chapter 4). At the moment, the share of investments in greenhouse gas  
31 reduction is relatively small in most recovery packages, and no structural shifts for climate policies  
32 are observed linked to the pandemic. Finally, most of the scenarios analysed in this Chapter do not  
33 include the 2020 emissions reduction related to the Covid-19 pandemic. The effect of the pandemic  
34 on the pathways will likely be very small. The assessment of climate mitigation pathways in this  
35 chapter should be interpreted as being almost exclusively based on the assumption of a fast recovery  
36 with limited persistent effects on emissions or structural changes.  
37

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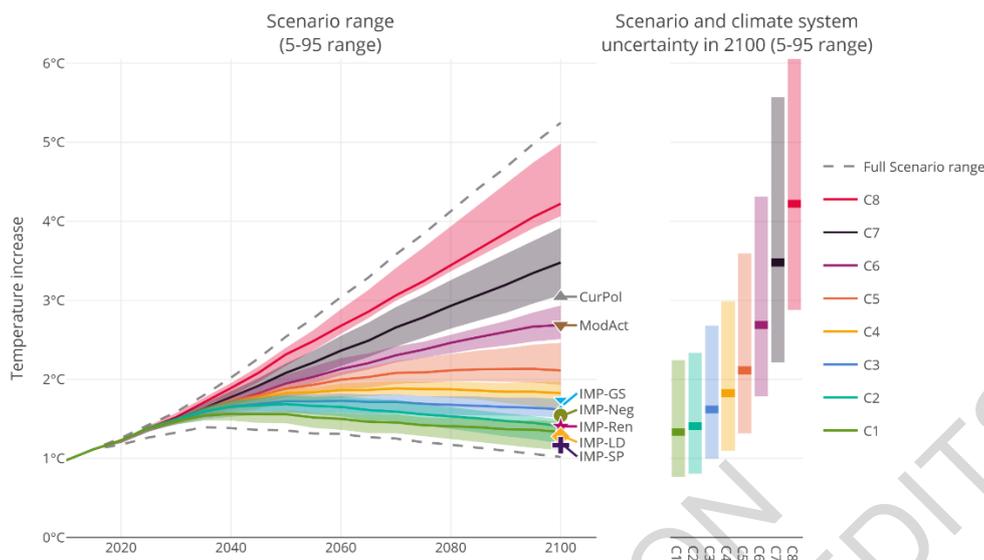


**Figure 3.10 Total emission profiles in the scenarios based on climate category for GHGs (AR6 GWP-100) and CO<sub>2</sub>. The IMPs are also indicated**

## START BOX HERE

### Box 3.3 The likelihood of high-end emission scenarios

At the time the Representative Concentration Pathways (RCPs) were published, they included 3 scenarios that could represent emission developments in the absence of climate policy: RCP4.5, RCP6 and RCP8.5, described as, respectively, low, medium and high-end scenarios in the absence of strong climate policy (van Vuuren et al. 2011). RCP8.5 was described as representative of the top 5% scenarios in the literature. The SSPs-based set of scenarios covered the RCP forcing levels adding a new low scenario (at 1.9 W/m<sup>2</sup>). Hausfather and Peters (2020) pointed out that since 2011, the rapid development of renewable energy technologies and emerging climate policy have made it considerably less likely that emissions could end up as high as RCP8.5. Still, emission trends in developing countries track RCP8.5 Pedersen et al. (2020), and high land-use emissions could imply that emissions would continue to do so in the future, even at the global scale (Schwalm et al. 2020). Other factors resulting in high emissions include higher population or economic growth as included in the SSPs (see subsection 3.3.1) or rapid development of new energy services. Climate projections of RCP8.5 can also result from strong feedbacks of climate change on (natural) emission sources and high climate sensitivity (see WGI Chapter 7), and therefore their median climate impacts might also materialise while following a lower emission path (e.g., Hausfather and Betts (2020)). The discussion also relates to a more fundamental discussion on assigning likelihoods to scenarios, which is extremely difficult given the deep uncertainty and direct relationship with human choice. However, it would help to appreciate certain projections (e.g., Ho et al. (2019)). All-in-all, this means that high-end scenarios have become considerably less likely since AR5 but cannot be ruled out. It is important to realize that RCP8.5 and SSP5-8.5 do not represent a typical ‘business-as-usual projection but are only useful as high-end, high-risk scenarios. Reference emission scenarios (without additional climate policy) typically end up in C5-C7 categories included in this assessment.

1 **END BOX HERE**

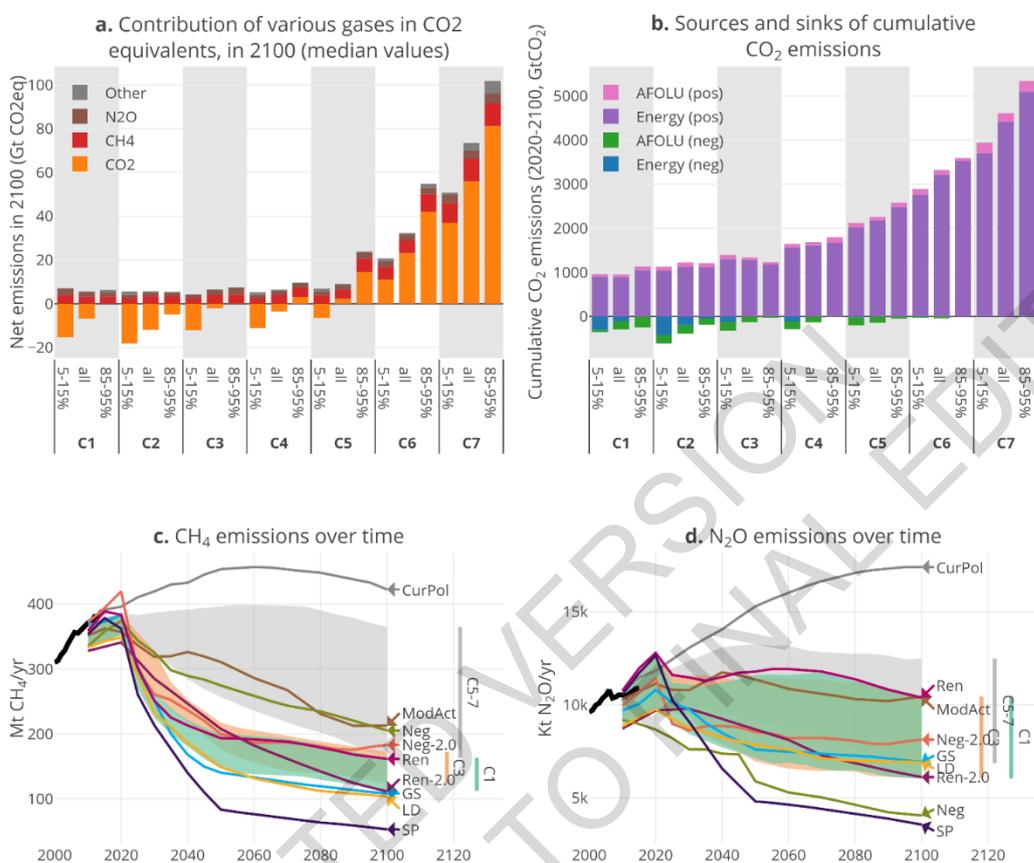
2  
3 **Figure 3.11: Global mean temperature outcome of the ensemble of scenarios included in the climate**  
4 **categories C1-C7 (based on RCM calibrated to the WGI assessment, both in terms of future and historic**  
5 **warming). The left panel shows the ranges of scenario uncertainty (shaded area) with the P50 RCM**  
6 **probability (line). The right panel shows the P5 to P95 range of RCM climate uncertainty (C1-C7 is**  
7 **explained in Table 3.1) and the P50 (line) and P66 (dashed line).**  
8

9 Figure 3.11 shows the possible consequences of the different scenario categories for global mean  
10 temperature calculated using a reduced complexity model calibrated to the IPCC WGI assessment  
11 (see Annex III and WGI report). For the C5-C7 categories (containing most of the reference and  
12 current policy scenarios), the global mean temperature is expected to increase throughout the century  
13 (and further increase will happen after 2100 for C6 and C7). While warming would likely be in the  
14 range from 2.2-3.8 °C – warming above 5°C cannot be excluded. The highest emissions scenarios in  
15 the literature combine assumptions about rapid long-term economic growth and pervasive climate  
16 policy failures, leading to a reversal of some recent trends (see box 3.3). For the categories C1-C4, a  
17 peak in global mean temperature is reached mid-century for most scenarios in the database, followed  
18 by a small (C3/C4) or more considerable decline (C1/C2). There is a clear distinction between the  
19 scenarios with no or limited overshoot (typically <0.1 °C, C1) compared to those with high overshoot  
20 (C2): in emissions, the C1 category is characterised by steep early reductions and a relatively small  
21 contribution of net negative emissions (like *LD* and *Ren*) (Figure 3.10). In addition to the temperature  
22 caused by the range of scenarios in each category (main panel), also climate uncertainties contribute  
23 to a range of temperature outcomes (including uncertainties regarding the carbon cycle, climate  
24 sensitivity, and the rate of change, see WGI). The bars on the right of Figure 3.11 show the  
25 uncertainty range for each category (combining scenario and uncertainty). While the C1 category  
26 more likely than not leads to warming below 1.5 °C by the end of the century, even with such a  
27 scenario, warming above 2°C cannot be excluded (95<sup>th</sup> percentile). The uncertainty range for the  
28 highest emission categories (C7) implies that these scenarios could lead to a warming above 6°C.  
29

### 30 3.3.2.2 *The role of carbon dioxide and other greenhouse gases*

31 The trajectory of future CO<sub>2</sub> emissions plays a critical role in mitigation, given CO<sub>2</sub> long-term impact  
32 and dominance in total greenhouse gas forcing. As shown in Figure 3.12, CO<sub>2</sub> dominates total  
33 greenhouse gas emissions in the high emissions scenarios but is also reduced most, going from  
34 scenarios in the highest to lower categories. In C4 and below, most scenarios exhibit net negative CO<sub>2</sub>  
35 emissions in the second half of the century compensating for some of the residual emissions of non-  
36 CO<sub>2</sub> gases as well as reducing overall warming from an intermediate peak. Still, early emission

1 reductions and further reductions in non-CO<sub>2</sub> emissions can also lead to scenarios without net  
 2 negative emissions in 2100, even in C1 and C3 (shown for the 85-95<sup>th</sup> percentile). In C1, avoidance of  
 3 significant overshoot implies that immediate gross reductions are more relevant than long-term net  
 4 negative emissions (explaining the lower number than in C2) but carbon dioxide removal is still  
 5 playing a role in compensating for remaining positive emissions in hard-to-abate sectors.



6

7 **Figure 3.12 Upper left: The role of CO<sub>2</sub> and other greenhouse gases. Emission in CO<sub>2</sub>-eq in 2100 (using**  
 8 **AR6 GWP-100) (other = halogenated gases) and upper right: Cumulative CO<sub>2</sub> emissions in the 2020-2100**  
 9 **period. The lower left and right panel show the development of CH<sub>4</sub> and N<sub>2</sub>O emissions over time.**  
 10 **Energy emissions include the contribution of BECCS. For both energy and AFOLU sectors, the positive**  
 11 **and negative values represent the cumulated annual balances. In both panels, the three bars per scenario**  
 12 **category represent the lowest 5-15<sup>th</sup> percentile, the average value and the highest 5-15<sup>th</sup> percentile. These**  
 13 **illustrate the range of scenarios in each category. The definition of C1-C7 can be found in Table 3.1**

14 CH<sub>4</sub> and N<sub>2</sub>O emissions are also reduced from C7 to C1, but this mostly occurs between C7 and C5.  
 15 The main reason is the characteristics of abatement potential: technical measures can significantly  
 16 reduce CH<sub>4</sub> and N<sub>2</sub>O emissions at relatively low costs to about 50% of the current levels (e.g., by  
 17 reducing CH<sub>4</sub> leaks from fossil fuel production and transport, reducing landfill emissions gazing, land  
 18 management and introducing measure related to manure management, see also Chapter 7 and 11).  
 19 However, technical potential estimates becomes exhausted even if the stringency of mitigation is  
 20 increased (Harmsen et al. 2019a,b; Höglund-Isaksson et al. 2020). Therefore, further reduction may  
 21 come from changes in activity levels, such as switching to a less meat-intensive diet reducing  
 22 livestock (Stehfest et al. 2009; Willett et al. 2019; Ivanova et al. 2020) (see also Chapter 7). Other  
 23 non-CO<sub>2</sub> GHG emissions (halogenated gases) are reduced to low levels for scenarios below 2.5°C.  
 24

1 Short-lived climate forcers (SLCFs) also play an important role in climate change, certainly for short-  
2 term changes (see Figure SPM.2, WGI) (Shindell et al. 2012). These forcers consist of 1) substances  
3 contributing to warming, such as methane, black carbon and tropospheric ozone and 2) substances  
4 contributing to cooling (other aerosols, such as related to sulphur emissions). Most SLCFs are also air  
5 pollutants, and reducing their emissions provides additional co-benefits (Shindell et al. 2017a,b;  
6 Hanaoka and Masui 2020). In the case of the first group, emission reduction thus leads to both air  
7 pollution and climate benefits. For the second, group there is a possible trade-off (Shindell and Smith  
8 2019; Lund et al. 2020). As aerosol emissions are mostly associated with fossil fuel combustion, the  
9 benefits of reducing CO<sub>2</sub> could, in the short term, be reduced as a result of lower aerosol cooling.  
10 There has been an active discussion on the exact climate contribution of SLCF focused policies in the  
11 literature. This discussion partly emerged from different assumptions on possible reductions in the  
12 absence of ambitious climate policy and the uncertain global climate benefit from aerosol (black  
13 carbon) (Rogelj et al. 2014). The latter is now assessed to be smaller than originally thought (Smith et  
14 al. 2020b; Takemura and Suzuki 2019) (see also WGI Chapter 6, Section 6.4). Reducing SLCF  
15 emissions is critical to meet long-term climate goals and might help reduce the rate of climate change  
16 in the short term. Deep SLCF emission reductions also increase the remaining carbon budget for a  
17 specific temperature goal (Rogelj et al. 2015a; Reisinger et al. 2021) (see Box 3.4). A more detailed  
18 discussion can be found in WGI Chapter 5 and 6.

19  
20 For accounting of emissions and the substitution of different gases as part of a mitigation strategy,  
21 typically, emission metrics are used to compare the climate impact of different gases. Most policies  
22 currently use Global Warming Potentials with a 100-year time horizon as this is also mandated for  
23 emissions reporting in the Paris Rulebook (for a wider discussion of GHG metrics, see Box 2.2 in  
24 Chapter 2 and WGI, Chapter 7, Section 7.6). Alternative metrics have also been proposed, such as  
25 those using a shorter or longer time horizon or those that focus directly on the consequences of  
26 reaching a certain temperature target (Global Temperature Change Potential, GTP), allowing a more  
27 direct comparison with cumulative CO<sub>2</sub> emissions (Allen et al. 2016; Lynch et al. 2020) or focusing  
28 on damages (Global Damage Potential) (an overview is given in Chapter 2, and Cross-Chapter Box  
29 3). Depending on the metric, the value attributed to reducing short-lived forcers like methane can be  
30 lower in the near term (e.g., in the case of GTP) or higher (GWP with short reference period). For  
31 most metrics, however, the impact on mitigation strategies is relatively small, among others, due to  
32 the marginal abatement cost curve of methane (low costs for low to medium mitigation levels;  
33 expensive for high levels). The timing of reductions across different gases impacts warming and the  
34 co-benefits (Harmsen et al. 2016; Cain et al. 2019). Nearly all scenarios in the literature use GWP-100  
35 in cost-optimisation, reflecting the existing policy approach; the use of GWP-100 deviates from cost-  
36 optimal mitigation pathways by at most a few percent for temperature goals of likely below 2°C and  
37 lower (see Box 2.2 in Chapter 2).

### 38 *Cumulative CO<sub>2</sub> emissions and temperature goals*

39  
40 The dominating role of CO<sub>2</sub> and its long lifetime in the atmosphere and some critical characteristics of  
41 the earth system implies that there is a strong relationship between cumulative CO<sub>2</sub> emissions and  
42 temperature outcomes (MacDougall and Friedlingstein 2015; Meinshausen et al. 2009; Allen et al.  
43 2009; Matthews et al. 2009). This is illustrated in Figure 3.13 that plots the cumulative CO<sub>2</sub> emissions  
44 against the projected outcome for global mean temperature, both until a temperature peak and full  
45 century. The deviations from in linear relationship in Figure 3.13 are mostly caused by different non-  
46 CO<sub>2</sub> emission and forcing levels (see also Rogelj et al. (2015b)). This means that reducing non-CO<sub>2</sub>  
47 emissions can play an important role in limiting peak warming: the smaller the residual non-CO<sub>2</sub>  
48 warming, the larger the carbon budget. This impact on carbon budgets can be substantial for stringent  
49 warming limits. For 1.5°C pathways, variations in non-CO<sub>2</sub> warming across different emission  
50 scenarios have been found to vary the remaining carbon budget by approximately 220 GtCO<sub>2</sub> (see  
51 WGI Chapter 5, Subsection 5.5.2.2). In addition to reaching net zero CO<sub>2</sub> emissions, a strong  
52 reduction in methane emissions is the most critical component in non-CO<sub>2</sub> mitigation to keep the Paris  
53 climate goals in reach (van Vuuren et al. 2018; Collins et al. 2018) (see also WGI, Chapter 5, 6 and  
54 7). It should be noted that the temperature categories (C1-C7) generally aligned with the horizontal  
55 axis, except for the end-of-century values for C1 and C2 that coincide.

**START BOX HERE****Box 3.4 Consistency of remaining carbon budgets in the WGI assessment and cumulative CO<sub>2</sub> emissions in WGIII mitigation pathways****Introduction**

The WGI assessment has shown that the increase in global mean temperature has a near-linear relationship with cumulative CO<sub>2</sub> emissions (Chapter 5, Section 5.5, Box 5.3). Consistently, WGI has confirmed that net zero CO<sub>2</sub> emissions are required to halt CO<sub>2</sub>-induced warming. This permits the estimation of carbon budgets consistent with specific temperature goals. In Chapter 3, we present the temperature outcomes and cumulative CO<sub>2</sub> emissions associated with different warming levels for around 1200 scenarios published in the literature and which were classified according to different warming levels (see Section 3.2 and Annex III, Part II.2.5). In this box, we discuss the consistency of the assessments presented here and in IPCC WGI. The box summarises how the remaining carbon budgets assessed by WGI relate to the remaining cumulative CO<sub>2</sub> emissions until the time of net zero CO<sub>2</sub> emissions in mitigation pathways (Table 3.2, Table SPM1) assessed by WGIII.

In its assessment, WGI uses a framework in which the various components of the remaining carbon budget are informed by various lines of evidence and assessed climate system characteristics. WGIII, instead, uses around 1200 emission scenarios with estimated warming levels that cover the scenario range presented in WGI but also contain many more intermediate projections with varying emission profiles and a combination of CO<sub>2</sub> emissions and other greenhouse gases. In order to assess their climate outcomes, climate model emulators are used. The emulators are reduced complexity climate models that are provided by WGI, and which are calibrated to the WGI assessment of future warming for various purposes (a detailed description of the use of climate model emulators in the WGI and WGIII assessments can be found in Cross-chapter Box 7.1 in the WGI report, with the connection of WGI and WGII discussed in Annex III.2.5.1).

**Remaining carbon budgets estimated by WGI**

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

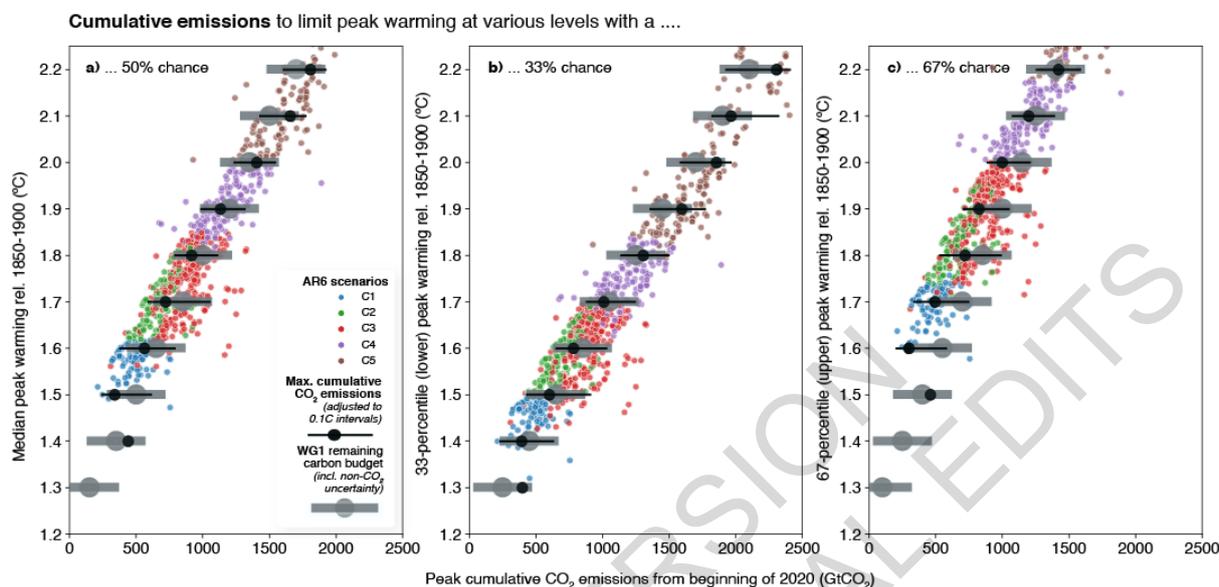
***Cumulative CO<sub>2</sub> emissions until net zero estimated by WGIII***

WGIII provides estimates of cumulative net CO<sub>2</sub> emissions (from 2020 inclusive) until the time of reaching net zero CO<sub>2</sub> emissions (henceforth called “peak cumulative CO<sub>2</sub> emissions”) and until the end of the century for eight temperature classes that span a range of warming levels. The numbers can be found in Table 3.2 (330-710 GtCO<sub>2</sub> for C1; 540-930 for C2 and 640-1160 for C3).

***Comparing the WGI remaining carbon budgets and remaining cumulative CO<sub>2</sub> emissions of the WGIII scenarios***

A comparison between WGI and WGIII findings requires recognising that, unlike in WGI, cumulative emissions in WGIII are not provided for a specific peak warming threshold or level but are instead provided for a set of scenarios in a category, representing a specific range of peak temperature

1 outcomes (for instance the C4 category contains scenarios with a median peak warming anywhere  
 2 between approximately 1.8°C and up to 2°C). When accounting for this difference, the WGI and  
 3 WGIII findings are very consistent for temperature levels below 2°C. Figure 1 compares the peak  
 4 temperatures and associated cumulative CO<sub>2</sub> emissions (i.e., peak cumulative CO<sub>2</sub> emissions) for the  
 5 WGIII scenarios to the remaining carbon budgets assessed by WGI. This shows only minor  
 6 differences between the WGI and WGIII approaches.  
 7

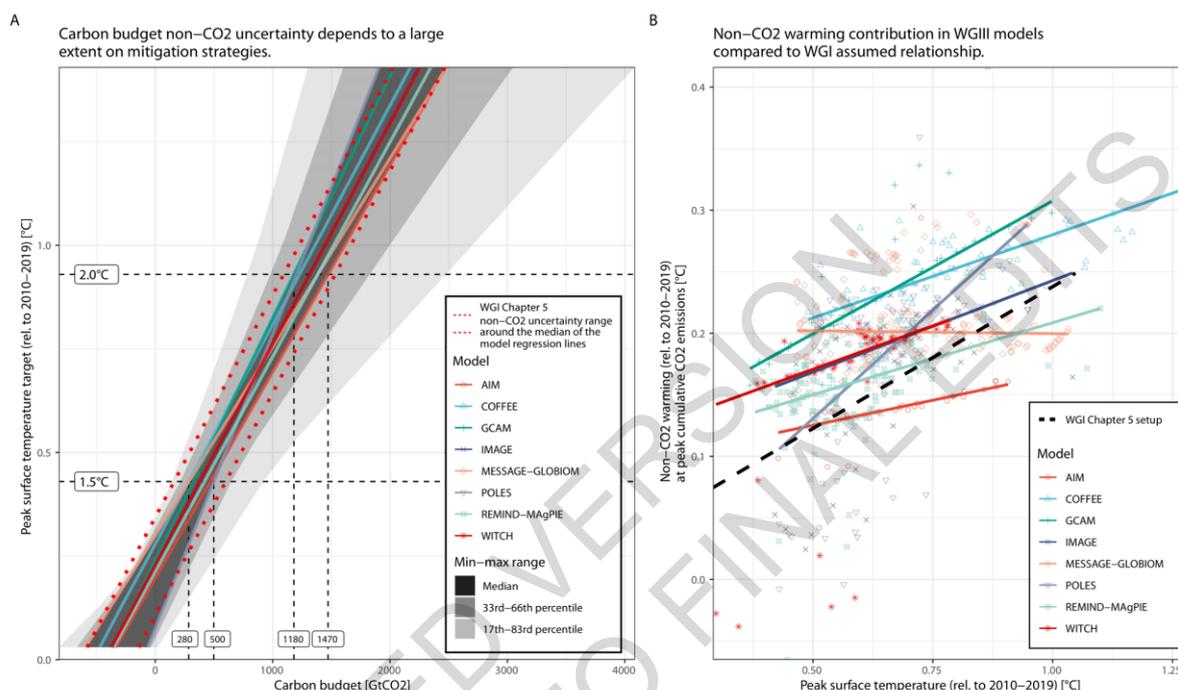


**Box 3.4 Figure 1: Cumulative CO<sub>2</sub> emissions from AR6 scenario categories (coloured dots), adjusted for distinct 0.1°C warming levels (black bars) in comparison to the WGI remaining carbon budgets (grey bars). The cumulative carbon emissions for the AR6 scenarios are shown for the median peak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

After correcting for the categorisation, some (small) differences between the WGI and WGIII numbers arise from remaining differences between the outcomes of the climate emulators and their set-up (see Cross-Chapter Box 7.1 in IPCC WGI AR6) and the differences in the underlying scenarios. Moreover, the WGI assessment estimated the non-CO<sub>2</sub> warming at the time of net zero CO<sub>2</sub> emissions based on a relationship derived from the SR1.5 scenario database with historical emission estimates as in Meinshausen et al. (2020) (WGI chapter 5). The WGIII assessment uses the same climate emulator with improved historical emissions estimates (Nicholls et al. 2021) (WGI Cross-Chapter Box 7.1). Annex III.2.5.1 further explores the effects of these factors on the relationship between non-CO<sub>2</sub> warming at peak cumulative CO<sub>2</sub> and peak surface temperature.

Estimates of the remaining carbon budgets thus vary with the assumed level of non-CO<sub>2</sub> emissions, which are a function of policies and technology development. The linear relationship used in the WGI assessment between peak temperature and the warming as a result of non-CO<sub>2</sub> emissions (based on the SR1.5 data) is shown in the right panel of Figure 2 (dashed line). In the WG3 approach, the non-CO<sub>2</sub> warming for each single scenario is based on the individual scenario characteristics. This shown

1 in the same figure by plotting the outcomes of scenario outcomes of a range models (dots). The lines  
 2 show the fitted data for individual models, emphasizing the clear differences across models and the  
 3 relationship with peak warming (policy level). In some scenarios stringent non-CO<sub>2</sub> emission  
 4 reductions provide an option to reach more stringent climate goals with the same carbon budget. This  
 5 is especially the case for scenarios with a very low non-CO<sub>2</sub> warming, for instance as a result of  
 6 methane reductions through diet change. The left panel shows how these differences impact estimates  
 7 of the remaining carbon budget. While the WGIII AR6 scenario database includes a broad range of  
 8 non-CO<sub>2</sub> emission projections the overall range is still very consistent with the WGI relationship and  
 9 the estimated uncertainty with a  $\pm 220$  GtCO<sub>2</sub> range (see also panel B of Figure II.2 in Annex III.2.5).  
 10



11  
 12 **Box 3.4 Figure 2: Panel A) Differences in regressions of the relationship between peak surface**  
 13 **temperature and associated cumulative CO<sub>2</sub> emissions from 2020 derived from scenarios of eight**  
 14 **integrated assessment model frameworks. The coloured lines show the regression at median for scenarios**  
 15 **of the 8 modelling frameworks, each with more than 20 scenarios in the database and a detailed land-use**  
 16 **representation. The red dotted lines indicate the non-CO<sub>2</sub> uncertainty range of WGI Chapter 5 ( $\pm 220$**   
 17 **GtCO<sub>2</sub>), here visualised around the median of the 8 model framework lines. Carbon budgets from 2020**  
 18 **until 1.5C (0.43K above 2010-2019 levels) and 2.0C (0.93K above 2010-2019 levels) are shown for**  
 19 **minimum and maximum model estimates at the median, rounded to the nearest 10GtCO<sub>2</sub>. Panel B)**  
 20 **Shows the relationship between the estimated non-CO<sub>2</sub> warming in mitigation scenarios that reach net**  
 21 **zero and the associated peak surface temperature outcomes. The coloured lines show the regression at**  
 22 **median for scenarios of the 8 modelling frameworks with more than 20 scenarios in the database and a**  
 23 **detailed land-use representation. The black dashed line indicates the non-CO<sub>2</sub> relationship based on the**  
 24 **scenarios and climate emulator setup as was assessed in WGI Chapter 5.**

25 Overall, the slight differences between the cumulative emissions in WGIII and the carbon budget in  
 26 WGI are because the non-CO<sub>2</sub> warming in the WGIII AR6 scenarios is slightly lower than in the  
 27 SR1.5 scenarios that are used for the budget estimates in WGI (Annex III.2.5.1). In addition,  
 28 improved consistency with Cross-Chapter Box 7.1 in WGI results in a non-CO<sub>2</sub> induced temperature  
 29 difference of about  $\sim 0.05$ K between the assessments. Re-calculating the remaining carbon budget  
 30 using the WGI methodology combined with the full WGIII AR6 scenario database results in a  
 31 reduction of the estimated remaining 1.5C carbon budget by about 100 GtCO<sub>2</sub> (-20%), and a reduction  
 32 of  $\sim 40$  GtCO<sub>2</sub> (-3%) for 2C. Accounting also for the categorisation effect, the difference between the  
 33 WGI and WGIII estimates is found to be small and well within the uncertainty range (Figure 1). This  
 34 means that the cumulative CO<sub>2</sub> emissions presented in WGIII and the WGI carbon budgets are highly  
 35 consistent.

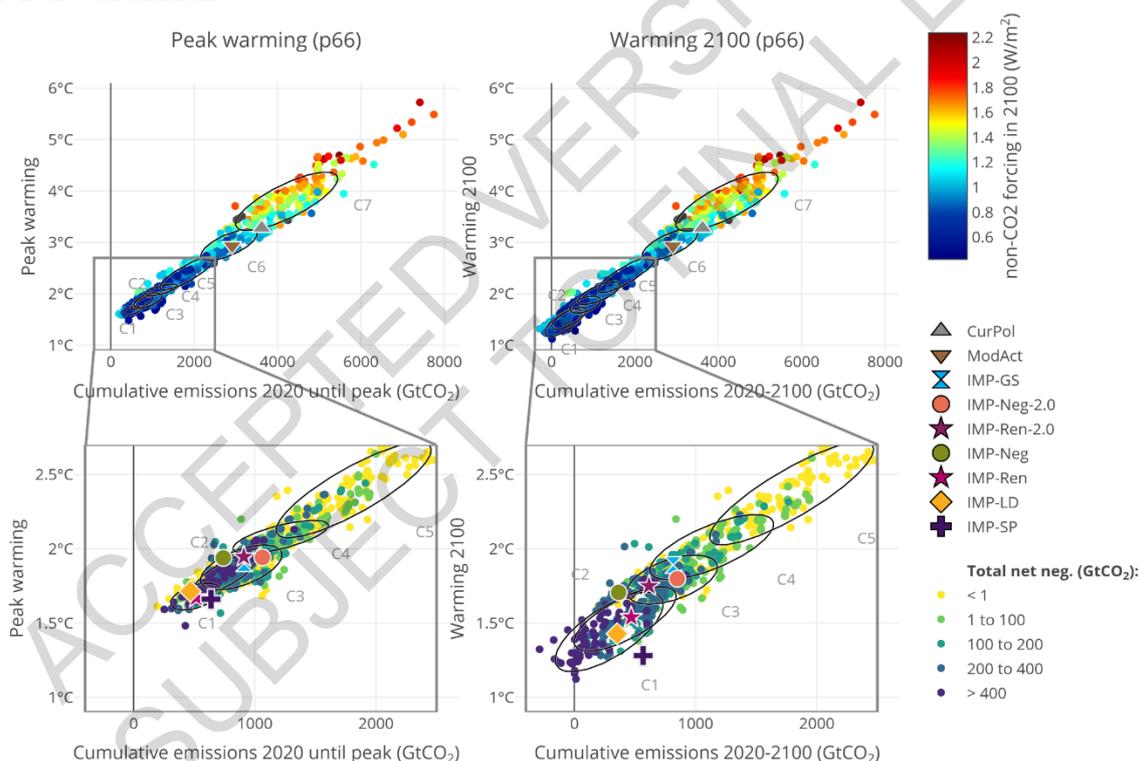
1 A detailed comparison of the impact of different assessment steps, i.e., the new emulators, scenarios,  
2 and harmonisation methods, has been made and is presented in Annex III.

### 3 *Policy implications*

4 The concept of a finite carbon budget means that the world needs to get to net zero CO<sub>2</sub>, no matter  
5 whether global warming is limited to 1.5°C or well below 2°C (or any other level). Moreover,  
6 exceeding the remaining carbon budget will have consequences by overshooting temperature levels.  
7 Still, the relationship between the timing of net zero and temperature targets is a flexible one, as  
8 discussed further in Cross-Chapter Box 3. It should be noted that national level inventory as used by  
9 UNFCCC for the land use, land-use change and forestry sector are different from the overall concept  
10 of anthropogenic emissions employed by IPCC WG1. For emissions estimates based on these  
11 inventories, the remaining carbon budgets must be correspondingly reduced by approximately 15%,  
12 depending on the scenarios (Grassi et al., 2021) (see also Chapter 7).

13 One of the uncertainties of the remaining carbon budget is the level of non-CO<sub>2</sub> emissions which is a  
14 function of policies and technology development. This represents a point of leverage for policies  
15 rather than an inherent geophysical uncertainty. Stringent non-CO<sub>2</sub> emission reductions hence can  
16 provide – to some degree – an option to reach more stringent climate goals with the same carbon  
17 budget.  
18  
19  
20

### 21 **END BOX HERE**



22 **Figure 3.13: The near-linear relationship between cumulative CO<sub>2</sub> emissions and temperature. The left**  
23 **panel shows cumulative emissions until net zero emission is reached. The right panel shows cumulative**  
24 **emissions until the end of the century, plotted against peak and end-of-century temperature, respectively.**  
25 **Both are shown as a function of non-CO<sub>2</sub> forcing and cumulative net negative CO<sub>2</sub> emissions. Position**  
26 **temperature categories (circles) and IPs are also indicated, including two 2°C sensitivity cases for *Neg***  
27 **(*Neg-2.0*) and *Ren* (*Ren-2.0*).**  
28

29 The near-linear relationship implies that cumulative CO<sub>2</sub> emissions are critically important for climate  
30 outcomes (Collins et al. 2013). The maximum temperature increase is a direct function of the  
31 cumulative emissions until net zero CO<sub>2</sub> emissions is reached (the emission budget) (Figure 3.13, left  
32 side). The end-of-century temperature correlates well with cumulative emissions across the century

1 (right panel). For long-term climate goals, positive emissions in the first half of the century can be  
2 offset by net removal of CO<sub>2</sub> from the atmosphere (net negative emissions) at the cost of a temporary  
3 overshoot of the target (Tokarska et al. 2019). The bottom panels of Figure 3.13 show the contribution  
4 of net negative CO<sub>2</sub> emissions.

5  
6 Focusing on cumulative emissions, the right-hand panel of Figure 3.12 shows that for high-end  
7 scenarios (C6-C7), most emissions originate from fossil fuels, with a smaller contribution from net  
8 deforestation. For C5 and lower, there is also a negative contribution to emissions from both AFOLU  
9 emissions and energy systems. For the energy systems, these negative emissions originate from bio-  
10 energy-and-carbon-capture-and-storage (BECCS), while for AFOLU, they originate from re- and  
11 afforestation. For C3-C5, reforestation has a larger CDR contribution than BECCS, mostly due to  
12 considerably lower costs (Rochedo et al. 2018). For C1 and C2, the tight carbon budgets imply in  
13 many scenarios more CDR use (Riahi et al. 2021). Please note that net negative emissions are not so  
14 relevant for peak temperature targets, and thus the C1 category, but CDR can still be used to offset the  
15 remaining positive emissions (Riahi et al. 2021). While positive CO<sub>2</sub> emissions from fossil fuels are  
16 significantly reduced, inertia and hard-to-abate sectors imply that in many C1-C3 scenarios, around  
17 800-1000 GtCO<sub>2</sub> of net positive cumulative CO<sub>2</sub> emissions remain. This is consistent with literature  
18 estimates that current infrastructure is associated with 650 GtCO<sub>2</sub> (best estimate) if operated until the  
19 end of its lifetime (Tong et al. 2019). These numbers are considerably above the estimated carbon  
20 budgets for 1.5 °C estimated in WGI, hence explaining CDR reliance (either to offset emissions  
21 immediately or later in time).

22  
23 Creating net negative emissions can thus be an important part of a mitigation strategy to offset  
24 remaining emissions or compensate for emissions earlier in time. As indicated above, there are  
25 different ways to potentially achieve this, including re- and afforestation and BECCS (as often  
26 covered in IAMs) but also soil carbon enhancement, direct air carbon capture and storage (DACCS)  
27 and ocean alkalization (see Chapter 12). Except for reforestation, these options have not been tested  
28 at large scale and often require more R&D. Moreover, the reliance on CDR in scenarios has been  
29 discussed given possible consequences of land use related to biodiversity loss and food security  
30 (BECCS and afforestation), the reliance on uncertain storage potentials (BECCS and DACCS), water  
31 use (BECCS), energy use (DACCS), the risks of possible temperature overshoot and the  
32 consequences for meeting sustainable development goals (Venton 2016; Peters and Geden 2017;  
33 Smith et al. 2016; van Vuuren et al. 2017; Anderson and Peters 2016; Honegger et al. 2021). In the  
34 case of BECCS, it should be noted that bio-energy typically is associated with early-on positive CO<sub>2</sub>  
35 emissions and net-negative effects are only achieved in time (carbon debt), and its potential is limited  
36 (Cherubini et al. 2013; Hanssen et al. 2020) (most IAMs have only a very limited representation of  
37 these time dynamics). Several scenarios have therefore explored how reliance on net negative CO<sub>2</sub>  
38 emissions can be reduced or even avoided by alternative emission strategies (Grubler et al. 2018; van  
39 Vuuren et al. 2018) or early reductions by more stringent emission reduction in the short-term (Rogelj  
40 et al. 2019b; Riahi et al. 2021). A more in-depth discussion of land-based mitigation options can be  
41 found in Chapter 7. It needs to be emphasized that even in strategies with net negative CO<sub>2</sub> emissions,  
42 the emission reduction via more conventional mitigation measures (efficiency improvement,  
43 decarbonisation of energy supply) is much larger than the CDR contribution (Tsutsui et al. 2020).

### 44 45 **3.3.2.3 The timing of net zero emissions**

46  
47 In addition to the constraints on change in global mean temperature, the Paris Agreement also calls for  
48 reaching a balance of sources and sinks of GHG emissions (Art. 4). Different interpretations of the  
49 concept related to balance have been published (Rogelj et al. 2015c; Fuglestedt et al. 2018). Key  
50 concepts include that of net zero CO<sub>2</sub> emissions (anthropogenic CO<sub>2</sub> sources and sinks equal zero)  
51 and net zero greenhouse gas emission (see also Annex I Glossary and Box 3.3). The same notion can  
52 be used for all GHG emissions, but here ranges also depend on the use of equivalence metrics  
53 (Chapter 2, Box 2.2). Moreover, it should be noted that while reaching net zero CO<sub>2</sub> emissions  
54 typically coincides with the peak in temperature increase; net zero GHG emissions (based on GWP-  
55 100) implies a decrease in global temperature (Riahi et al. 2021) and net zero GHG emission typically

1 requires negative CO<sub>2</sub> emissions to compensate for the remaining emissions from other GHGs. Many  
2 countries have started to formulate climate policy in the year that net zero emissions (either CO<sub>2</sub> or all  
3 greenhouse gases) are reached – although, at the moment, formulations are often still vague (Rogelj et  
4 al. 2021). There has been increased attention on the timing of net zero emissions in the scientific  
5 literature and ways to achieve it.

6  
7 Figure 3.14 shows that there is a relationship between the temperature target, the cumulative CO<sub>2</sub>  
8 emissions budget, and the net zero year for CO<sub>2</sub> emissions (left) and the sum of greenhouse gases  
9 (right) for the scenarios published in the literature. In other words, the temperature targets from the  
10 Paris Agreement can, to some degree, be translated into a net zero emission year (Tanaka and O'Neill  
11 2018). There is, however, a considerable spread. In addition to the factors influencing the emission  
12 budget (see WGI and section 3.3.2.2), this is influenced by the emission trajectory until net zero is  
13 reached, decisions related to temperature overshoot and non-CO<sub>2</sub> emissions (especially for the  
14 moment CO<sub>2</sub> reaches net zero emissions). Scenarios with limited or no net negative emissions and  
15 rapid near-term emission reductions can allow small positive emissions (e.g., in hard-to-abate-  
16 sectors). They may therefore have a later year that net zero CO<sub>2</sub> emissions are achieved. High  
17 emissions in the short-term, in contrast, require an early net zero year.

18  
19 For the scenarios in the C1 category (warming below 1.5°C (50% probability) with limited  
20 overshoot), the net zero year for CO<sub>2</sub> emissions is typically around 2035-2070. For scenarios in C3  
21 (likely limiting warming to below 2°C), CO<sub>2</sub> emissions reach net zero around 2060-2100. Similarly,  
22 also the years for net zero GHG emissions can be calculated (see right graph). The GHG net zero  
23 emissions year is typically around 10-20 years later than the carbon neutrality. Residual non-CO<sub>2</sub>  
24 emissions at the time of reaching net zero CO<sub>2</sub> range between 4-11 GtCO<sub>2</sub>-eq in pathways that *likely*  
25 limit warming to 2.0°C or below. In pathways likely limiting warming to 2°C, methane is reduced by  
26 around 20% (1-46%) in 2030 and almost 50% (26-64%) in 2050, and in pathways limiting warming to  
27 1.5°C with no or limited overshoot by around 33% (19-57) in 2030 and a similar 50% (33-69%) in  
28 2050. Emissions reduction potentials assumed in the pathways become largely exhausted when  
29 limiting warming to below 2°C. N<sub>2</sub>O emissions are reduced too, but similar to CH<sub>4</sub>, emission  
30 reductions saturate for stringent climate goals. In the mitigation pathways, the emissions of cooling  
31 aerosols are reduced due to reduced use of fossil fuels. The overall impact on non-CO<sub>2</sub>-related  
32 warming combines these factors.

33 In cost-optimal scenarios, regions will mostly achieve net zero emissions as a function of options for  
34 emission reduction, CDR, and expected baseline emission growth (van Soest et al. 2021b). This  
35 typically implies relatively early net zero emission years in scenarios for the Latin America region and  
36 relatively late net zero years for Asia and Africa (and average values for OECD countries). However,  
37 an allocation based on equity principles (such as responsibility, capability and equality) might result  
38 in different carbon neutrality years, based on the principles applied – with often earlier net zero years  
39 for the OECD (Fyson et al. 2020; van Soest et al. 2021b). Therefore, the emission trajectory until net  
40 zero emissions is a critical determinant of future warming (see Section 3.5). The more CO<sub>2</sub> is emitted  
41 until 2030, the less CO<sub>2</sub> can be emitted after that to stay below a warming limit (Riahi et al. 2015). As  
42 discussed before, also non-CO<sub>2</sub> forcing plays a key role in the short term.

## 43 44 **START CCB HERE**

### 45 46 **Cross-Chapter Box 3: Understanding net zero CO<sub>2</sub> and net zero GHG emissions**

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4  
5 This cross-chapter box surveys scientific, technical and policy aspects of net zero carbon dioxide  
6 (CO<sub>2</sub>) and net zero greenhouse gas (GHG) emissions, with a focus on timing, the relationship with  
7 warming levels, and sectoral and regional characteristics of net zero emissions. Assessment of net  
8 zero GHG emissions additionally requires consideration of non-CO<sub>2</sub> gases and choice of GHG  
9 emission metrics used to aggregate emissions and removals of different GHGs (Cross-Chapter Box 2  
10 in Chapter 2; Cross-Chapter Box 7 in Chapter 10). The following considers net zero CO<sub>2</sub> and GHG  
11 emissions globally, followed by regional and sectoral dimensions.

12  
13 *Net zero CO<sub>2</sub>*

14 **Reaching net zero CO<sub>2</sub> emissions globally is necessary for limiting global warming to any level.**

15 At the point of net zero CO<sub>2</sub>, the amount of CO<sub>2</sub> human activity is putting into the atmosphere equals  
16 the amount of CO<sub>2</sub> human activity is removing from the atmosphere (see Glossary). Reaching and  
17 sustaining net zero CO<sub>2</sub> emissions globally stabilizes CO<sub>2</sub>-induced warming. Reaching net zero CO<sub>2</sub>  
18 emissions and then moving to net negative CO<sub>2</sub> emissions globally leads to a peak and decline in  
19 CO<sub>2</sub>-induced warming (WGI AR6 Chapter 5.5, 5.6).

20 **Limiting warming to 1.5°C or likely to 2°C requires deep, rapid, and sustained reductions of**  
21 **other greenhouse gases including methane alongside rapid reductions of CO<sub>2</sub> emissions to net**  
22 **zero.** This ensures that the warming contributions from non-CO<sub>2</sub> forcing agents as well as from CO<sub>2</sub>  
23 emissions are both limited at low levels. WGI estimated remaining carbon budgets until the time of  
24 reaching net zero CO<sub>2</sub> emissions for a range of warming limits, taking into account historical CO<sub>2</sub>  
25 emissions and projections of the warming from non-CO<sub>2</sub> forcing agents (WGI AR6 Chapter 5.5,  
26 Cross-chapter box 3).

27 **The earlier global net zero CO<sub>2</sub> emissions are reached, the lower the cumulative net amount of**  
28 **CO<sub>2</sub> emissions and human-induced global warming, all else being equal** (Figure 1a in this Box).  
29 For a given net zero date, a variation in the shape of the CO<sub>2</sub> emissions profile can lead to a variation  
30 in the cumulative net amount of CO<sub>2</sub> emissions until the time of net zero CO<sub>2</sub> and as a result to  
31 different peak warming levels. For example, cumulative net CO<sub>2</sub> emissions until the time of reaching  
32 net zero CO<sub>2</sub> will be smaller, and peak warming lower, if emissions are reduced steeply and then more  
33 slowly compared to reducing emissions slowly and then more steeply (Figure 1b in this Box).

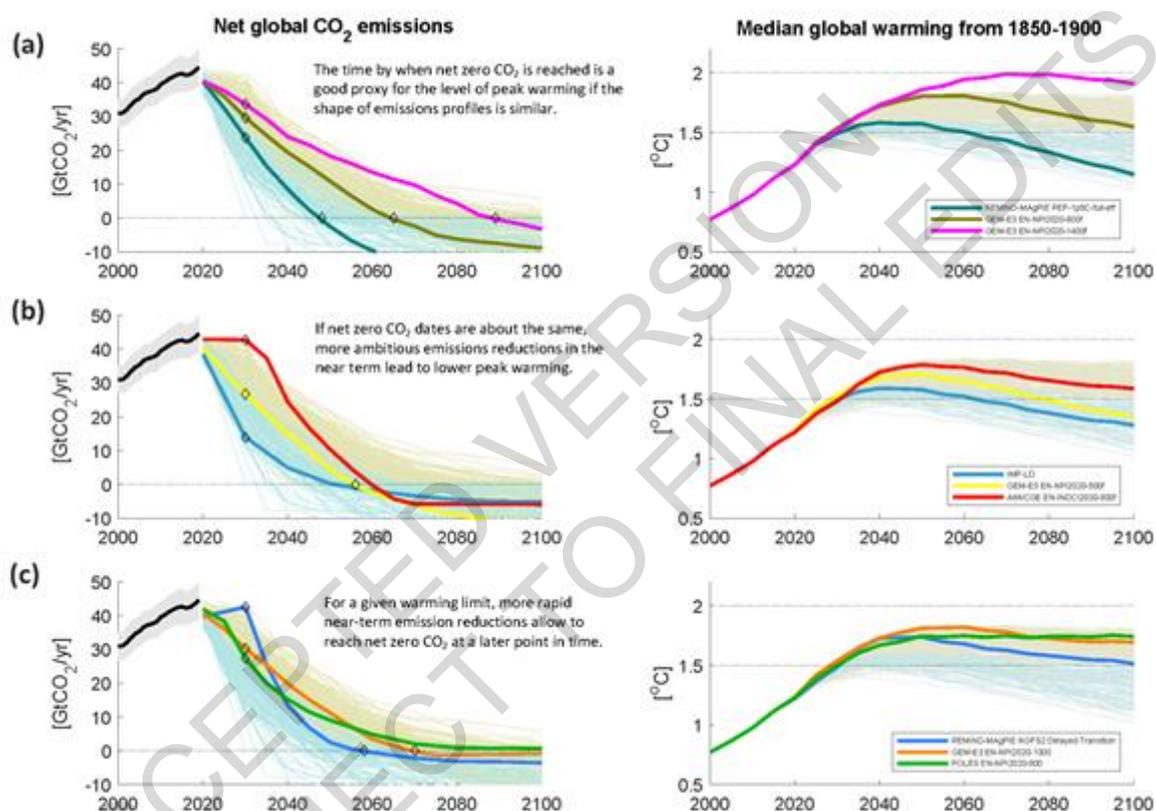
34 **Net zero CO<sub>2</sub> emissions are reached between 2050-2055 (2035-2070) in global emissions**  
35 **pathways limiting warming to 1.5°C with no or limited overshoot, and between 2070-2075**  
36 **(2060-...) in pathways likely limiting warming to 2°C as reported in the AR6 scenario database**  
37 **(median five-year interval and 5<sup>th</sup>-95<sup>th</sup> percentile ranges)<sup>3</sup>.** The variation of non-CO<sub>2</sub> emissions in 1.5-  
38 2°C pathways varies the available remaining carbon budget which can move the time of reaching net  
39 zero CO<sub>2</sub> in these pathways forward or backward<sup>4</sup>. The shape of the CO<sub>2</sub> emissions reduction profile

---

FOOTNOTE <sup>3</sup> A small fraction of pathways in the AR6 scenarios database that likely limit warming to 2°C (9%) or are as likely as not to limit warming to 2°C (14%) do not reach net-zero CO<sub>2</sub> emissions during the 21st century. This is not inconsistent with the fundamental scientific requirement to reach net-zero CO<sub>2</sub> emissions for a stable climate, but reflects that in some pathways, concurrent reductions in non-CO<sub>2</sub> emissions temporarily compensate for on-going warming from CO<sub>2</sub> emissions. These would have to reach net-zero CO<sub>2</sub> emissions eventually after 2100 to maintain these warming limits. For the two classes of pathways, the 95th percentile cannot be deduced from the scenario database as more than 5% of them do not reach net zero CO<sub>2</sub> by 2100.

FOOTNOTE <sup>4</sup> WGI Chapter 5.5 estimates a variation of the remaining carbon budget by ± 220 GtCO<sub>2</sub> due to variations of the non-CO<sub>2</sub> warming contribution in 1.5-2°C pathways. This translates to a shift of the timing of

1 also affects the time of reaching net zero CO<sub>2</sub> (Figure 1c in this Box). Global emission pathways that  
 2 more than halve CO<sub>2</sub> emissions from 2020 to 2030 can follow this rapid reduction by a more gradual  
 3 decline towards net zero CO<sub>2</sub> and still limit warming to 1.5°C with no or limited overshoot, reaching  
 4 the point of net zero after 2050. The literature since SR1.5 included a larger fraction of such pathways  
 5 than were available at the time of SR1.5. This is the primary reason for the small backward shift in the  
 6 median estimate of reaching global net zero CO<sub>2</sub> emissions in 1.5°C pathways collected in the AR6  
 7 scenario database compared to SR1.5. This does not mean that the world is assessed to have more  
 8 time to rapidly reduce current emissions levels compared to SR1.5. The assessment of emissions  
 9 reductions by 2030 and 2040 in pathways limiting warming to 1.5°C with no or limited overshoot has  
 10 not changed substantially. It only means that the exact timing of reaching net zero CO<sub>2</sub> after a steep  
 11 decline of CO<sub>2</sub> emissions until 2030 and 2040 can show some variation, and the SR1.5 median value  
 12 of 2050 is still close to the middle of the current range (Figure 1c in this Box ).



13

14 **Cross-Chapter Box 3 Figure 1: Selected global CO<sub>2</sub> emissions trajectories with similar shape and**  
 15 **different net zero CO<sub>2</sub> date (Panel a), different shape and similar net zero CO<sub>2</sub> date (Panel b), and similar**  
 16 **peak warming, but varying shapes and net zero CO<sub>2</sub> dates (Panel c). Funnels show pathways limiting**  
 17 **warming to 1.5°C with no or limited overshoot (light blue) and likely limiting warming to 2°C (beige).**  
 18 **Historic CO<sub>2</sub> emissions from Chapter 2.2 (EDGAR v6).**

19 **Pathways coinciding with emissions levels projected from the implementation of current NDCs**  
 20 **would result in substantially (>0.1°C) exceeding 1.5°C. They would have to reach net zero CO<sub>2</sub>**

net zero CO<sub>2</sub> by about ±10 years, assuming global CO<sub>2</sub> emissions decrease linearly from current levels of around 40 GtCO<sub>2</sub> to net zero.

1 **around 5-10 years later<sup>5</sup> than in pathways with no or limited overshoot in order to reach the net**  
2 **negative emissions that would then be required to return warming to 1.5°C by 2100.** Those high  
3 overshoot pathways have higher transient warming and higher reliance on net-negative CO<sub>2</sub> emissions  
4 towards the end of the 21st century. As they need to reach net zero CO<sub>2</sub> only a few years later, with  
5 2030 CO<sub>2</sub> emission levels being around twice as high, they imply post-2030 CO<sub>2</sub> emissions reduction  
6 rates that are almost double that of pathways limiting warming to 1.5°C with no or limited overshoot  
7 (Section 3.5).

8 **Pathways following emissions levels projected from the implementation of current NDCs until**  
9 **2030 would have to reach net zero CO<sub>2</sub> around 10 years earlier<sup>6</sup> than cost-effective pathways to**  
10 **likely limit warming to 2°C.** While cost-effective pathways take around 50-55 years to reach net  
11 zero CO<sub>2</sub> emissions, those pathways would only have 35-40 years left for transitioning to net zero  
12 CO<sub>2</sub> from 2030 onwards, close to the transition times that 1.5°C pathways are faced with today.  
13 Current CO<sub>2</sub> emissions and 2030 emission levels projected under the current NDCs are in a similar  
14 range. (3.5, 4.2)

15 *Net zero GHG emissions*

16 **The amount of CO<sub>2</sub>-equivalent emissions and the point when net zero GHG emissions are**  
17 **reached in multi-GHG emissions pathways depends on the choice of GHG emissions metric.**  
18 Various GHG emission metrics are available for this purpose<sup>7</sup>. GWP100 is the most commonly used  
19 metric for reporting CO<sub>2</sub>-equivalent emissions and is required for emissions reporting under the  
20 Rulebook of the Paris Agreement. (Cross-Chapter Box 2 in Chapter 2, Annex II section 9, Annex I)

21 **For most choices of GHG emissions metric, reaching net zero GHG emissions requires net**  
22 **negative CO<sub>2</sub> emissions in order to balance residual CH<sub>4</sub>, N<sub>2</sub>O and F-gas emissions.** Under  
23 foreseen technology developments, some CH<sub>4</sub>, N<sub>2</sub>O and F-gas emissions from, e.g., agriculture and  
24 industry will remain over the course of this century. Net negative CO<sub>2</sub> emissions will therefore be  
25 needed to balance these remaining non-CO<sub>2</sub> GHG emissions to obtain net zero GHG emissions at a  
26 point in time after net zero CO<sub>2</sub> has been reached in emissions pathways. Both the amount of net  
27 negative CO<sub>2</sub> emissions and the time lag to reaching net zero GHG depend on the choice of GHG  
28 emission metric.

29 **Reaching net zero GHG emissions globally in terms of GWP100 leads to a reduction in global**  
30 **warming from an earlier peak.** This is due to net negative CO<sub>2</sub> emissions balancing the GWP100-  
31 equivalent emissions of short lived GHG emissions, which by themselves do not contribute to further  
32 warming if sufficiently declining (Fuglestad et al. 2018; Rogelj et al. 2021). Hence, 1.5-2°C

---

FOOTNOTE <sup>5</sup> Pathways following emissions levels of current NDCs to 2030 and then returning median warming to below 1.5°C in 2100 reach net zero during 2055-2060 (2045-2070) (median five year interval and 5th-95th percentile range).

FOOTNOTE <sup>6</sup> Pathways that follow emission levels projected from the implementation of current NDCs until 2030 and that still likely limit warming to 2°C reach net zero CO<sub>2</sub> emissions during 2065 - 2070 (2060 - ...) compared with 2075 - 2080 (2060 - ...) in cost-effective pathways acting immediately to likely limit warming to 2°C (median five year interval and 5th-95th percentile range). See Footnote 1 for the lack of 95<sup>th</sup> percentile. (Chapter 3.3 Table 3.1.)

FOOTNOTE <sup>7</sup> Defining net zero GHG emissions for a basket of greenhouse gases (GHGs) relies on a metric to convert GHG emissions including methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), fluorinated gases (F-gases), and potentially other gases, to CO<sub>2</sub>-equivalent emissions. The choice of metric ranges from Global Warming Potentials (GWPs) and Global Temperature change Potentials (GTP) to economically-oriented metrics. All metrics have advantages and disadvantages depending on the context in which they are used (Cross-Chapter Box 2 in Chapter 2).

1 emissions pathways in the AR6 scenario database that reach global net zero GHG emissions in the  
2 second half of the century show warming being halted at some peak value followed by a gradual  
3 decline towards the end of the century (WGI Chapter 1 Box 1.4).

4 **Global net zero GHG emissions measured in terms of GWP100 are reached between 2095-2100**  
5 **(2055 - ...)<sup>8</sup> in emission pathways limiting warming to 1.5°C with no or limited overshoot**  
6 (median and 5th-95th percentile). Around 50% of pathways limiting warming to 1.5°C with no or  
7 limited overshoot and 70% of pathways limiting likely warming to 2°C do not reach net zero GHG  
8 emissions in terms of GWP100 before 2100. These pathways tend to show less reduction in warming  
9 after the peak than pathways that reach net zero GHG emissions. For the subset of pathways that  
10 reach net zero GHG emissions before 2100, including 90% of pathways that return warming to 1.5°C  
11 by 2100 after a high (>0.1°C) overshoot, the time lag between reaching net zero CO<sub>2</sub> and net zero  
12 GHG is 11-14 (6-40) years and the amount of net negative CO<sub>2</sub> emissions deployed to balance non-  
13 CO<sub>2</sub> emissions at the time of net zero is -6 to -7 (-10 to -4) GtCO<sub>2</sub> (range of medians and lowest 5th  
14 to highest 95 percentile across the four scenario classes that limit median warming to 2°C or lower).  
15 (section 3.3, Table 3.1)

16 *Sectoral and regional aspects of net zero*

17 **The timing of net zero CO<sub>2</sub> or GHG emissions may differ across regions and sectors. Achieving**  
18 **net zero emissions globally implies that some sectors and regions must reach net zero CO<sub>2</sub> or**  
19 **GHG ahead of the time of global net zero CO<sub>2</sub> or GHG if others reach it later.** Similarly, some  
20 sectors and regions would need to achieve net negative CO<sub>2</sub> or GHG emissions to compensate for  
21 continued emissions by other sectors and regions after the global net zero year. Differences in the  
22 timing to reach net zero emissions between sectors and regions depend on multiple factors, including  
23 the potential of countries and sectors to reduce GHG emissions and undertake carbon dioxide  
24 removal, the associated costs, and the availability of policy mechanisms to balance emissions and  
25 removals between sectors and countries (Fyson et al. 2020; Strefler et al. 2021a; van Soest et al.  
26 2021b). A lack of such mechanisms could lead to higher global costs to reach net zero emissions  
27 globally, but less interdependencies and institutional needs (Fajardy and Mac Dowell 2020). Sectors  
28 will reach net zero CO<sub>2</sub> and GHG emissions at different times if they are aiming for such targets with  
29 sector-specific policies or as part of an economy-wide net zero emissions strategy integrating  
30 emissions reductions and removals across sectors. In the latter case, sectors with large potential for  
31 achieving net-negative emissions would go beyond net zero to balance residual emissions from  
32 sectors with low potential which in turn would take more time compared to the case of sector-specific  
33 action. Global pathways project global AFOLU emissions to reach global net zero CO<sub>2</sub> the earliest,  
34 around 2030-2035 in pathways likely to limit warming to 2°C and below, by rapid reduction of  
35 deforestation and enhancing carbon sinks on land, although net zero GHG emissions from global  
36 AFOLU are typically reached 30 years later, if at all. The ability of global AFOLU CO<sub>2</sub> emissions to  
37 reach net zero as early as in the 2030s in modelled pathways hinges on optimistic assumptions about  
38 the ability to establish global cost-effective mechanisms to balance emissions reductions and removals  
39 across regions and sectors. These assumptions have been challenged in the literature and the Special  
40 Report on Climate Change and Land (IPCC SRCCL).

41 **The adoption and implementation of net zero CO<sub>2</sub> or GHG emission targets by countries and**  
42 **regions also depends on equity and capacity criteria.** The Paris Agreement recognizes that peaking  
43 of emissions will occur later in developing countries (Article 4.1). Just transitions to net zero CO<sub>2</sub> or  
44 GHG could be expected to follow multiple pathways, in different contexts. Regions may decide about  
45 net zero pathways based on their consideration of potential for rapid transition to low-carbon  
46 development pathways, the capacity to design and implement those changes, and perceptions of  
47 equity within and across countries. Cost-effective pathways from global models have been shown to

---

FOOTNOTE <sup>8</sup> The 95th percentile cannot be deduced from the scenario database as more than 5% of pathways do not reach net zero GHG by 2100 (Chapter 3.3 Table 3.1.), hence denoted by -...

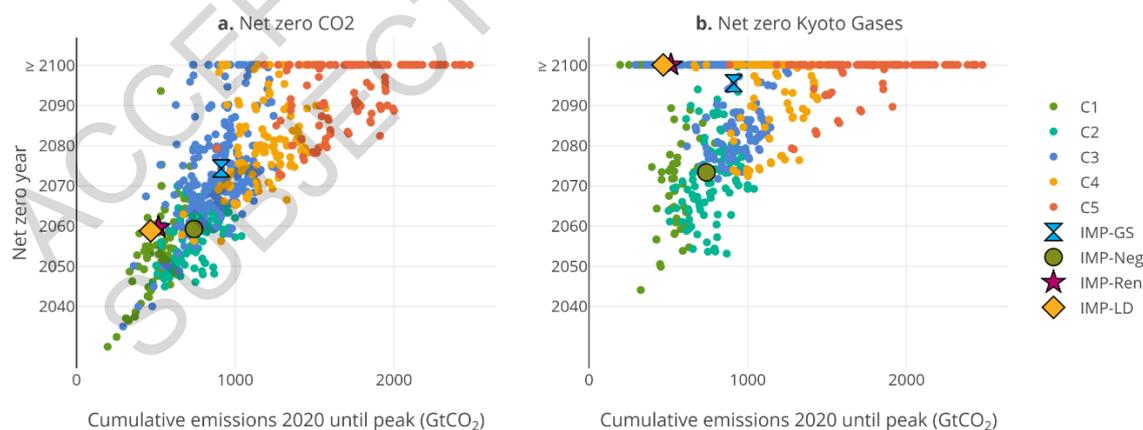
1 distribute the mitigation effort unevenly and inequitably in the absence of financial support  
 2 mechanisms and capacity building (Budolfson et al. 2021), and hence would require additional  
 3 measures to become aligned with equity considerations (Fyson et al. 2020; van Soest et al. 2021b).  
 4 Formulation of net zero pathways by countries will benefit from clarity on scope, roadmaps and  
 5 fairness (Rogelj et al. 2021; Smith 2021). Achieving net zero emission targets relies on policies,  
 6 institutions and milestones against which to track progress. Milestones can include emissions levels,  
 7 as well as markers of technological diffusion.

8 **The accounting of anthropogenic carbon dioxide removal on land matters for the evaluation of**  
 9 **net zero CO<sub>2</sub> and net zero GHG strategies.** Due to the use of different approaches between national  
 10 inventories and global models, the current net CO<sub>2</sub> emissions are lower by 5.5 GtCO<sub>2</sub>, and cumulative  
 11 net CO<sub>2</sub> emissions in modelled 1.5-2°C pathways would be lower by 104-170 GtCO<sub>2</sub>, if carbon  
 12 dioxide removals on land are accounted based on national GHG inventories. National GHG  
 13 inventories typically consider a much larger area of managed forest than global models, and on this  
 14 area additionally consider the fluxes due to human-induced global environmental change (indirect  
 15 effects) to be anthropogenic, while global models consider these fluxes to be natural. Both approaches  
 16 capture the same land fluxes, only the accounting of anthropogenic vs. natural emission is different.  
 17 Methods to convert estimates from global models to the accounting scheme of national GHG  
 18 inventories will improve the use of emission pathways from global models as benchmarks against  
 19 which collective progress is assessed. (7.2.2.5, Cross-Chapter Box 3 in this chapter)

20 **Net zero CO<sub>2</sub> and carbon neutrality have different meanings in this assessment, as is the case for**  
 21 **net zero GHG and GHG neutrality. They apply to different boundaries in the emissions and**  
 22 **removals being considered.** Net zero (GHG or CO<sub>2</sub>) refers to emissions and removals under the  
 23 direct control or territorial responsibility of the reporting entity. In contrast, (GHG or carbon)  
 24 neutrality includes anthropogenic emissions and anthropogenic removals within and also those  
 25 beyond the direct control or territorial responsibility of the reporting entity. At the global scale, net  
 26 zero CO<sub>2</sub> and carbon neutrality are equivalent, as is the case for net zero GHG and GHG neutrality.  
 27 The term “climate neutrality” is not used in this assessment because the concept of climate neutrality  
 28 is diffuse, used differently by different communities, and not readily quantified.

29 **END BOX HERE**

30



31  
 32 **Figure 3.14: Net zero year for CO<sub>2</sub> and all GHGs (based on AR6 GWP-100) as a function of remaining**  
 33 **carbon budget and temperature outcomes (not that stabilize (near) zero are also included in determining**  
 34 **the net zero year)**

35 Table 3.2 summarizes the key characteristics for all temperature categories in terms of cumulative  
 36 CO<sub>2</sub> emissions, near-term emission reductions, and the years of peak emission and net zero CO<sub>2</sub> and  
 37 GHG emissions. The table shows again that many pathways in the literature likely limit global  
 38 warming to 2°C or limit warming to 1.5°C with limited overshoot compared to preindustrial levels.

1 Cumulative net CO<sub>2</sub> emissions from the year 2020 until the time of net zero CO<sub>2</sub> in pathways that  
2 limit warming to 1.5°C with no or limited overshoot are 510 (330-710) GtCO<sub>2</sub> and in pathways *likely*  
3 to limit warming to below 2.0°C 890 (640-1160) GtCO<sub>2</sub> (see also Cross-Chapter Box 3 in this  
4 chapter). Mitigation pathways *likely* to limit global warming to 2°C compared to pre-industrial levels  
5 are associated with net global GHG emissions of 40 (32–55) GtCO<sub>2</sub>-eq yr<sup>-1</sup> by 2030 and 20 (13-26)  
6 GtCO<sub>2</sub>-eq yr<sup>-1</sup> in 2050. These correspond to GHG emissions reductions of 21 (1-42) % by 2030, and  
7 64 (53-77) % by 2050 relative to 2019 emission levels. Pathways that limit global warming to below  
8 1.5°C with no or limited overshoot require a further acceleration in the pace of the transformation,  
9 with GHG emissions reductions of 43 (34–60) % by 2030 and 84 (74–98) % in 2050 relative to  
10 modelled 2019 emission levels. The likelihood of limiting warming to below 1.5°C with no or limited  
11 overshoot of the most stringent mitigation pathways in the literature (C1) has declined since SR1.5.  
12 This is because emissions have risen since 2010 by about 9 GtCO<sub>2</sub> yr<sup>-1</sup>, resulting in relatively higher  
13 near-term emissions of the AR6 pathways by 2030 and slightly later dates for reaching net zero CO<sub>2</sub>  
14 emissions compared to SR1.5

15  
16 Given the larger contribution of scenarios in the literature that aim to reduce net-negative emissions,  
17 emission reductions are somewhat larger in the short-term compared to similar categories in the IPCC  
18 SR1.5. At the same time, the year of net zero emissions is somewhat later (but only if these rapid,  
19 short-term emission reductions are achieved). The scenarios in the literature in C1-C3 show a peak in  
20 global emissions before 2025. Not achieving this requires a more rapid reduction after 2025 to still  
21 meet the Paris goals (see Section 3.5).  
22

1  
2

**Table 3.2 GHG, CO<sub>2</sub> emissions and warming characteristics of different mitigation pathways submitted to the AR6 scenarios database and as categorized in the climate assessment.**

p50 (p5-p95) <sup>(6)</sup>	Global Mean Surface Air Temperature change	GHG emissions Gt CO <sub>2</sub> -eq/yr	GHG emissions reductions from 2019 % <sup>(8)</sup>	Emissions milestones <sup>(6,7)</sup>				Cumulative CO <sub>2</sub> emissions Gt CO <sub>2</sub> <sup>(9)</sup>		Cumulative net- negative CO <sub>2</sub> emissions Gt CO <sub>2</sub>	Temperature change 50% probability <sup>(10)</sup> °C		Likelihood of staying below (%) <sup>(11)</sup>			Time when specific temperature levels are reached (with a 50% probability)							
				2030	2040	2050	2030	2040	2050		Peak CO <sub>2</sub> emissions	Peak GHG emissions	net-zero CO <sub>2</sub> [% net-zero pathways]	net-zero GHGs <sup>(8)</sup> [% net-zero pathways]	2020 to net-zero CO <sub>2</sub>	2020-2100	year of net-zero CO <sub>2</sub> to 2100	at peak warming	2100	<1.5°C	<2.0°C	<3.0°C	1.5°C
<b>C1</b> [97]	Below 1.5°C with no or limited overshoot	SP, LD Ren, SSP1-1.9	31 (21-36)	17 (6-23)	9 (1-15)	43 (34-60)	69 (58-90)	84 (73-98)	2020-2025 [100%] (2020-2025)	2020-2025 [100%] (2020-2025)	2050-2055 [100%] (2020-2025)	2095-2100 [52%] (2050-...)	510 (330-710)	320 (-210-570)	-200 (-560-0)	1.6 (1.3-1.6)	1.3 (0.8-1.5)	38 (33-73)	90 (86-98)	100 (99-100)	2030-2035 [90%] (2030-...)	... [0%] (...)	... [0%] (...)
<b>C2</b> [103]	Below 1.5°C with high overshoot	Neg	42 (31-55)	25 (16-34)	14 (5-21)	23 (0-44)	55 (40-71)	75 (62-91)	2020-2025 [100%] (2020-2030)	2020-2025 [100%] (2020-2030)	2055-2060 [100%] (2045-2070)	2070-2075 [87%] (2055-...)	720 (540-930)	400 (-90-620)	-330 (-620--30)	1.7 (1.4-1.8)	1.4 (0.8-1.5)	24 (15-58)	82 (71-95)	100 (99-100)	2030-2035 [100%] (2030-2035)	... [0%] (...)	... [0%] (...)
<b>C3</b> [311]	Likely below 2°C	SSP2-2.6	44 (32-55)	29 (20-36)	20 (13-26)	21 (1-42)	46 (34-63)	64 (53-77)	2020-2025 [100%] (2020-2030)	2020-2025 [100%] (2020-2030)	2070-2075 [91%] (2060-...)	... [30%] (2075-...)	890 (640-1160)	800 (500-1140)	-40 (-280-0)	1.7 (1.4-1.8)	1.6 (1.1-1.8)	20 (13-66)	76 (68-97)	99 (98-100)	2030-2035 [100%] (2030-2040)	... [0%] (...)	... [0%] (...)
<b>C3a</b> [204]	Immediate action		41 (30-49)	29 (21-36)	20 (13-27)	26 (12-46)	47 (35-63)	63 (52-77)	2020-2025 [100%] (2020-2025)	2020-2025 [100%] (2020-2025)	2070-2075 [88%] (2060-...)	... [24%] (2080-...)	880 (640-1180)	790 (480-1160)	-20 (-280-0)	1.7 (1.4-1.8)	1.6 (1.1-1.8)	22 (14-71)	78 (69-97)	100 (98-100)	2030-2035 [100%] (2030-2040)	... [0%] (...)	... [0%] (...)
<b>C3b</b> [97]	NDCs	GS	52 (47-55)	29 (20-36)	18 (10-25)	5 (0-14)	46 (34-63)	68 (56-82)	2020-2025 [100%] (2020-2030)	2020-2025 [100%] (2020-2030)	2065-2070 [96%] (2060-2100)	... [42%] (2075-...)	910 (720-1150)	800 (560-1050)	-70 (-300-0)	1.8 (1.4-1.8)	1.6 (1.1-1.7)	17 (12-61)	73 (67-96)	99 (98-99)	2030-2035 [100%] (2030-2035)	... [0%] (...)	... [0%] (...)
<b>C4</b> [153]	Below 2°C		50 (41-56)	38 (28-43)	28 (19-35)	10 (0-27)	31 (20-50)	49 (35-65)	2020-2025 [100%] (2020-2030)	2020-2025 [100%] (2020-2030)	2075-2080 [86%] (2065-...)	... [31%] (2075-...)	1210 (970-1500)	1160 (700-1490)	-30 (-390-0)	1.9 (1.5-2.0)	1.8 (1.2-2.0)	11 (7-50)	59 (50-93)	98 (95-99)	2030-2035 [100%] (2030-2035)	... [0%] (...)	... [0%] (...)
<b>C5</b> [212]	Below 2.5°C		52 (46-56)	45 (36-52)	39 (30-49)	6 (-1-18)	18 (4-33)	29 (11-48)	2020-2025 [100%] (2020-2035)	2020-2025 [100%] (2020-2035)	... [40%] (2075-...)	... [11%] (2090-...)	1780 (1400-2360)	1780 (1260-2360)	0 (-140-0)	2.2 (1.6-2.5)	2.1 (1.5-2.5)	4 (0-28)	37 (18-84)	91 (83-99)	2030-2035 [100%] (2030-2035)	2060-2065 [99%] (2055-2095)	... [0%] (...)
<b>C6</b> [97]	Below 3°C	SSP2-4.5 Mod-Act	54 (50-62)	53 (48-61)	52 (45-57)	2 (-10-11)	3 (-14-14)	5 (-2-18)	2030-2035 [100%] (2020-2085)	2030-2035 [100%] (2020-2085)	... [0%] (...)	... [0%] (...)	2790 (2440-3520)	2790 (2440-3520)	0 (0-0)	2.7 (2.0-2.9)	2.7 (2.0-2.9)	0 (0-2)	8 (2-45)	71 (53-96)	2030-2035 [100%] (2030-2035)	2050-2055 [100%] (2045-2060)	... [0%] (...)
<b>C7</b> [164]	Below 4°C	SSP3-7.0 Cur-Pol	62 (53-69)	67 (56-76)	70 (58-83)	-11 (-18-3)	-19 (-31-0)	-24 (-41--2)	2090-2095 [100%] (2035-2100)	2090-2095 [100%] (2035-2100)	... [0%] (...)	... [0%] (...)	4220 (3160-5000)	4220 (3160-5000)	0 (0-0)	3.5 (2.5-3.9)	3.5 (2.5-3.9)	0 (0-0)	0 (0-5)	22 (7-80)	2030-2035 [100%] (2030-2035)	2045-2050 [100%] (2045-2055)	2080-2085 [100%] (2070-2100)
<b>C8</b> [29]	Above 4°C	SSP5-8.5	71 (68-80)	79 (77-96)	87 (82-112)	-20 (-34--17)	-35 (-66-29)	-46 (-92--36)	2080-2085 [100%] (2060-2100)	2080-2085 [100%] (2060-2100)	... [0%] (...)	... [0%] (...)	5600 (4910-7450)	5600 (4910-7450)	0 (0-0)	4.2 (3.3-5.0)	4.2 (3.3-5.0)	0 (0-0)	0 (0-0)	4 (0-27)	2030-2035 [100%] (2025-2035)	2040-2045 [100%] (2040-2050)	2065-2070 [100%] (2060-2075)

3  
4

0 Values in the table refer to the 50th and (5th-95th) percentile values. For emissions-related columns this relates to the distribution of all the scenarios in that category. For Temperature Change and Likelihood columns, single upper row values are the 50th percentile value across scenarios in that Category for the MAGICC climate model emulator.

For the bracketed ranges for temperatures and likelihoods, the median warming for every scenario in that category is calculated for each of the three climate model emulators (MAGICC, FaIR and CICERO-SCM). Subsequently, the 5th and 95th percentile values across all scenarios is calculated. The coolest and warmest outcomes (i.e., the lowest p5 of three emulators, and the highest p95, respectively) are shown in the brackets. Thus, these ranges cover the extent of scenario and climate model emulator uncertainty.

1 Category definitions consider at peak warming and warming at the end-of-century (2100).

C1: Below 1.5°C in 2100 with a greater than 50% probability and a peak warming higher than 1.5°C with less than 67% probability.

C2: Below 1.5°C in 2100 with a greater than 50% probability but peak warming higher than 1.5°C with greater than or equal to 67% probability.

C3: Likely below 2°C throughout the century with greater than 67% probability.

C4, C5, C6, C7: Below 2°C, 2.5°C, 3°C and 4°C throughout the century, respectively, with greater than 50% probability.

C8: Peak warming above 4°C with greater than or equal to 50% probability.

2 All warming levels are relative to the pre-industrial temperatures from the 1850-1900 period.

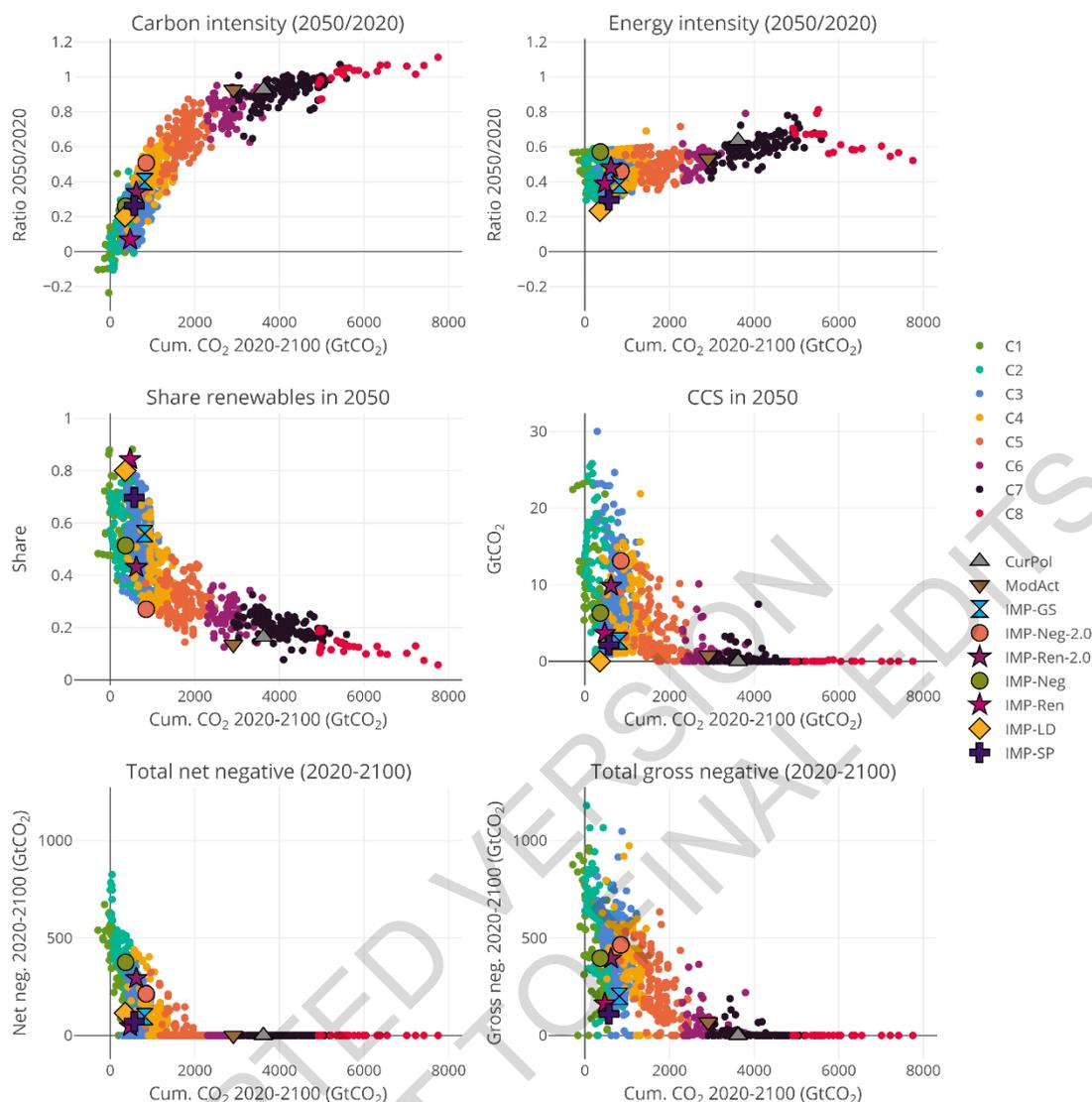
3 The warming profile of **Neg** peaks around 2060 and declines to below 1.5°C (50% likelihood) shortly after 2100. Whilst technically classified as a C3, it strongly exhibits the characteristics of C2 high overshoot scenarios.

- 4 C3 scenarios are sub-categorized according to policy ambition and consistent with Figure SPM 6. Hence the subtotals of C3a & C3b do not match the total of C3 scenarios, as there are C3 scenarios with policy categorizations not covered by C3a and C3b.
- 5 Percentage GHG reduction ranges shown here compare 2019 estimates from historical emissions assessed in Chapter 2 (58 Gt CO<sub>2</sub>) to the harmonized and infilled projections from the models. Negative values (e.g., in C7, C8) represent an increase in emissions.
- 6 Gross, % reductions and emissions milestones are based on model data for CO<sub>2</sub> & GHG emissions, which has been harmonized to 2015 values. See also Footnote 6.
- 7 Percentiles reported across all pathways in that category including pathways that do not reach net zero before 2100 (fraction in square brackets). If the fraction of pathways that reach net zero before 2100 (one minus fraction in square brackets) is lower than the fraction of pathways covered by a percentile (e.g., 0.95 for the 95th percentile), the percentile is not defined and denoted with "...".
- 8 For cases where models do not report all GHGs, missing GHG species are infilled and calculated as Kyoto basket with AR6 GWP-100 CO<sub>2</sub>-equivalent factors. For each scenario, a minimum of native reporting of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions to 2100 was required for the assessment of the climate response and assignment to a climate category. Emissions scenarios without climate assessment are not included in the ranges. See Annex III.
- 9 For better comparability with the WGI assessment of the remaining carbon budget, the cumulative CO<sub>2</sub> emissions of the pathways are harmonized to the 2015 CO<sub>2</sub> emissions levels used in the WGI assessment and are calculated for the future starting on 1 January 2020.
- 10 Temperature change (Global Surface Air Temperature - GSAT) for category (at peak and in 2100), based on the median warming for each scenario assessed using the probabilistic climate model emulators.
- 11 Probability of staying below the temperature thresholds for the scenarios in each category, taking into consideration the range of uncertainty from the climate model emulators consistent with the WGI AR6 assessment. The probabilities refer to the probability at peak temperature. Note that in the case of temperature overshoot (E.g., category C2 and some scenarios in C1), the probabilities at the end of the century are higher than the probability at peak temperature.

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#### 1 3.3.2.4 *Mitigation strategies*

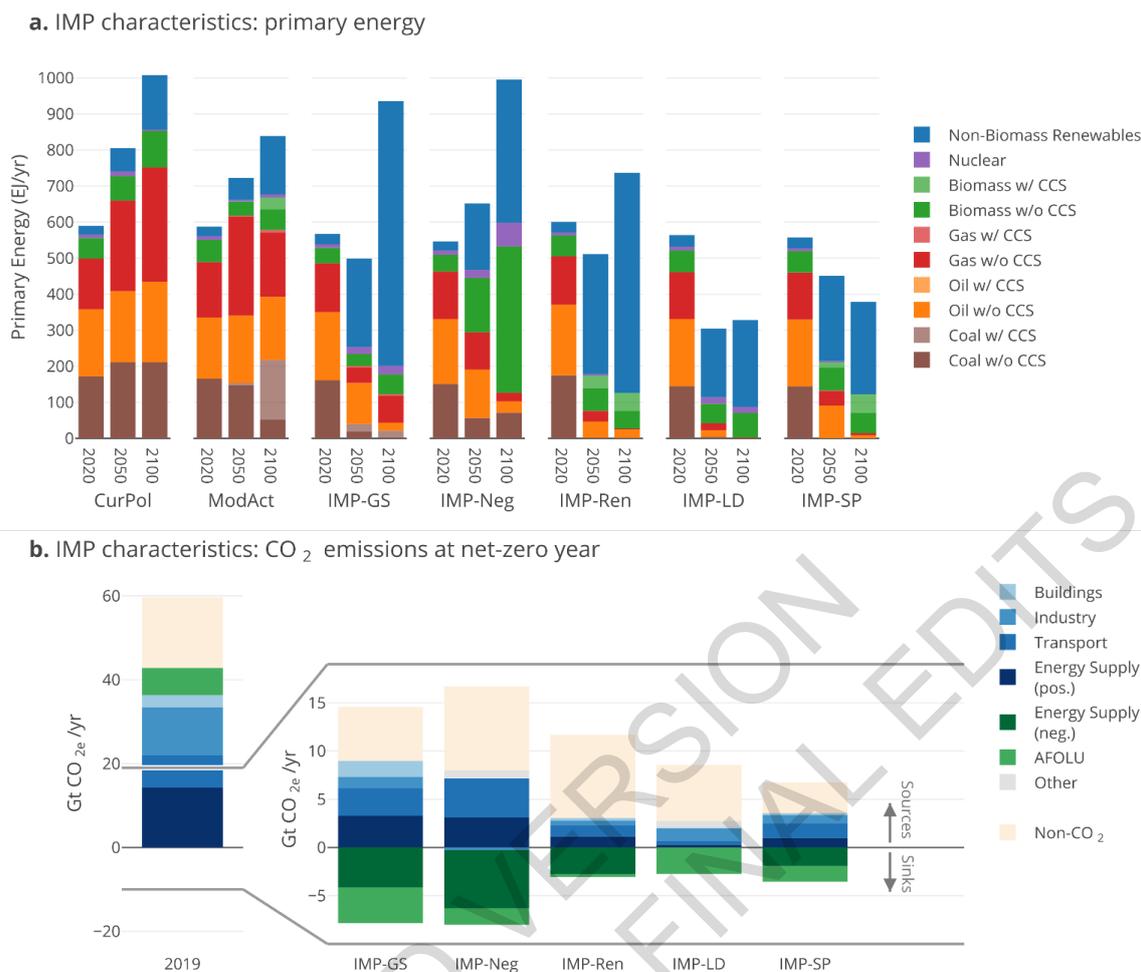
2 Detailed sectoral implications are discussed in Section 3.4 and Chapters 5-11 (see also Table 3.3). The  
3 stringency of climate policy has clear implications for mitigation action (Figure 3.15). There are a  
4 number of important commonalities of pathways likely limiting warming to 2C and below: for  
5 instance, they all rely on significant improvement of energy efficiency, rapid decarbonisation of  
6 supply and, many of them, CDR (in energy supply or AFOLU), either in terms of net negative  
7 emissions or to compensate residual emissions. Still, there are also important differences and the  
8 (IMPs) show how different choices can steer the system into alternative directions with different  
9 combinations of response options. For decarbonisation of energy supply many options exist, including  
10 CCS, nuclear power, and renewables (see Chapter 6). In the majority of the scenarios reaching low  
11 greenhouse targets, a considerable amount of CCS is applied (panel d). The share of renewables is  
12 around 30-70% in the scenarios reaching a global average temperature change of likely below 2°C and  
13 clearly above 40% for scenarios reaching 1.5°C (panel c). Scenarios have been published with 100%  
14 renewable energy systems even at a global scale, partly reflecting the rapid progress made for these  
15 technologies in the last decade (Breyer and Jefferson 2020; Creutzig et al. 2017; Jacobson et al. 2018).  
16 These scenarios do not show in the graph due to a lack of information from non-energy sources. There  
17 is a debate in the literature on whether it is possible to achieve a 100% renewable energy system by  
18 2050 (Brook et al. 2018). This critically depends on assumptions made on future system integration,  
19 system flexibility, storage options, consequences for material demand and the ability to supply high-  
20 temperature functions and specific mobility functions with renewable energy. The range of studies  
21 published showing 100% renewable energy systems show that it is possible to design such systems in  
22 the context of energy system models (Lehtveer and Hedenus 2015a,b; Hong et al. 2014a,b; Zappa et  
23 al. 2019; Pfenninger and Keirstead 2015; Sepulveda et al. 2018; IEA 2021b) (see also Box 6.6 in  
24 Chapter 6 on 100% renewables in net zero CO<sub>2</sub> systems). Panel e and f, finally, show the contribution  
25 of CDR – both in terms of net negative emissions and gross CDR. The contribution of total CDR  
26 obviously exceeds the net negative emissions. It should be noted that while a majority of scenarios  
27 relies on net negative emissions to reach stringent mitigation goals – this is not the case for all of  
28 them.



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

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2  
3  
4  
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6 The spread shown in Figure 3.15 implies different mitigation strategies that could all lead to  
7 emissions levels consistent with the Paris Agreement (and reach zero emissions). The IMPs illustrate  
8 some options for different decarbonization pathways with heavy reliance on renewables (**Ren**), strong  
9 emphasis on energy demand reductions (**LD**), wide-spread deployment of CDR methods coupled with  
10 CCS (BECCS and DACCS) (**Neg**), mitigation in the context of sustainable development (**SP**) (Figure  
11 3.16). For example, in some scenarios, a small part of the energy system is still based on fossil fuels in  
12 2100 (**Neg**), while in others, fossil fuels are almost or completely phased out (**Ren**). Nevertheless, in  
13 all scenarios, fossil fuel use is greatly reduced and unabated coal use is completely phased out by  
14 2050. Also, nuclear power can be part of a mitigation strategy (however, the literature only includes  
15 some scenarios with high-nuclear contributions, such as Berger et al. (2017)). This is explored further  
16 in Section 3.5. The different strategies are also clearly apparent in the way they scenarios reach net  
17 zero emissions. While **GS** and **Neg** rely significantly on BECCS and DACCS, their use is far more  
18 restricted in the other IMPs. Consistently, in these IMPs also residual emissions are also significantly  
19 lower.



**Figure 3.16: Primary energy use and net emissions at net zero year for the different IMPS**

Mitigation pathways also have a regional dimension. In 2010, about 40% of emissions originated from the Developed Countries and Eastern Europe and west-central Asia regions. According to the projections shown in

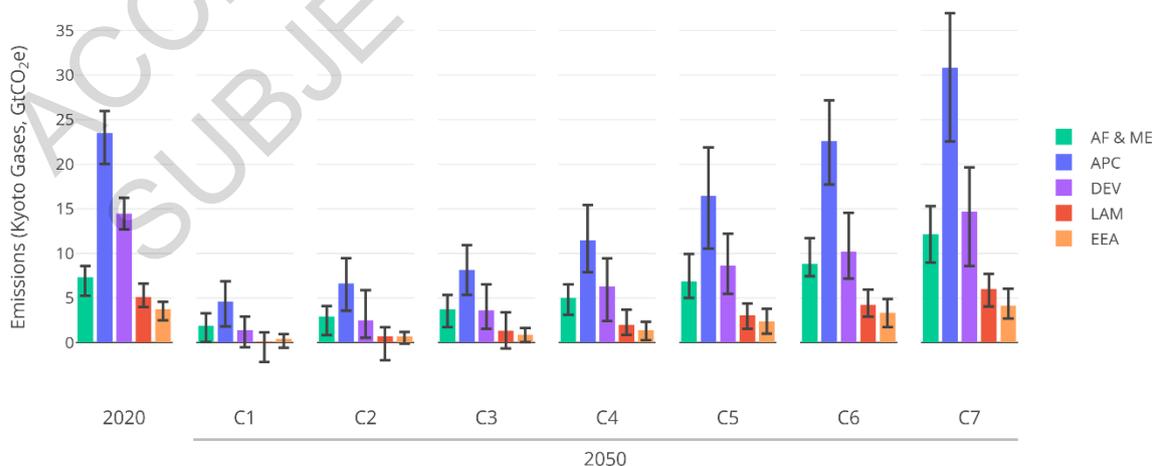


Figure 3.17, the share of the latter regions will further increase to about 70% by 2050. In the scenarios in the literature, emissions are typically almost equally reduced across the regions.

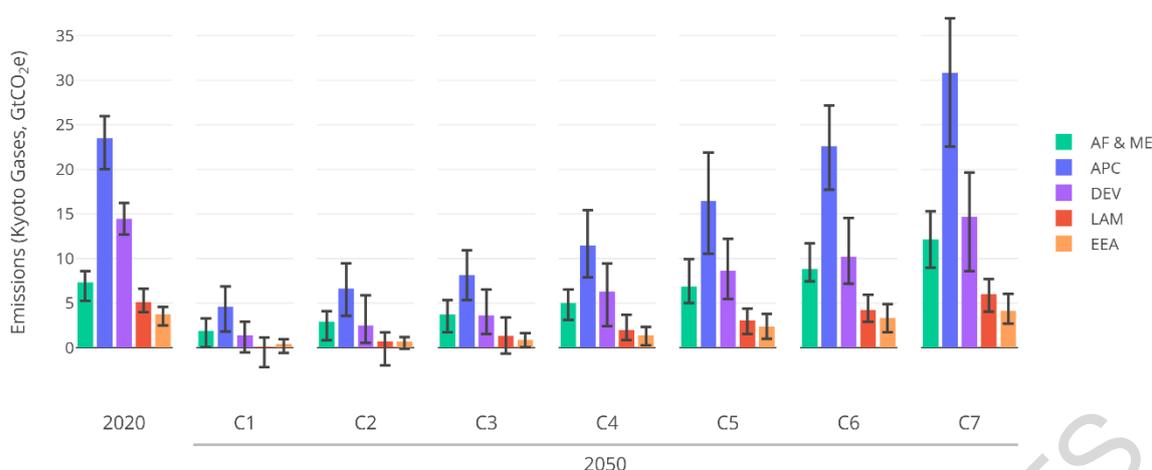


Figure 3.17<sup>9</sup>: Emissions by region (including 5-95<sup>th</sup> percentile range)

### 3.3.3 Climate impacts on mitigation potential

At the moment, climate change impact on mitigation potential is hardly considered in model-based scenarios. While a detailed overview of climate impacts is provided in IPCC WGII and Section 3.6 discusses the economic consequences, here we concentrate on the implications for mitigation potential. Climate change directly impacts the carbon budget via all kinds of feedbacks – which is included in the ranges provided for the carbon budget (e.g., 300-900 GtCO<sub>2</sub> for 17<sup>th</sup>-83<sup>rd</sup> percentile for not exceeding 1.5 °C; see Chapter 5 IPCC, 2021). Climate change, however, alters the production and consumption of energy (see also Chapter 6.5). An overview of the literature is provided by Yalew et al. (2020). In terms of supply, impacts could influence the cooling capacity of thermal plants, the potential and predictability of renewable energy, and energy infrastructure (Cronin et al. 2018a; van Vliet et al. 2016; Turner et al. 2017; Lucena et al. 2018; Gernaat et al. 2021; Yalew et al. 2020). Although the outcomes of these studies differ, they seem to suggest that although impacts might be relatively small at the global scale, they could be substantial at the regional scale (increasing or decreasing potential). Climate change can also impact energy demand, with rising temperatures resulting in decreases in heating demand and increases in cooling demand (Isaac and van Vuuren 2009; Zhou et al. 2014; Labriet et al. 2015; McFarland et al. 2015; Auffhammer et al. 2017; Clarke et al. 2018; van Ruijven et al. 2019; Yalew et al. 2020). As expected, the increase in cooling demand dominates the impact in warm regions and decreases in heating demand in cold regions (Clarke et al. 2018; Zhou et al. 2014; Isaac and van Vuuren 2009). Globally, most studies show a net increase in energy demand at the end of the century due to climate impacts (van Ruijven et al. 2019; Isaac and van Vuuren 2009; Clarke et al. 2018); however, one study shows a net decrease (Labriet et al. 2015). Only a few studies quantify the combined impacts of climate change on energy supply and energy demand (Emodi et al. 2019; Steinberg et al. 2020; McFarland et al. 2015; Mima and Criqui 2015). These studies show increases in electricity generation in the USA (McFarland et al. 2015; Steinberg et al. 2020) and increases in CO<sub>2</sub> emissions in Australia (Emodi et al. 2019) or the USA (McFarland et al. 2015).

Climate change can impact the potential for AFOLU mitigation action by altering terrestrial carbon uptake, crop yields and bioenergy potential (see also Chapter 7). Carbon sequestration in forests may be positively or adversely affected by climate change and CO<sub>2</sub> fertilization. On the one hand, elevated CO<sub>2</sub> levels and higher temperatures could enhance tree growth rates, carbon sequestration, and timber and biomass production (Beach et al. 2015; Kim et al. 2017; Anderegg et al. 2020). On the other hand,

FOOTNOTE<sup>9</sup> The countries and areas classification in this figure deviate from the standard classification scheme adopted by WGIII as set out in Annex II, section 1.

1 climate change could lead to greater frequency and intensity of disturbance events in forests, such as  
 2 fires, prolonged droughts, storms, pests and diseases (Kim et al. 2017; Anderegg et al. 2020). The  
 3 impact of climate change on crop yields could also indirectly impact the availability of land for  
 4 mitigation and AFOLU emissions (Meijl et al. 2018; Calvin et al. 2013; Kyle et al. 2014; Bajželj and  
 5 Richards 2014; Beach et al. 2015). The impact is, however, uncertain, as discussed in WGII Chapter  
 6 5. A few studies estimate the effect of climate impacts on AFOLU on mitigation, finding increases in  
 7 carbon prices or mitigation costs by 1-6% in most scenarios (Calvin et al. 2013; Kyle et al. 2014).

8  
 9 In summary, a limited number of studies quantify the impact of climate on emissions pathways. The  
 10 most important impact in energy systems might be through the impact on demand, although climate  
 11 change could also impact renewable mitigation potential –certainly at the local and regional scale.  
 12 Climate change might be more important for land-use related mitigation measures, including  
 13 afforestation, bioenergy and nature-based solutions. The net effect of changes in climate and CO<sub>2</sub>  
 14 fertilization are uncertain but could be substantial (see also Chapter 7).

### 16 3.4 Integrating sectoral analysis into systems transformations

17 This section describes the role of sectors in long-term emissions pathways (see Table 3.3). We discuss  
 18 both sectoral aspects of IAM pathways and some insights from sectoral studies. Sectoral studies  
 19 typically include more detail and additional mitigation options compared to IAMs. However, sectoral  
 20 studies miss potential feedbacks and cross-sectoral linkages that are captured by IAMs. Additionally,  
 21 since IAMs include all emissions sources, these models can be used to identify pathways to a  
 22 particular climate goals. In such pathways, emissions are balanced across sectors typically based on  
 23 relative marginal abatement costs; as a result, some sectors are sources and some are sinks at the time  
 24 of net zero CO<sub>2</sub> emissions. For these reasons, the mitigation observed in each sector in an IAM may  
 25 differ from the potential in sectoral studies. Given the strengths and limitations of each type of model,  
 26 IAMs and sectoral models are complementary, providing different perspectives.

27 **Table 3.3: Section 3.4 structure, definitions, and relevant chapters**

Section	Sector	What is included	Relevant chapter(s)
3.4.1	Cross-sector	Supply and demand, bioenergy, timing of net zero CO <sub>2</sub> , other interactions among sectors	Chapter 5, 12
3.4.2	Energy supply	Energy resources, transformation (e.g., electricity generation, refineries, etc.)	Chapter 6
3.4.3	Buildings <sup>1</sup>	Residential and commercial buildings, other non-specified <sup>2</sup>	Chapter 9
3.4.4	Transportation <sup>1</sup>	Road, rail, aviation, and shipping	Chapter 10
3.4.5	Industry <sup>1</sup>	Industrial energy use and industrial processes	Chapter 11
3.4.6	AFOLU	Agriculture, forestry, and other land use	Chapter 7
3.4.7	Other CDR	CDR options not included in individual sectors (e.g., direct air carbon capture and sequestration, enhanced weathering)	Chapter 12

29 <sup>1</sup> Direct energy use and direct emissions only; emissions do not include those associated with energy  
 30 production

31 <sup>2</sup> Other non-specified fuel use, including military. Some models report this category in the buildings  
 32 sector, while others report it in the “Other” sector

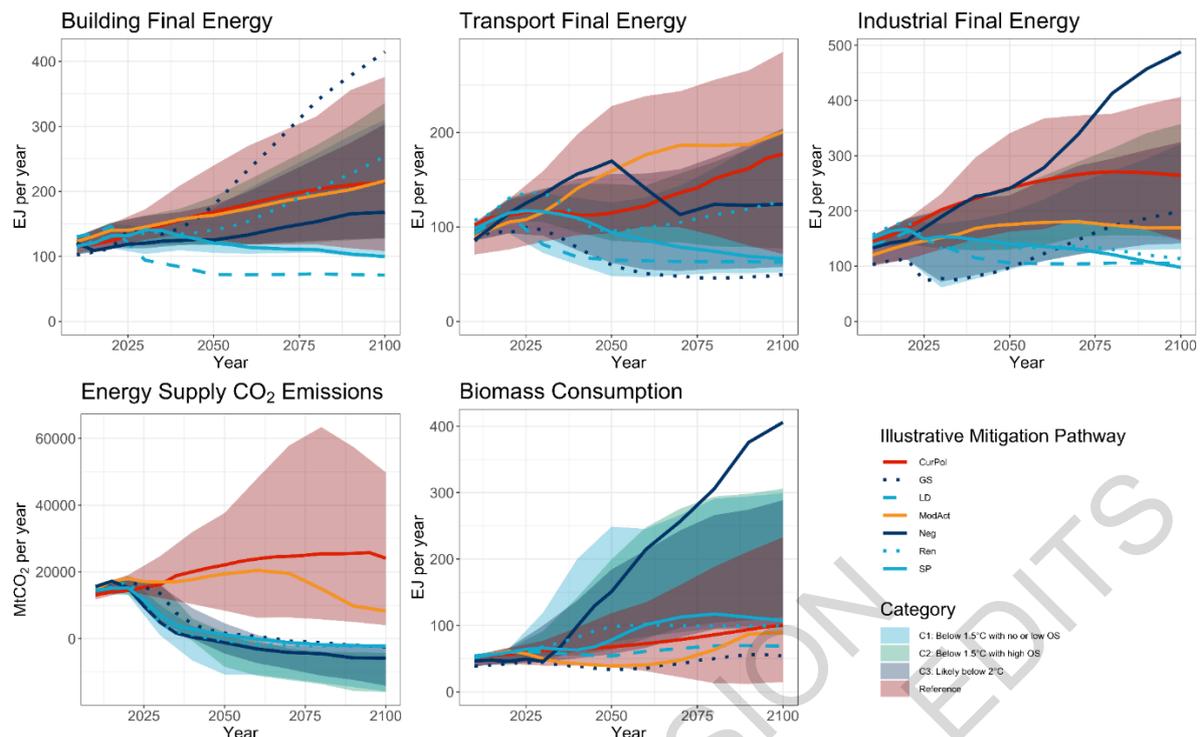
### 1 3.4.1 Cross-sector linkages

#### 2 3.4.1.1 Demand and supply strategies

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

13  
14 A small number of mitigation pathways include stringent demand-side mitigation, including changes  
15 in thermostat set points (van Vuuren et al. 2018; van Sluisveld et al. 2016), more efficient or smarter  
16 appliances (Grubler et al. 2018; Napp et al. 2019; van Sluisveld et al. 2016), increased recycling or  
17 reduced industrial goods (van de Ven et al. 2018; Liu et al. 2018; van Sluisveld et al. 2016; Grubler et  
18 al. 2018; Napp et al. 2019), telework and travel avoidance (van de Ven et al. 2018; Grubler et al.  
19 2018), shifts to public transit (van Vuuren et al. 2018; van Sluisveld et al. 2016; Grubler et al. 2018),  
20 reductions in food waste (van de Ven et al. 2018) and less meat intensive diets (van de Ven et al.  
21 2018; van Vuuren et al. 2018; Liu et al. 2018). These pathways show reduced dependence on CDR  
22 and reduced pressure on land (van de Ven et al. 2018; van Vuuren et al. 2018; Grubler et al. 2018;  
23 Rogelj et al. 2018a) (Chapter 5.3.3). However, the representation of these demand-side mitigation  
24 options in IAMs is limited, with most models excluding the costs of such changes (van Sluisveld et al.  
25 2016), using stylised assumptions to represent them (van den Berg et al. 2019), and excluding  
26 rebound effects (Brockway et al. 2021; Krey et al. 2019). Furthermore, there are questions about the  
27 achievability of such pathways, including whether the behavioural changes included are feasible  
28 (Azevedo et al. 2021) and the extent to which development and demand can be decoupled (Semieniuk  
29 et al. 2021; Steckel et al. 2013; Keyßer and Lenzen 2021; Brockway et al. 2021).

30  
31 Figure 3.18: Indicators of demand and supply-side mitigation in the Illustrative Pathways (lines) and  
32 the 5-95% range of Reference, 1.5°C and 2°C scenarios (shaded areas). shows indicators of supply-  
33 and demand-side mitigation in the IMPs, as well as the range across the database. Two of these IMPs  
34 (*SP*, *LD*) show strong reductions in energy demand, resulting in less reliance on bioenergy and  
35 limited CDR from energy supply. In contrast, *Neg* has higher energy demand, depending more on  
36 bioenergy and net negative CO<sub>2</sub> emissions from energy supply.  
37



1  
2 **Figure 3.18: Indicators of demand and supply-side mitigation in the Illustrative Pathways (lines) and the**  
3 **5-95% range of Reference, 1.5°C and 2°C scenarios (shaded areas).**

#### 4 3.4.1.2 Sectoral emissions strategies and the timing of net zero

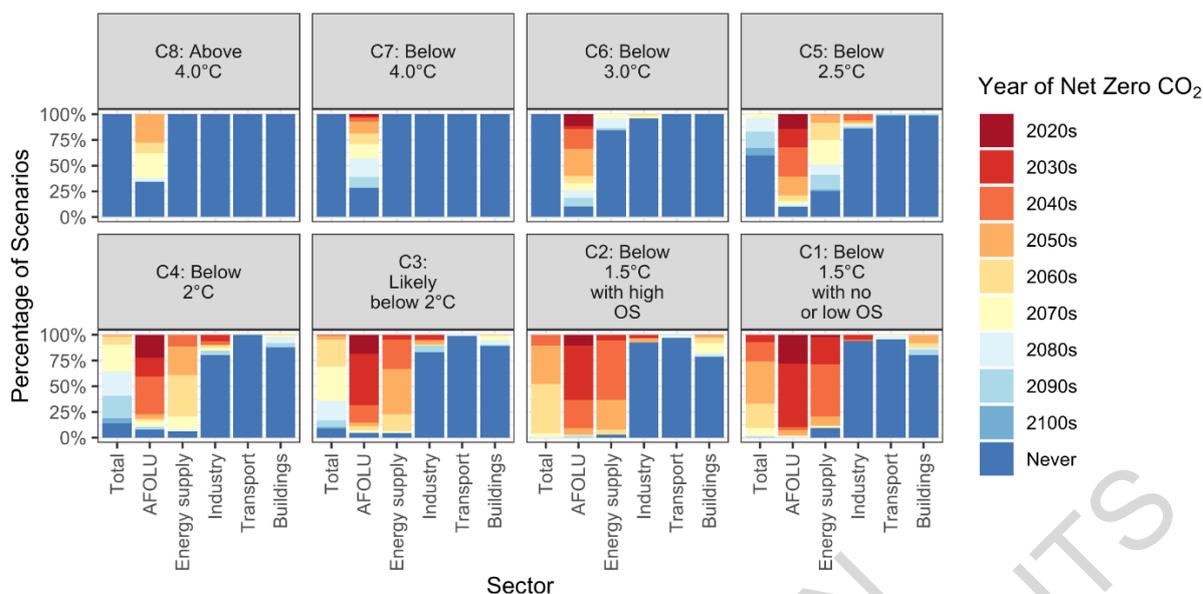
5 Mitigation pathways show differences in the timing of decarbonization (Figure 3.20) and the timing of  
6 net zero (Figure 3.19) across sectors and regions (*high confidence*); the timing in a given sector  
7 depends on the cost of abatement in it, the availability of CDR options, the scenario design, near-term  
8 emissions levels, and the amount of non-CO<sub>2</sub> abatement (Yeh et al. 2017; Emmerling et al. 2019;  
9 Rogelj et al. 2019a,b; Johansson et al. 2020; van Soest et al. 2021b; Ou et al. 2021; Azevedo et al.  
10 2021) (Cross-Chapter Box 3 in this chapter). However, delaying emissions reductions, or more  
11 limited emissions reductions in one sector or region, involves compensating reductions in other  
12 sectors or regions if warming is to be limited (*high confidence*) (Rochedo et al. 2018; Price and Keppo  
13 2017; Grubler et al. 2018; van Soest et al. 2021b).

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

p50 (p5-p95) <sup>(1)</sup>	Global Mean Surface Air Temperature change	WG1 SSP & IPs alignment	Low-carbon share of Primary Energy <sup>(3,4)</sup> [%] 2020 = 16 (12-18)			CO <sub>2</sub> intensity of Primary Energy Index 2020 = 100			Final energy demand [EJ/yr] 2020 = 419 (367-458)			Final energy intensity of GDP Index 2020 = 100			Electricity share in final energy [%] 2020 = 20 (18-25)			CO <sub>2</sub> intensity of electricity [Mt CO <sub>2</sub> /TWh] 2020 = 469 (419-538)			Non-energy GHG emissions [Gt CO <sub>2</sub> -eq] 2020 = 18 (15-21)			Fossil CCS (2100) [Gt CO <sub>2</sub> ] 2020 = 0 (0-0)				CDR (2100) [Gt CO <sub>2</sub> ] 2020 = 0 (0-4)			
			2030	2050	2100	2030	2050	2100	2030	2050	2100	2030	2050	2100	2030	2050	2100	2030	2050	2100	2030	2050	2100	2020- 2100	2030	2050	2100	2020- 2100			
<b>C1</b> [197]	Below 1.5°C with no or limited overshoot	SP, LD Ren, SSP1-1.9	32 (17-48)	68 (25-86)	75 (19-98)	65 (49-75)	8 (-8-24)	-3 (-20-8)	399 (293-447)	410 (325-540)	612 (321-818)	71 (59-81)	46 (34-60)	26 (14-45)	27 (23-35)	52 (40-64)	66 (50-78)	99 (4-215)	-5 (-66-11)	-4 (-104-1)	10 (5-13)	5 (1-9)	2 (-2-9)	1 (0-5)	2 (0-13)	3 (0-16)	196 (3-882)	1 (0-4)	6 (1-13)	13 (0-20)	659 (63-1012)
<b>C2</b> [133]	Below 1.5°C with high overshoot	Neg	24 (11-35)	57 (19-77)	86 (25-97)	79 (66-94)	18 (2-37)	-14 (-25-0)	458 (372-504)	442 (345-561)	675 (415-819)	76 (64-88)	44 (35-63)	23 (15-45)	25 (20-29)	45 (34-56)	61 (49-73)	218 (99-353)	0 (-75-16)	-1 (-118-3)	13 (10-19)	6 (2-9)	1 (-7-7)	0 (0-4)	3 (0-13)	1 (0-16)	280 (7-831)	1 (0-4)	6 (0-17)	17 (-1-26)	687 (0-1282)
<b>C3</b> [311]	Likely below 2°C	SSP2-2.6 GS	24 (16-32)	51 (29-75)	73 (34-94)	84 (70-95)	31 (9-47)	-1 (-19-8)	446 (356-491)	448 (344-540)	625 (421-788)	77 (65-88)	50 (36-62)	26 (18-41)	24 (20-29)	42 (30-54)	60 (43-72)	248 (93-375)	5 (-72-51)	-8 (-105-5)	12 (6-18)	7 (3-12)	5 (-1-8)	0 (0-3)	3 (0-12)	5 (0-15)	266 (7-773)	1 (0-4)	5 (0-11)	13 (0-20)	569 (0-923)
<b>C4</b> [153]	Below 2°C		21 (14-24)	39 (24-63)	71 (34-91)	92 (80-100)	45 (26-64)	-3 (-21-9)	459 (379-497)	489 (362-601)	641 (450-786)	76 (71-87)	45 (39-65)	22 (19-41)	23 (19-28)	35 (23-44)	56 (44-69)	322 (227-381)	24 (-48-112)	-14 (-117-7)	13 (8-19)	9 (3-12)	2 (-1-9)	0 (0-2)	2 (0-9)	6 (0-16)	279 (7-684)	1 (0-4)	4 (0-9)	15 (0-19)	553 (0-841)
<b>C5</b> [212]	Below 2.5°C		21 (12-24)	31 (22-44)	67 (42-84)	92 (84-102)	66 (50-84)	9 (-13-32)	466 (389-499)	519 (435-585)	680 (383-812)	77 (74-88)	51 (45-66)	23 (18-40)	23 (19-28)	32 (19-41)	53 (40-65)	341 (257-418)	107 (14-208)	-3 (-73-34)	15 (10-19)	10 (5-15)	4 (-1-11)	0 (0-1)	1 (0-7)	5 (0-15)	200 (5-730)	1 (0-4)	2 (0-5)	11 (0-18)	392 (0-720)
<b>C6</b> [97]	Below 3°C	SSP2-4.5 Mod-Act	20 (11-23)	25 (14-36)	47 (28-65)	94 (87-101)	82 (67-92)	47 (21-78)	467 (410-508)	551 (471-632)	701 (432-910)	79 (75-89)	55 (50-70)	26 (20-42)	23 (19-28)	29 (19-38)	48 (30-56)	354 (257-469)	216 (69-317)	28 (-20-166)	17 (11-20)	13 (9-17)	8 (2-12)	0 (0-0)	0 (0-4)	4 (0-16)	47 (0-536)	1 (0-4)	2 (0-5)	6 (0-12)	222 (0-474)
<b>C7</b> [164]	Below 4°C	SSP3-7.0 Cur-Pol	17 (11-21)	19 (8-29)	29 (8-51)	98 (91-101)	94 (80-101)	73 (56-106)	492 (434-540)	599 (513-701)	804 (557-983)	85 (76-91)	64 (54-76)	33 (27-48)	24 (20-28)	29 (23-35)	41 (29-50)	414 (311-538)	311 (130-499)	185 (12-461)	19 (13-24)	19 (14-25)	16 (9-26)	0 (0-0)	0 (0-2)	0 (0-8)	0 (0-221)	0 (0-3)	0 (0-3)	0 (0-5)	6 (0-318)
<b>C8</b> [29]	Above 4°C	SSP5-8.5	13 (11-17)	13 (9-20)	29 (14-45)	102 (99-103)	106 (104-109)	91 (87-95)	540 (413-574)	696 (504-858)	941 (692-1136)	89 (88-92)	73 (64-79)	47 (25-51)	26 (22-30)	31 (28-35)	43 (35-50)	463 (372-514)	425 (352-484)	189 (142-441)	20 (19-25)	21 (20-29)	20 (13-31)	0 (0-0)	0 (0-0)	0 (0-2)	0 (0-38)	0 (0-1)	0 (0-2)	0 (0-3)	0 (0-207)

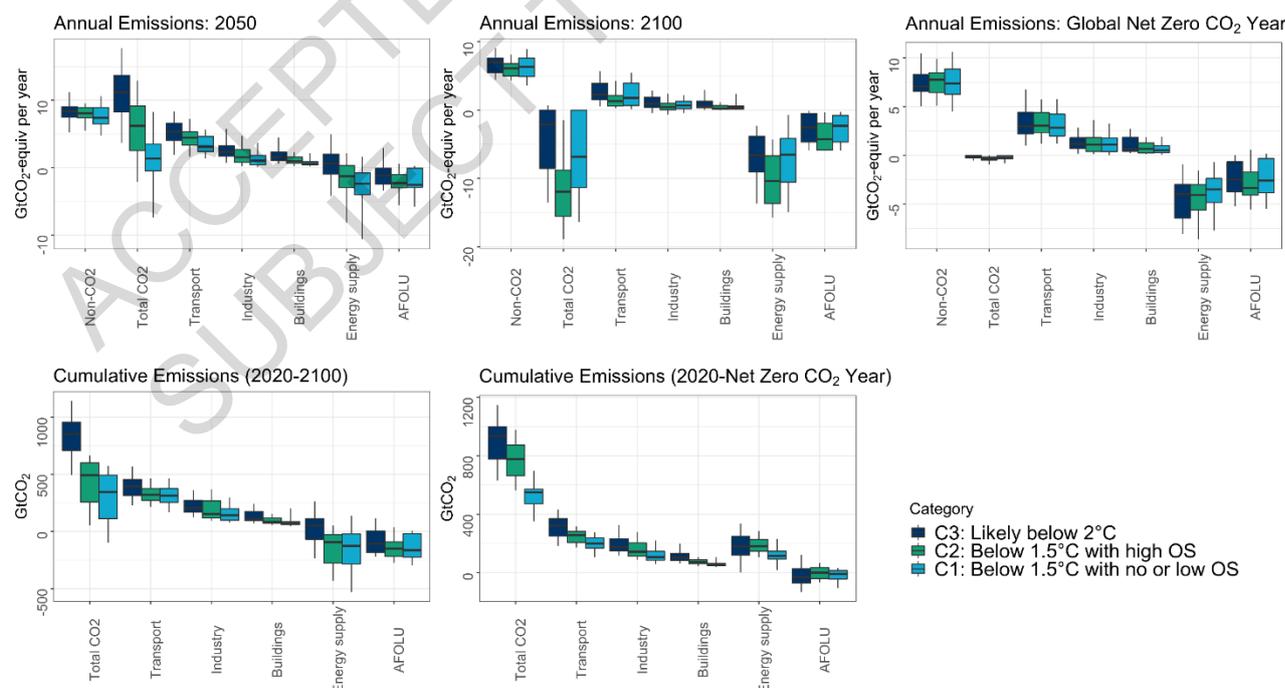
2 **Footnotes**

- 0 Values in the table refer to the 50th and (5th-95th) percentile values.
- 1 Category definitions consider at peak warming and warming at the end-of-century (2100).  
 C1: Below 1.5°C in 2100 with a greater than 50% probability and a peak warming higher than 1.5°C with less than 67% probability.  
 C2: Below 1.5°C in 2100 with a greater than 50% probability but peak warming higher than 1.5°C with greater than or equal to 67% probability.  
 C3: Likely below 2 °C throughout the century with greater than 67% probability.  
 C4, C5, C6, C7: Below 2 °C, 2.5 °C, 3 °C and 4 °C throughout the century, respectively, with greater than 50% probability.  
 C8: Peak warming above 4 °C with greater than or equal to 50% probability.
- 2 The warming profile of *Neg* peaks around 2060 and declines thereafter to below 1.5°C (50% likelihood) shortly after 2100. Whilst technically classified as a C3, it strongly exhibits the characteristics of C2 high overshoot scenarios.
- 3 Primary Energy as calculated in 'Direct Equivalent' terms according to IPCC reporting conventions.
- 4 Low carbon energy here defined to include: renewables (including biomass, solar, wind, hydro, geothermal, ocean); fossil fuels when used with CCS; and, nuclear power.



**Figure 3.19: Decade in which sectoral CO<sub>2</sub> emissions first reach net negative values. Each panel is a different temperature level. The colours indicate the decade in which CO<sub>2</sub> emissions go negative; the y-axis indicates the share of scenarios achieving net zero in that decade. Only scenarios that pass the vetting criteria are included (see Section 3.2). Scenarios achieving net zero prior to 2020 are excluded.**

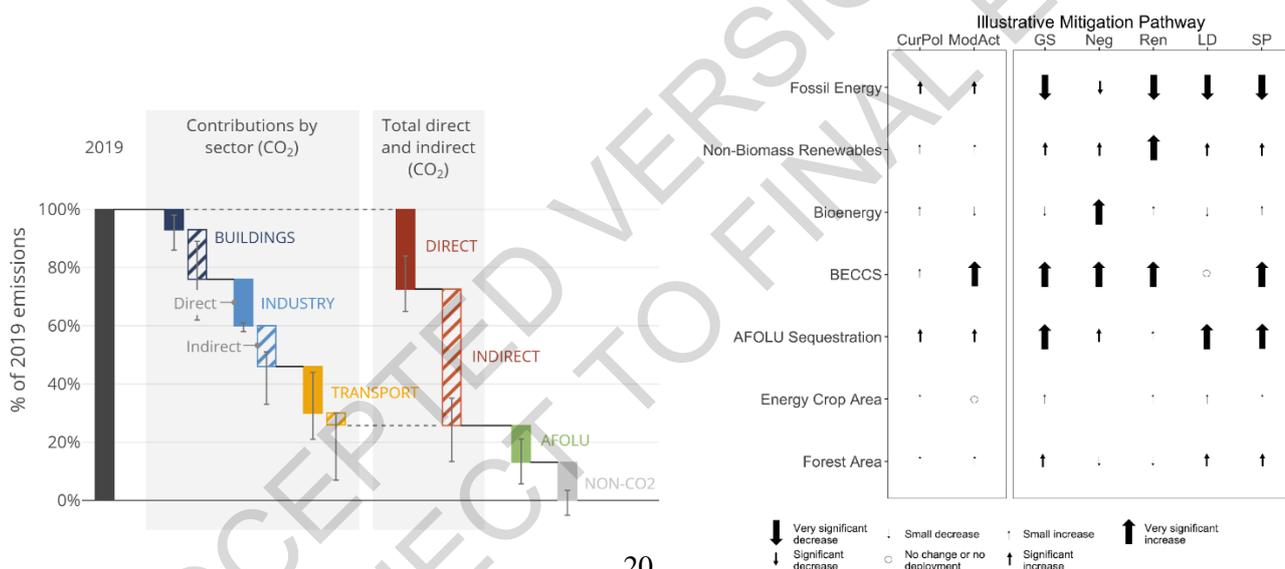
At the time of net zero global CO<sub>2</sub> emissions, emissions in some sectors are positive and some negative. In cost-effective mitigation pathways, the energy supply sector typically reaches net zero CO<sub>2</sub> before the economy as a whole, while the demand sectors reach net zero CO<sub>2</sub> later, if at all (Pietzcker et al. 2014; Price and Keppo 2017; Luderer et al. 2018; Rogelj et al. 2018a,b; Méjean et al. 2019; Azevedo et al. 2021) (Chapter 6.7). CO<sub>2</sub> emissions from transport, industry, and buildings are positive, and non-CO<sub>2</sub> GHG emissions are also positive at the time of global net zero CO<sub>2</sub> emissions (Figure 3.20).



**Figure 3.20: Greenhouse gas emissions, including CO<sub>2</sub> emissions by sector and total non-CO<sub>2</sub> GHGs in 2050 (top left), 2100 (top middle), year of global net zero CO<sub>2</sub> (top right), cumulative CO<sub>2</sub> emissions from**

1 **2020-2100 (bottom left), and cumulative CO<sub>2</sub> emissions from 2020 until the year of net zero CO<sub>2</sub> for**  
 2 **scenarios that limit warming to below 2°C. Scenarios are grouped by their temperature category.**  
 3 **“Industry” includes CO<sub>2</sub> emissions associated with industrial energy use only; sectors shown in this figure**  
 4 **do not necessarily sum to total CO<sub>2</sub>. In this, and other figures in Section 3.4, unless stated otherwise, only**  
 5 **scenarios that pass the vetting criteria are included (see Section 3.2). Boxes indicate the interquartile**  
 6 **range, the median is shown with a horizontal black line, while vertical lines show the 5 to 95% interval.**

7 So, while pathways indicate some flexibility in emissions reductions across sectors, all pathways  
 8 involve substantial CO<sub>2</sub> emissions reductions in all sectors and regions (*high confidence*) (Rogelj et al.  
 9 2018a,b; Luderer et al. 2018; Méjean et al. 2019; Azevedo et al. 2021). Projected CO<sub>2</sub> emissions  
 10 reductions between 2019 and 2050 in 1.5°C pathways with no or limited overshoot are around 77%  
 11 for energy demand, with a 5-95% range of 31 to 96%,<sup>10</sup> 115% for energy supply (90 to 167%), and  
 12 148% for AFOLU (94 to 387%). In likely 2°C pathways, projected CO<sub>2</sub> emissions are reduced  
 13 between 2019 and 2050 by around 49% for energy demand, 97% for energy supply, and 136% for  
 14 AFOLU (see also 3.4.2-3.4.6). Almost 75% of GHG reductions at the time of net zero GHG are from  
 15 the energy system, 13% are from AFOLU CO<sub>2</sub>, and 13% from non-CO<sub>2</sub> (Figure 3.21). These  
 16 reductions are achieved through a variety of sectoral strategies, illustrated in Figure 3.21 (right panel),  
 17 and described in Sections 3.4.2 to 3.4.7; the primary strategies include declines in fossil energy,  
 18 increases in low carbon energy use, and CDR to address residual emissions.



21 **Figure 3.21: Left panel: Greenhouse gas emissions reductions from 2019 by sector at the year of net zero**  
 22 **GHG for all scenarios that reach net zero GHG. Emissions reductions by sector for direct (demand) and**  
 23 **indirect (upstream supply) are shown as the percent of total GHG reductions.**

24 **Right panel: key indicators in 2050 for the IMPs. Definitions of significant and very significant are**  
 25 **defined relative to 2019 and vary between indicators, as follows: fossil energy (significant >10%, very**  
 26 **significant >50%), renewables (>150 EJ yr<sup>-1</sup>, >200 EJ yr<sup>-1</sup>), bioenergy (>100%, >200%), BECCS (>2.0**  
 27 **GtCO<sub>2</sub> yr<sup>-1</sup>, >3.5 GtCO<sub>2</sub> yr<sup>-1</sup>), AFOLU (>100% decline, >130%), energy crops (>150 million ha, >400),**  
 28 **forest (>5% increase, >15%).**

30 In the context of mitigation pathways, only a few studies have examined solar radiation modification  
 31 (SRM), typically focusing on Stratospheric Aerosol Injection (Emmerling and Tavoni 2018a,b;  
 32 Arino et al. 2016; Belaia et al. 2021; Rickels et al. 2020; Heutel et al. 2018; Helweggen et al. 2019).  
 33 These studies find that substantial mitigation is required to limit warming to a given level, even if

FOOTNOTE <sup>10</sup> Unless otherwise specified, the values in parentheses in Section 3.4 from this point forward indicate the 5-95% range.

1 SRM is available (Moreno-Cruz and Smulders 2017; Emmerling and Tavoni 2018b; Belaia et al.  
2 2021). SRM may reduce some climate impacts, reduce peak temperatures, lower mitigation costs, and  
3 extend the time available to achieve mitigation; however, SRM does not address ocean acidification  
4 and may involve risks to crop yields, economies, human health, or ecosystems (WGII Chapter 16;  
5 WGI TS; WGI Ch 5; SR1.5 SPM; Cross-Working Group Box 4 in Chapter 14). There also are  
6 significant uncertainties surrounding SRM, including uncertainties on the costs and risks, which can  
7 substantially alter the amount of SRM used in modelled pathways (Tavoni et al. 2017; NASEM 2021;  
8 Heutel et al. 2018; Helwegen et al. 2019; IPCC 2018). Furthermore, the degree of international  
9 cooperation can influence the amount of SRM deployed in scenarios, with uncoordinated action  
10 resulting in larger SRM deployment and consequently larger risks/impacts from SRM (Emmerling  
11 and Tavoni 2018a). Bridging research and governance involves consideration of the full range of  
12 societal choices and ramifications (Sugiyama et al. 2018). More information on SRM, including the  
13 caveats, risks, uncertainties, and governance issues is found in WGI Chapter 4, WGIII Chapter 14,  
14 and Cross-Working Group Box 4 in Chapter 14).

### 16 3.4.1.3 *Linkages among sectors*

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

28 Mitigation in one sector can also result in additional emissions in another. One example is  
29 electrification of end use which can result in increased emissions from energy supply. However, one  
30 comparatively well-researched example of this linkage is bioenergy. An increase in demand for  
31 bioenergy within the energy system has the potential to influence emissions in the AFOLU sector  
32 through the intensification of land and forest management and/or via land use change (Smith et al.  
33 2019; Daioglou et al. 2019; Smith et al. 2020a; IPCC 2019a). The effect of bioenergy and BECCS on  
34 mitigation depends on a variety of factors in modelled pathways. In the energy system, the emissions  
35 mitigation depends on the scale of deployment, the conversion technology, and the fuel displaced  
36 (Calvin et al. 2021). Limiting or excluding bioenergy and/or BECCS increases mitigation cost and  
37 may limit the ability of a model to reach a low warming level (Edmonds et al. 2013; Calvin et al.  
38 2014b; Muratori et al. 2020; Luderer et al. 2018). In AFOLU, bioenergy can increase or decrease  
39 terrestrial carbon stocks and carbon sequestration, depending on the scale, biomass feedstock, land  
40 management practices, and prior land use (Calvin et al. 2014c; Wise et al. 2015; Smith et al. 2019,  
41 2020a; IPCC 2019a; Calvin et al. 2021).

43 Pathways with very high biomass production for energy use typically include very high carbon prices  
44 in the energy system (Popp et al. 2017; Rogelj et al. 2018b), little or no land policy (Calvin et al.  
45 2014b), a high discount rate (Emmerling et al. 2019), and limited non-BECCS CDR options (e.g.,  
46 afforestation, DACCS) (Fuhrman et al. 2020; Realmonte et al. 2019; Chen and Tavoni 2013;  
47 Marcucci et al. 2017; Calvin et al. 2014b). Higher levels of bioenergy consumption are likely to  
48 involve trade-offs with mitigation in other sectors, notably in construction (i.e., wood for material and  
49 structural products) and AFOLU (carbon stocks and future carbon sequestration), as well as trade-offs  
50 with sustainability (Section 3.7) and feasibility concerns (Section 3.8). Not all of these trade-offs are

1 fully represented in all IAMs. Based on sectoral studies, the technical potential for bioenergy, when  
2 constraints for food security and environmental considerations are included, are 5-50 and 50-250 EJ  
3 yr<sup>-1</sup> in 2050 for residues and dedicated biomass production systems, respectively (Chapter 7).  
4 Bioenergy deployment in IAMs is within the range of these potentials, with between 75 and 248 EJ  
5 yr<sup>-1</sup> in 2050 in pathways that limit warming to 1.5°C with no or limited overshoot. Finally, IAMs do  
6 not include all potential feedstock and management practices, and have limited representation of  
7 institutions, governance, and local context (Butnar et al. 2020; Brown et al. 2019; Calvin et al. 2021).

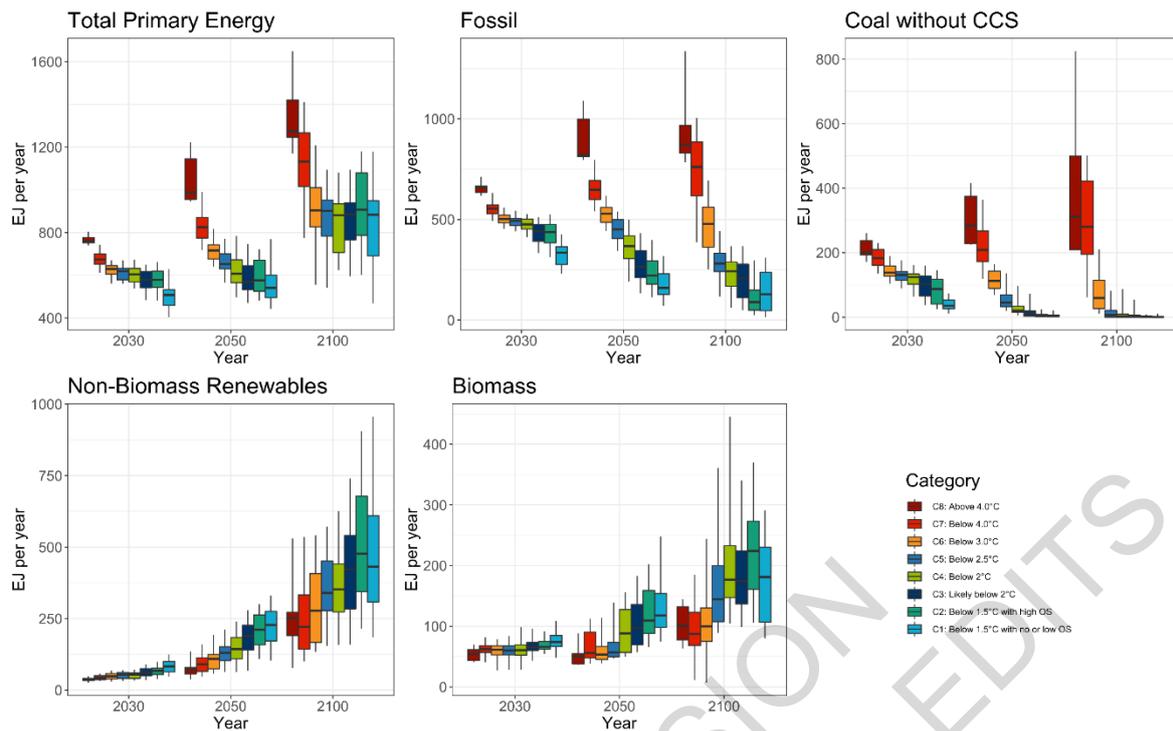
8 The inclusion of CDR options, like BECCS, can affect the timing of emissions mitigation in IAM  
9 scenarios, i.e., delays in mitigations actions are compensated by net negative emissions in the second  
10 half of the century. However, studies with limited net negative emissions in the long-term require very  
11 rapid declines in emissions in the near-term (van Vuuren et al. 2017). Especially in forest-based  
12 systems, increased harvesting of forests can perturb the carbon balance of forestry systems, increasing  
13 emissions for some period; the duration of this period of increased emissions, preceding net emissions  
14 reductions, can be very variable (Mitchell et al. 2012; Lamers and Junginger 2013; Röder et al. 2019;  
15 Hanssen et al. 2020; Cowie et al. 2021). However, the factors contributing to differences in recovery  
16 time are known (Zanchi et al. 2012; Laganière et al. 2017; Mitchell et al. 2012; Lamers and Junginger  
17 2013; Röder et al. 2019). Some studies that consider market-mediated effects find that an increased  
18 demand for biomass from forests can provide incentives to maintain existing forests and potentially to  
19 expand forest areas, providing additional carbon sequestration as well as additional biomass (Kim et al.  
20 2018; Dwivedi et al. 2014; Baker et al. 2019; Favero et al. 2020). However, these responses are  
21 uncertain and likely to vary geographically.

### 22 23 **3.4.2 Energy supply**

24 Without mitigation, energy consumption and supply emissions continue to rise (*high confidence*)  
25 (Riahi et al. 2017; Bauer et al. 2017; Kriegler et al. 2016; Mcjeon et al. 2021) (see also Chapter 6.7).  
26 While the share of renewable energy continues to grow in reference scenarios, fossil fuel accounts for  
27 the largest share of primary energy (Riahi et al. 2017; Bauer et al. 2017; Price and Keppo 2017).

28 In scenarios likely to limit warming to 2°C and below, transition of the energy supply sector to a low  
29 or no carbon system is rapid (Rogelj et al. 2016, 2018b; Luderer et al. 2018; Grubler et al. 2018; van  
30 Vuuren et al. 2018). CO<sub>2</sub> emissions from energy supply reach net zero around 2041 (2033 to 2057) in  
31 pathways limiting warming to below 1.5°C with no or limited overshoot and around 2053 (2040 to  
32 2066) in pathways likely to limit warming to 2°C. Emissions reductions continue, with emissions  
33 reaching -7.1 GtCO<sub>2</sub> per year (-15 to -2.3 GtCO<sub>2</sub> per year) in 2100 in all pathways likely to limit  
34 warming to 2°C and below.

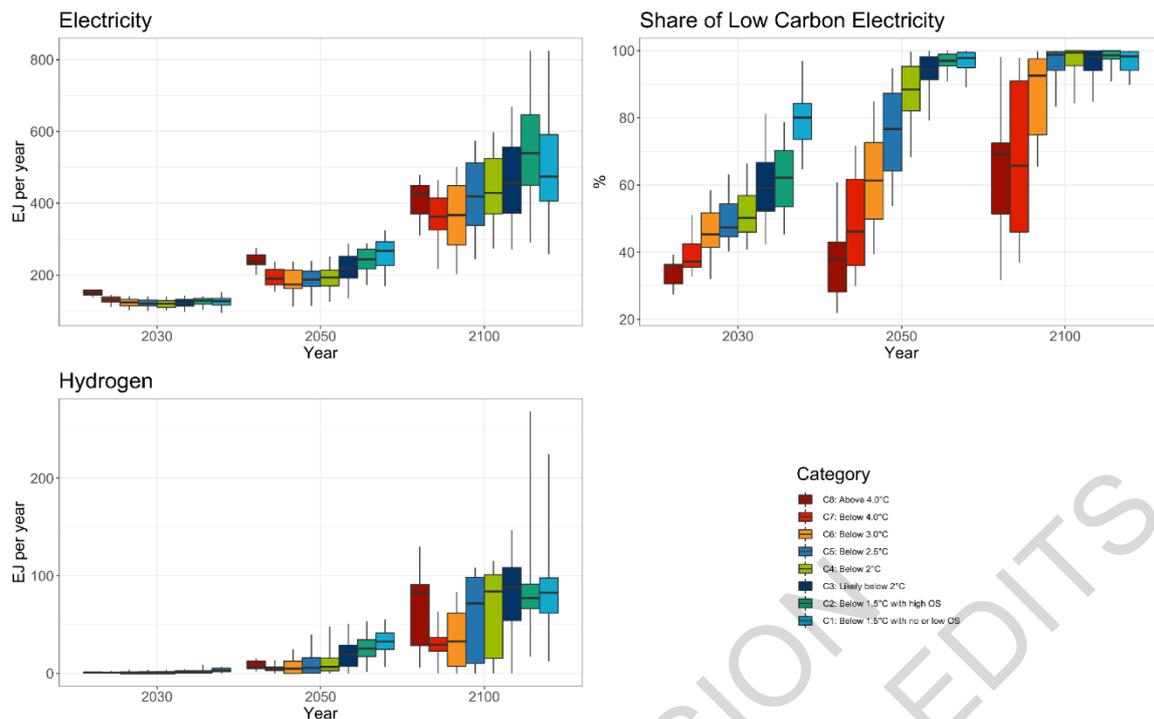
35 All pathways likely to limit warming to 2°C and below show substantial reductions in fossil fuel  
36 consumption and a near elimination of the use of coal without CCS (*high confidence*) (Welsby et al.  
37 2021; Bauer et al. 2017; van Vuuren et al. 2018; Rogelj et al. 2018a,b; Grubler et al. 2018; Luderer et  
38 al. 2018; Azevedo et al. 2021; Mcjeon et al. 2021) (Figure 3.22). In these pathways, the use of coal,  
39 gas and oil is reduced by 90, 25, and 41%, respectively, between 2019 and 2050 and 91, 39, and 78%  
40 between 2019 and 2100; coal without CCS is further reduced to 99% below its 2019 levels in 2100.  
41 These pathways show an increase in low carbon energy, with 88% (69-97%) of primary energy from  
42 low carbon sources in 2100, with different combinations of low carbon fuels (e.g., non-biomass  
43 renewables, biomass, nuclear, and CCS) (Rogelj et al. 2018a,b; van Vuuren et al. 2018) (Chapter 6.7,  
44 Section 3.4.1). Across all pathways likely to limit warming to 2°C and below, non-biomass  
45 renewables account for 52% (24 to 77%) of primary energy in 2100 (Pietzcker et al. 2017; Creutzig et  
46 al. 2017; Rogelj et al. 2018b); Figure 3.22, Chapter 6). There are some studies analysing the potential  
47 for 100% renewable energy systems (Hansen et al. 2019); however, there are a range of issues around  
48 such systems (see Chapter 6.6, Box 6.6).



1

2 **Figure 3.22 Primary energy consumption across scenarios: total primary energy (top left), fossil fuels (top**  
 3 **middle), coal without CCS (top right), non-biomass renewables (bottom left), and biomass (bottom**  
 4 **middle). Scenarios are grouped by their temperature category. Primary energy is reported in direct**  
 5 **equivalent, where one unit of nuclear or non-biomass renewable energy output is reported as one unit of**  
 6 **primary energy. Not all subcategories of primary energy are shown.**

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



1

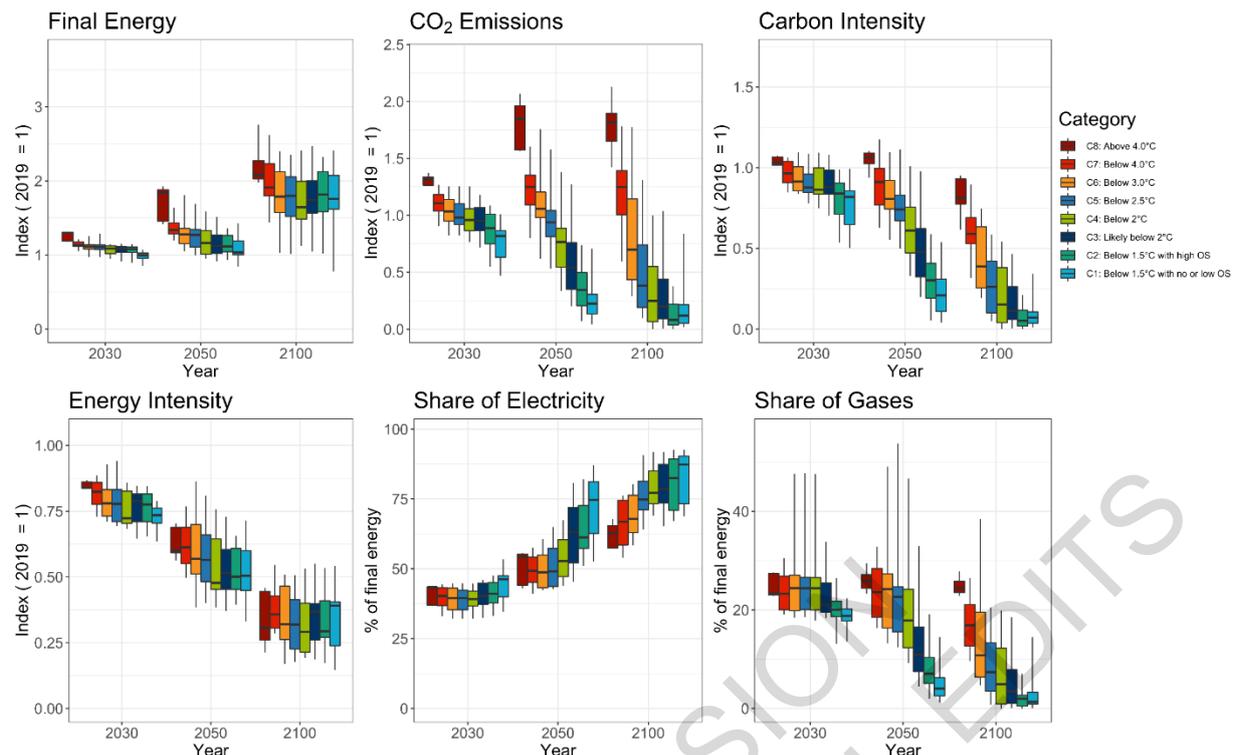
2

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

6

### 7 3.4.3 Buildings

8 Global final energy use in the building sector increases in all pathways as a result of population  
 9 growth and increasing affluence (Figure 3.24). There is very little difference in final energy intensity  
 10 for the buildings sector across scenarios. Direct CO<sub>2</sub> emissions from the buildings sector vary more  
 11 widely across temperature stabilization levels than energy consumption. In 2100, scenarios above 3°C  
 12 [C7-C8] still show an increase of CO<sub>2</sub> emissions from buildings around 29% above 2019, while all  
 13 scenarios likely to limit warming to 2°C and below have emission reductions of around 85% (8-  
 100%). Carbon intensity declines in all scenarios, but much more sharply as the warming level is  
 reduced.



**Figure 3.24: Buildings final energy (top left), CO<sub>2</sub> emissions (top middle), carbon intensity (top right), energy intensity (bottom left), share of final energy from electricity (bottom middle), and share of final energy from gases (bottom right). Energy intensity is final energy per unit of GDP. Carbon intensity is CO<sub>2</sub> emissions per EJ of final energy. The first four indicators are indexed to 2019<sup>11</sup>, where values less than 1 indicate a reduction.**

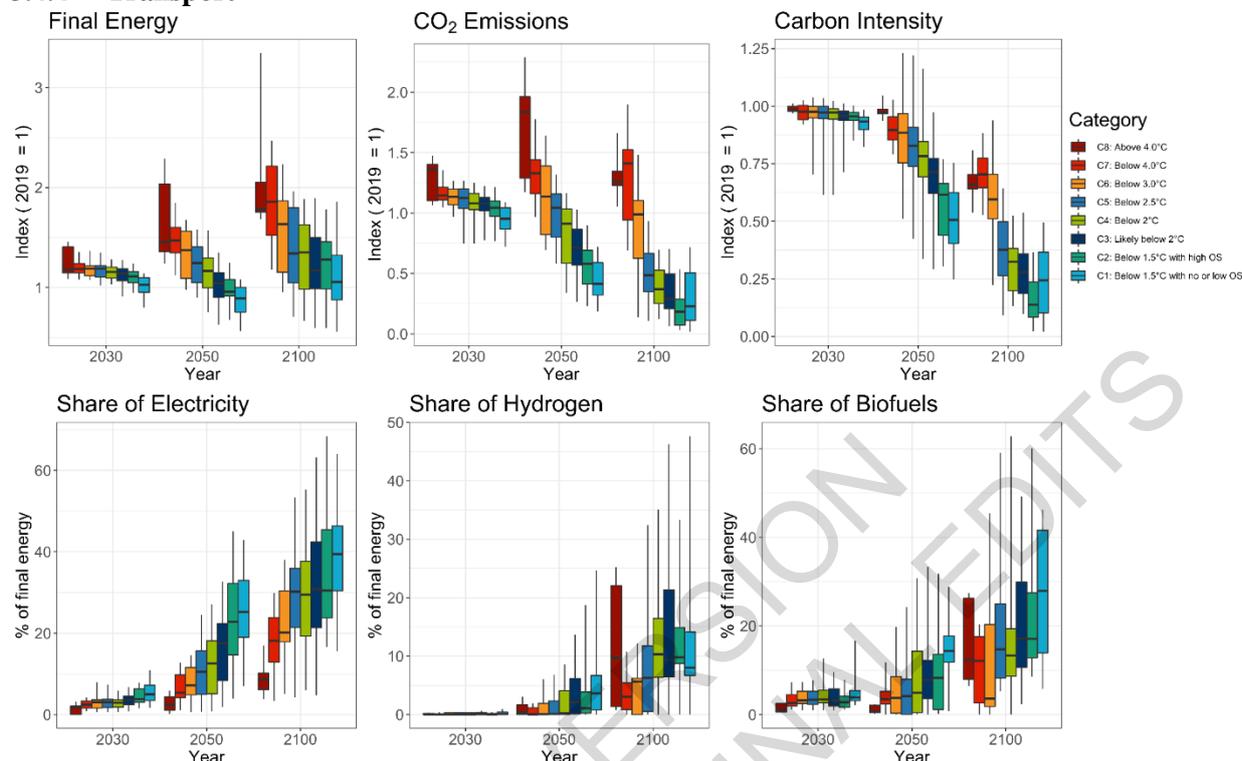
In all scenarios, the share of electricity in final energy use increases, a trend that is accelerated by 2050 for the scenarios likely to limit warming to 2°C and below (Figure 3.23). By 2100, the low warming scenarios show large shares of electricity in final energy consumption for buildings. The opposite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

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

FOOTNOTE <sup>11</sup> 2019 values are from model results and interpolated from other years when not directly reported.

1 van Sluisveld et al. 2016). The in-depth dynamics of mitigation in the building sector are explored in  
 2 Chapter 9.

### 3 3.4.4 Transport



4 **Figure 3.25: Transport final energy (top left), CO<sub>2</sub> emissions (top middle), carbon intensity (top right),**  
 5 **and share of final energy from electricity (bottom left), hydrogen (bottom middle), and biofuels (bottom**  
 6 **right). See Chapter 10 for a discussion of energy intensity. Carbon intensity is CO<sub>2</sub> emissions per EJ of**  
 7 **final energy. The first three indicators are indexed to 2019<sup>12</sup>, where values less than 1 indicate a**  
 8 **reduction.**  
 9

10 Reference scenarios show growth in transport demand, particularly in aviation and freight (Yeh et al.  
 11 2017; Sharmina et al. 2020; Müller-Casseres et al. 2021b). Energy consumption continues to be  
 12 dominated by fossil fuels in reference scenarios, with some increases in electrification (Edelenbosch  
 13 et al. 2020; Yeh et al. 2017). CO<sub>2</sub> emissions from transport increase for most models in reference  
 14 scenarios (Yeh et al. 2017; Edelenbosch et al. 2020).

15 The relative contribution of demand-side reduction, energy efficiency improvements, fuel switching,  
 16 and decarbonisation of fuels, varies by model, level of mitigation, mitigation options available, and  
 17 underlying socio-economic pathway (Longden 2014; Wise et al. 2017; Luderer et al. 2018; Yeh et al.  
 18 2017; Edelenbosch et al. 2020; Müller-Casseres et al. 2021a,b). IAMs typically rely on technology-  
 19 focused measures like energy efficiency improvements and fuel switching to reduce carbon emissions  
 20 (Pietzcker et al. 2014; Edelenbosch et al. 2017a; Yeh et al. 2017; Zhang et al. 2018a,b; Rogelj et al.  
 21 2018b; Sharmina et al. 2020). Many mitigation pathways show electrification of the transport system  
 22 (Luderer et al. 2018; Pietzcker et al. 2014; Longden 2014; Zhang et al. 2018a); however, without  
 23 decarbonization of the electricity system, transport electrification can increase total energy system  
 24 emissions (Zhang and Fujimori 2020). A small number of pathways include demand-side mitigation  
 25 measures in the transport sector; these studies show reduced carbon prices and reduced dependence on

FOOTNOTE <sup>12</sup> 2019 values are from model results and interpolated from other years when not directly reported.

1 CDR (Grubler et al. 2018; Méjean et al. 2019; van de Ven et al. 2018; Zhang et al. 2018c) (Section  
2 3.4.1).

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

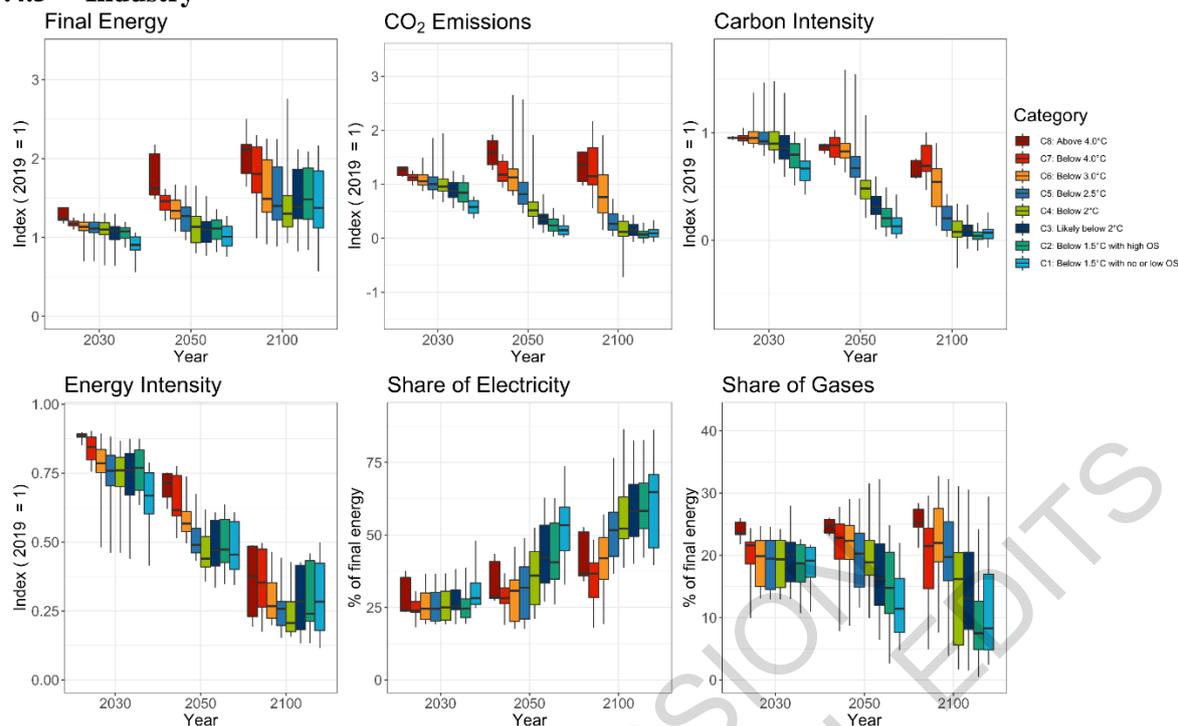
7 The transport sector has more detail than other sectors in many IAMs (Edelenbosch et al. 2020);  
8 however, there is considerable variation across models. Some models (e.g., GCAM, IMAGE,  
9 MESSAGE-GLOBIOM) represent different transport modes with endogenous shifts across modes as  
10 a function of income, price, and modal speed (Edelenbosch et al. 2020).<sup>13</sup> However, IAMs, including  
11 those with detailed transport, exclude several supply-side (e.g., synthetic fuels) and demand-side (e.g.,  
12 behaviour change, reduced shipping, telework and automation) mitigation options (Davis et al. 2018;  
13 Köhler et al. 2020; Mittal et al. 2017; Gota et al. 2019; Wilson et al. 2019; Creutzig et al. 2016;  
14 Sharmina et al. 2020; Pietzcker et al. 2014; Lefèvre et al. 2021; Müller-Casseres et al. 2021a,b).

15  
16 As a result of these missing options and differences in how mitigation is implemented, IAMs tend to  
17 show less mitigation than the potential from national transport/energy models (Wachsmuth and  
18 Duscha 2019; Gota et al. 2019; Yeh et al. 2017; Edelenbosch et al. 2020). For the transport sector as a  
19 whole, studies suggest a mitigation potential of 4-5 GtCO<sub>2</sub> per year in 2030 (Edelenbosch et al. 2020)  
20 with complete decarbonization possible by 2050 (Gota et al. 2019; Wachsmuth and Duscha 2019).  
21 However, in the scenarios assessed in this chapter that limit warming to below 1.5°C with no or  
22 limited overshoot, transport sector CO<sub>2</sub> emissions are reduced by only 59% (28% to 81%) in 2050  
23 compared to 2015. IAM pathways also show less electrification than the potential from other studies;  
24 pathways that limit warming to below 1.5°C with no or limited overshoot show a median of 25% (7 to  
25 43%) of final energy from electricity in 2050, while the IEA NZE scenario includes 45% (IEA  
26 2021a).

27

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FOOTNOTE <sup>13</sup> Some of these models are treated as global transport energy sectoral models (GTEMs) in Chapter 10.

1 **3.4.5 Industry**

2  
3 **Figure 3.26: Industrial final energy, including feedstocks (top left), CO<sub>2</sub> emissions (top middle), carbon**  
4 **intensity (top right), energy intensity (bottom left), share of final energy from electricity (bottom middle),**  
5 **and share of final energy from gases (bottom right). Energy intensity is final energy per unit of GDP.**  
6 **Carbon intensity is CO<sub>2</sub> emissions per EJ of final energy. The first four indicators are indexed to 2019,<sup>14</sup>**  
7 **where values less than 1 indicate a reduction. Industrial sector CO<sub>2</sub> emissions include fuel combustion**  
8 **emissions only.**

9 Reference scenarios show declines in energy intensity, but increases in final energy use in the  
10 industrial sector (Edelenbosch et al. 2017b). These scenarios show increases in CO<sub>2</sub> emissions both  
11 for the total industrial sector (Edelenbosch et al. 2020; Luderer et al. 2018; Edelenbosch et al. 2017b)  
12 and individual subsectors like cement and iron and steel (van Ruijven et al. 2016; van Sluisveld et al.  
13 2021) or chemicals (Daioglou et al. 2014; van Sluisveld et al. 2021).

14 In mitigation pathways, CO<sub>2</sub> emissions reductions are achieved through a combination of energy  
15 savings (via energy efficiency improvements and energy conservation), structural change, fuel  
16 switching, and decarbonization of fuels (Grubler et al. 2018; Luderer et al. 2018; Edelenbosch et al.  
17 2017b, 2020). Mitigation pathways show reductions in final energy for industry compared to the  
18 baseline (Edelenbosch et al. 2017b; Luderer et al. 2018; Edelenbosch et al. 2020) and reductions in  
19 the carbon intensity of the industrial sector through both fuel switching and the use of CCS (Paltsev et  
20 al. 2021; Luderer et al. 2018; Edelenbosch et al. 2017b, 2020; van Ruijven et al. 2016; van Sluisveld  
21 et al. 2021). The mitigation potential differs depending on the industrial subsector and the availability  
22 of CCS, with larger potential reductions in the steel sector (van Ruijven et al. 2016) and cement  
23 industry (Sanjuán et al. 2020) than in the chemicals sector (Daioglou et al. 2014). Many scenarios,  
24 including stringent mitigation scenarios, show continued growth in final energy; however, the carbon  
25 intensity of energy declines in all mitigation scenarios (Figure 3.26).

26 The representation of the industry sector is very aggregate in most IAMs, with only a small subset of  
27 models disaggregating key sectors such as cement, fertilizer, chemicals, and iron and steel (Pauliuk et

FOOTNOTE <sup>14</sup> 2019 values are from model results and interpolated from other years when not directly reported.

1 al. 2017; Edelenbosch et al. 2017b; Daioglou et al. 2014; van Sluisveld et al. 2021) (Napp et al. 2019).  
2 IAMs often account for both energy combustion and feedstocks (Edelenbosch et al. 2017b), but IAMs  
3 typically ignore material flows and miss linkages between sectors (Kermeli et al. 2019; Pauliuk et al.  
4 2017). By excluding these processes, IAMs misrepresent the mitigation potential of the industry  
5 sector, e.g. by overlooking mitigation from material efficiency and circular economies (Sharmina et  
6 al. 2020), which can have substantial mitigation potential (Chapter 5.3.4, Chapter 11.3).

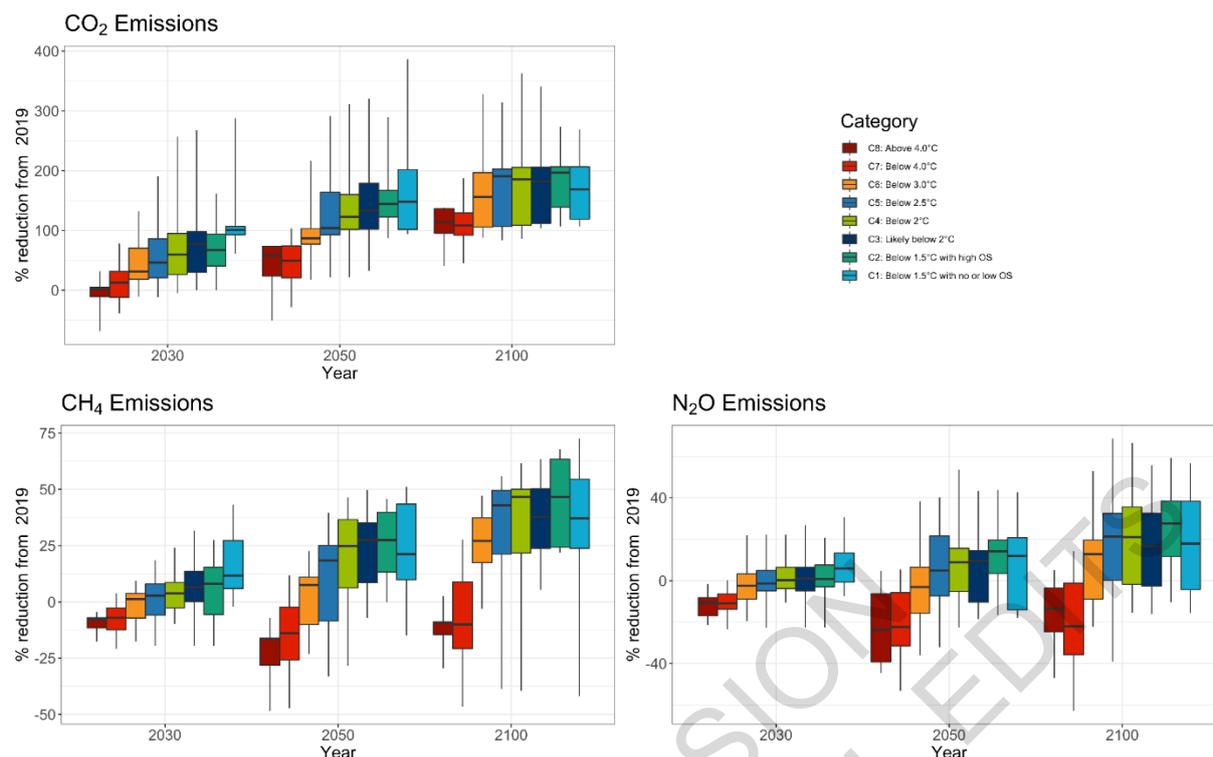
7 Sectoral studies indicate a large mitigation potential in the industrial sector by 2050, including the  
8 potential for net zero CO<sub>2</sub> emissions for steel, plastics, ammonia, and cement (Section 11.4.1).  
9 Detailed industry sector pathways show emissions reductions between 39 and 94% by mid-century  
10 compared to present day<sup>15</sup> (Section 11.4.2) and a substantial increase in direct electrification (IEA  
11 2021a). IAMs show comparable mitigation potential to sectoral studies with median reductions in  
12 CO<sub>2</sub> emissions between 2019 and 2050 of 70% in scenarios likely to limit warming to 2°C and below  
13 and a maximum reduction of 96% (Figure 3.26). Some differences between IAMs and sectoral models  
14 can be attributed to differences in technology availability, with IAMs sometimes including more  
15 technologies (van Ruijven et al. 2016) and sometimes less (Sharmina et al. 2020). Figure 3.27:  
16 Reduction in AFOLU GHG emissions from 2019. The AFOLU CO<sub>2</sub> estimates in this figure are not  
17 necessarily comparable with country GHG inventories (see Chapter 7).

### 18 **3.4.6 Agriculture, Forestry and Other Land Use (AFOLU)**

19 Mitigation pathways show substantial reductions in CO<sub>2</sub> emissions, but more modest reductions in  
20 AFOLU CH<sub>4</sub> and N<sub>2</sub>O emissions (*high confidence*) (Popp et al. 2017; Roe et al. 2019; Reisinger et al.  
21 2021) (Figure 3.27). Pathways limiting warming to likely 2°C or below are projected to reach net zero  
22 CO<sub>2</sub> emissions in the AFOLU sector around 2033 (2024-2060); however AFOLU CH<sub>4</sub> and N<sub>2</sub>O  
23 emissions remain positive in all pathways (Figure 3.27). While IAMs include many land-based  
24 mitigation options, these models exclude several options with large mitigation potential, such as  
25 biochar, agroforestry, restoration/avoided conversion of coastal wetlands, and restoration/avoided  
26 conversion of peatland (Smith et al. 2019; IPCC 2019a) (see also Chapter 7, Section 3.4). Sectoral  
27 studies show higher mitigation potential than IAM pathways, as these studies include more mitigation  
28 options than IAMs (*medium confidence*) (Chapter 7).  
29

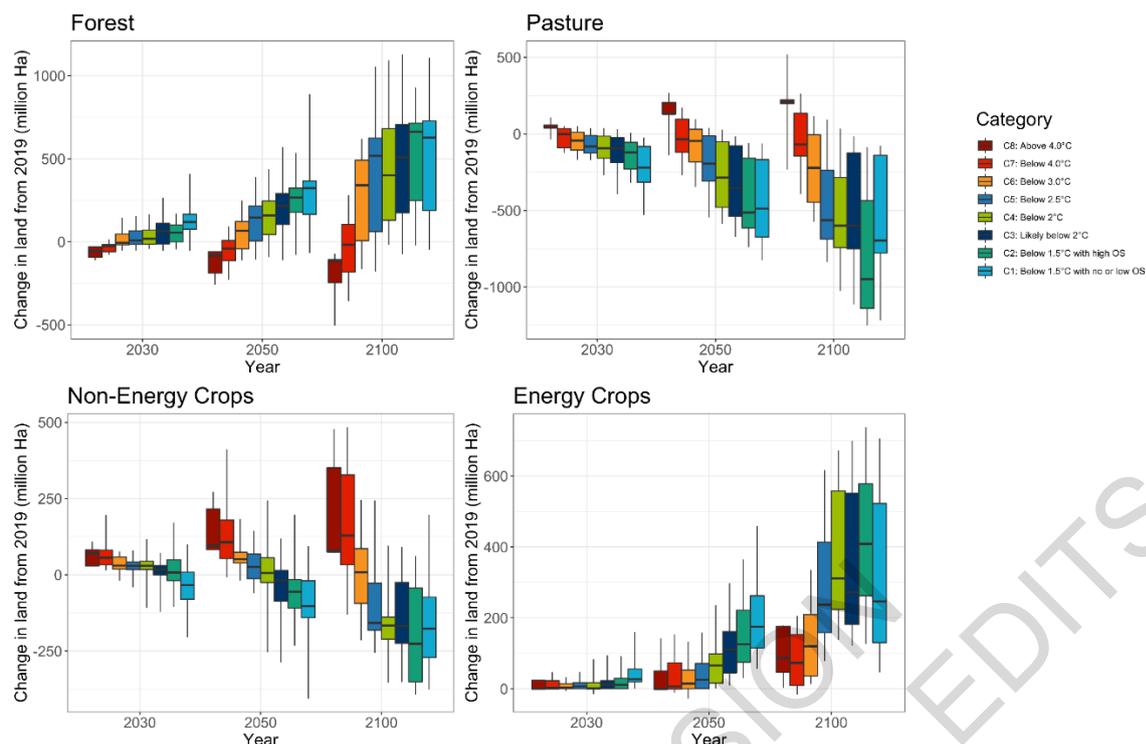
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FOOTNOTE <sup>15</sup> Some studies calculate emissions reductions in 2050 compared to 2014, while others note emissions reductions in 2060 relative to 2018.



1  
2 **Figure 3.27: Reduction in AFOLU GHG emissions from 2019. The AFOLU CO<sub>2</sub> estimates in this figure**  
3 **are not necessarily comparable with country GHG inventories (see Chapter 7).**

4 Limiting warming to likely 2°C or below can result in large scale transformation of the land surface  
5 (*high confidence*) (Popp et al. 2017; Rogelj et al. 2018a,b; Brown et al. 2019; Roe et al. 2019). The  
6 scale of land transformation depends, *inter alia*, on the temperature goal and the mitigation options  
7 included (Popp et al. 2017; Rogelj et al. 2018a; IPCC 2019a). Pathways with more demand-side  
8 mitigation options show less land transformation than those with more limited options (van Vuuren et  
9 al. 2018; Grubler et al. 2018; IPCC 2019a). Most of these pathways show increases in forest cover,  
10 with an increase of 322 million ha (-67 to 890 million ha) in 2050 in 1.5°C pathways with no or  
11 limited overshoot, whereas bottom up models portray an economic potential of 300-500 million ha of  
12 additional forest (Chapter 7). Many IAM pathways also include large amounts of energy cropland  
13 area, to supply biomass for bioenergy and BECCS, with 199 (56-482) million ha in 2050 in 1.5°C  
14 pathways with no or limited overshoot. Large land transformations, such as afforestation/reforestation  
15 and widespread planting of energy crops, can have implications for biodiversity and sustainable  
16 development (see Section 3.7, Chapter 7 - Subsection 7.7.4, Chapter 12 - Section 12.5).



**Figure 3.28: Change in Land Cover from 2019 in million hectares. Positive values indicate an increase in area.**

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

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

Chapter 5). Maintaining the resultant high vegetation and soil carbon stocks could limit future land use options, as maintaining these carbon stocks would require retaining the land use and land cover configuration implemented to achieve the increased stocks.

Anthropogenic land CO<sub>2</sub> emissions and removals in IAM pathways cannot be directly compared with those reported in national GHG inventories (high confidence) (Grassi et al. 2018, 2021) (Chapter 7.2).

Due to differences in definitions for the area of managed forests and what is emissions and removals are considered anthropogenic, the reported anthropogenic land CO<sub>2</sub> emissions and removals differ by ~5.5 GtCO<sub>2</sub> yr<sup>-1</sup> between IAMs, which rely on bookkeeping approaches (e.g., (Houghton and Nassikas 2017), and national GHG inventories (Grassi et al. 2021). Such differences in definitions can alter the reported time at which anthropogenic net zero CO<sub>2</sub> emissions are reached for a given emission scenario. Using national inventories would lead to an earlier reported time of net zero (van Soest et al. 2021b) or to lower calculated cumulative emissions until the time of net zero (Grassi et al. 2021) as compared to IAM pathways. The numerical differences are purely due to differences in the conventions applied for reporting the anthropogenic emissions and do not have any implications for the underlying land-use changes or mitigation measures in the pathways. Grassi et al. (Grassi et al. 2021) offers a methodology for adjusting to reconcile these differences and enable a more accurate assessment of the collective progress achieved under the Paris Agreement (Chapter 7, Cross-Chapter Box 6 in Chapter 7).

### 3.4.7 Other Carbon Dioxide Removal Options

**Table 3.5: Carbon dioxide removal in assessed pathways. Scenarios are grouped by temperature categories, as defined in section 3.2.4. Quantity indicates the median and 5-95% range of cumulative sequestration from 2020 to 2100 in GtCO<sub>2</sub>. Count indicates the number of scenarios with positive values for that option.**

CDR Option	Below 1.5°C with no or limited OS		Below 1.5°C with high OS		Likely below 2°C	
	Quantity	Count	Quantity	Count	Quantity	Count
Total CDR	584 (192 to 959)	95	645 (333 to 1221)	123	533 (193 to 895)	294
CO <sub>2</sub> removal on managed land including A/R	262 (17 to 397)	64	330 (28 to 439)	82	209 (20 to 415)	196
BECCS	334 (32 to 780)	91	464 (226 to 842)	122	291 (174 to 653)	294
Enhanced weathering	0 (0 to 47)	2	0 (0 to 0)	1	0 (0 to 0)	1
DACCS	30 (0 to 308)	31	109 (0 to 539)	24	19 (0 to 253)	91

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

1 detailed description of the individual technologies, including their costs, potentials, financing, risks,  
2 impacts, maturity and upscaling.

3 Very few studies and pathways include other CDR options (Table 3.5). Pathways with DACCS  
4 include potentially large removal from DACCS (up to 37 GtCO<sub>2</sub> yr<sup>-1</sup> in 2100) in the second half of the  
5 century (Realmonte et al. 2019; Marcucci et al. 2017; Chen and Tavoni 2013; Fuhrman et al. 2020,  
6 2021; Shayegh et al. 2021; Akimoto et al. 2021) and reduced cost of mitigation (Bistline and Blanford  
7 2021; Strefler et al. 2021a). At large scales, the use of DACCS has substantial implications for energy  
8 use, emissions, land, and water; substituting DACCS for BECCS results in increased energy usage,  
9 but reduced land use change and water withdrawals (Fuhrman et al., 2020, 2021; Chapter 12.3.2;  
10 IPCC WGI Chapter 5). The level of deployment of DACCS is sensitive to the rate at which it can be  
11 scaled up, the climate goal or carbon budget, the underlying socioeconomic scenario, the availability  
12 of other decarbonization options, the cost of DACCS and other mitigation options, and the strength of  
13 carbon cycle feedbacks (Honegger and Reiner 2018; Fuss et al. 2013; Fuhrman et al. 2021; Bistline  
14 and Blanford 2021; Chen and Tavoni 2013; Strefler et al. 2021a; Fuhrman et al. 2020; Realmonte et  
15 al. 2019) (IPCC WGI Chapter 5). Since DACCS consumes energy, its effectiveness depends on the  
16 type of energy used; the use of fossil fuels would reduce its sequestration efficiency (Creutzig et al.  
17 2019; Babacan et al. 2020; NASEM 2019). Studies with additional CDR options in addition to  
18 DACCS (e.g., enhanced weathering, BECCS, afforestation, biochar, and soil carbon sequestration)  
19 find that CO<sub>2</sub> removal is spread across available options (Holz et al. 2018; Strefler et al. 2021a).  
20 Similar to DACCS, the deployment of deep ocean storage depends on cost and the strength of carbon  
21 cycle feedbacks (Rickels et al. 2018).

22  
23

### 24 **3.5 Interaction between near-, medium- and long-term action in** 25 **mitigation pathways**

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

31 The assessment in this section shows that if mitigation ambitions in current NDCs<sup>16</sup> are followed until  
32 2030, leading to estimated emissions of 47-57 GtCO<sub>2</sub>-eq in 2030<sup>17</sup> (Chapter 4.2.2), it is no longer  
33 possible to stay below 1.5°C warming with no or limited overshoot (*high confidence*). Instead, it  
34 would entail high overshoot (typically >0.1°C) and reliance on net negative CO<sub>2</sub> emissions with  
35 uncertain potential to return warming to 1.5°C by the end of the century. It would also strongly  
36 increase mitigation challenges to likely limit warming to 2°C (*high confidence*). GHG emissions

---

FOOTNOTE <sup>16</sup> The term “**current NDCs**” used in this section and throughout the report refers to the most recent nationally determined contributions submitted to the UNFCCC as well as those publicly announced with sufficient detail on targets, but not yet submitted, up to 11 October 2021, and reflected in studies published up to 11 October 2021. In contrast, “**original NDCs**” refers to nationally determined contributions that were initially submitted to the Paris Agreement by parties, largely reflecting the state of submissions until the year 2019. See Chapter 4.2.

FOOTNOTE <sup>17</sup> In this section, the emissions range associated with current (or original) NDCs refer to the combined emissions ranges from the two cases of implementing only the unconditional elements of current NDCs (50-57 GtCO<sub>2</sub>-eq) and implementing both unconditional and conditional elements of current NDCs (47-53 GtCO<sub>2</sub>-eq), if not specified otherwise.

1 reductions would need to abruptly increase after 2030 to an annual average rate of 1.3-2.1 GtCO<sub>2</sub>-eq  
2 during the period 2030-2050, around 70% higher than in mitigation pathways assuming immediate  
3 action<sup>18</sup> to likely limit warming to 2°C. The higher post-2030 reduction rates would have to be  
4 obtained in an environment of continued build-up of fossil fuel infrastructure and less development of  
5 low carbon alternatives until 2030. A lock-in into fossil-fuel intensive production systems (carbon  
6 lock-in) will increase the societal, economic and political strain of a rapid low-carbon transition after  
7 2030 (*high confidence*).

8 The section builds on previous assessments in the IPCC's Fifth Assessment Report (Clarke et al.  
9 2014) and Special Report on 1.5°C Warming (Rogelj et al. 2018a). The literature assessed in these  
10 two reports has focused on delayed action until 2030 in the context of limiting warming to 2°C (den  
11 Elzen et al. 2010; van Vuuren and Riahi 2011; Kriegler et al. 2015; Luderer et al. 2013, 2016; Riahi et  
12 al. 2015; Rogelj et al. 2013a) and 1.5°C (Strefler et al. 2018; Luderer et al. 2018; Rogelj et al. 2013b).  
13 Here we provide an update of these assessments drawing on the most recent literature on global  
14 mitigation pathways. New studies have focused, inter alia, on constraining near term developments by  
15 peak warming limits (Rogelj et al. 2019b; Strefler et al. 2021b; Riahi et al. 2021) and updating  
16 assumptions about near- and medium term emissions developments based on national plans and long-  
17 term strategies (Roelfsema et al. 2020) (Chapter 4.2). Several studies have explored new types of  
18 pathways with accelerated action bridging between current policy plans and the goal of limiting  
19 warming below 2°C (Kriegler et al. 2018a; van Soest et al. 2021a) and looked at hybrid international  
20 policy regimes to phase in global collective action (Bauer et al. 2020).

### 21 **3.5.1 Relationship between long-term climate goals and near- to medium-term emissions** 22 **reductions**

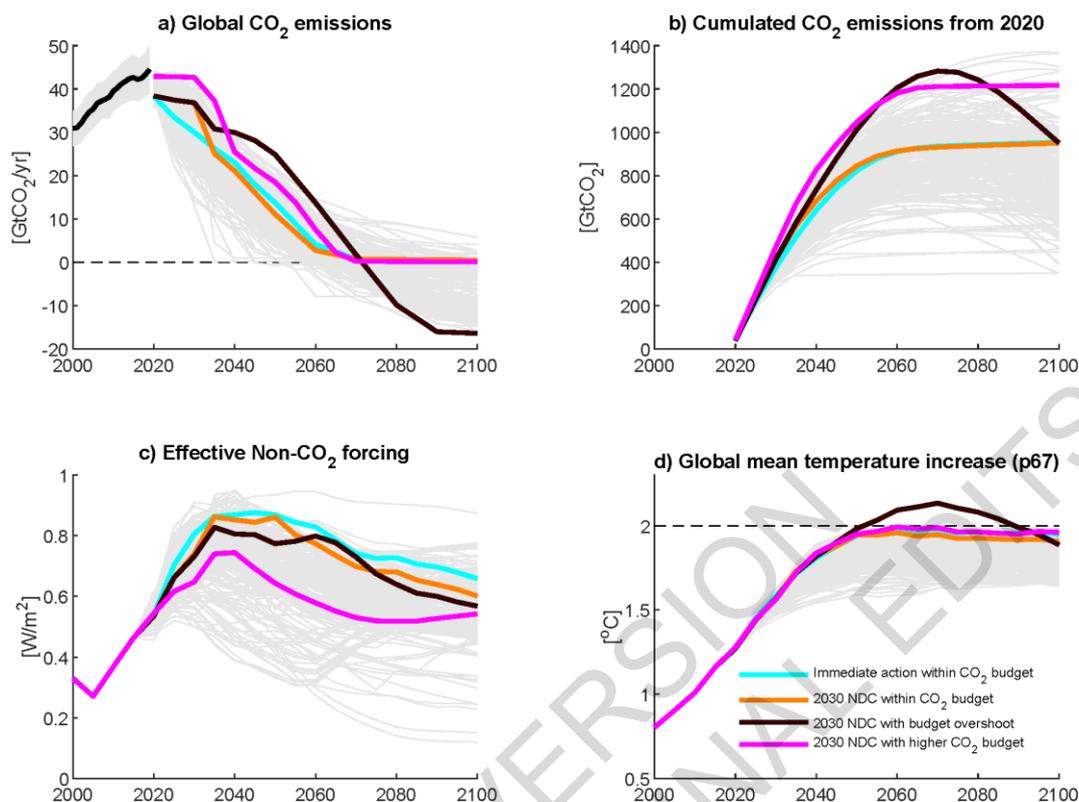
23 The close link between cumulative CO<sub>2</sub> emissions and warming has strong implications for the  
24 relationship between near-, medium-, and long-term climate action to limit global warming. The AR6  
25 WGI Assessment has estimated a remaining carbon budget of 500 (400) GtCO<sub>2</sub> from the beginning of  
26 2020 onwards for staying below 1.5°C with 50% (67%) likelihood, subject to additional uncertainties  
27 about historic warming and the climate response and variations in warming from non-CO<sub>2</sub> climate  
28 forcers (Canadell and Monteiro 2019) (see also WGI Chapter 5, Section 5.5). For comparison, if  
29 current CO<sub>2</sub> emissions of more than 40 GtCO<sub>2</sub> are keeping up until 2030, more than 400 GtCO<sub>2</sub> will  
30 be emitted during 2021–2030, already exhausting the remaining carbon budget for 1.5°C by 2030.

31 The relationship between warming limits and near term action is illustrated in Figure 3.29, using a set  
32 of 1.5-2°C scenarios with different levels of near term action, overshoot and non-CO<sub>2</sub> warming  
33 contribution from a recent study (Riahi et al. 2021). In general, the more CO<sub>2</sub> is emitted until 2030,  
34 the less CO<sub>2</sub> can be emitted thereafter to stay within a remaining carbon budget and below a warming  
35 limit. Scenarios with immediate action to observe the warming limit give the longest time to exhaust  
36 the associated remaining carbon budget and reach net zero CO<sub>2</sub> emissions (light blue line in Figure  
37 3.29, Cross-Chapter Box 3 in this chapter). In comparison, following projected NDC emissions until  
38 2030 would imply a more pronounced drop in emissions from 2030 levels to net zero to make up for  
39 the additional near-term emissions (orange lines in Figure 3.29). If such a drop does not occur, the  
40 remaining carbon budget is exceeded and net negative CO<sub>2</sub> emissions are required to return global  
41 mean temperature below the warming limit (black lines in Figure 3.29) (Fuss et al. 2014; Clarke et al.  
42 2014; Rogelj et al. 2018a).  
43

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FOOTNOTE <sup>18</sup> In this section, near term emissions outcomes are often compared to near term emissions in mitigation **pathways with immediate action** towards a warming limit. These are defined as pathways that immediately after imposing the warming limit turn to global mitigation action tapping into all least cost abatement options available globally. These pathways are often called cost-effective or least-cost pathways in the literature. The onset of immediate action is defined by scenario design and is typically chosen to be the first time step after 2020 in immediate action scenarios assessed in this report.

1 The relationship between warming limits and near-term action is also affected by the warming  
2 contribution of non-CO<sub>2</sub> greenhouse gases and other short lived climate forcers (3.3, Working Group I  
3 6.7). The estimated budget values for limiting warming to 1.5-2°C already assume stringent  
4 reductions in non-CO<sub>2</sub> greenhouse gases and non-CO<sub>2</sub> climate forcing as found in 1.5-2°C pathways  
5 (3.3, Cross-Working Group Box 1; Working Group I 5.5, Box 5.2). Further variations in non-CO<sub>2</sub>  
6 warming observed across 1.5-2°C pathways can vary the median estimate for the remaining carbon  
7 budget by 220 GtCO<sub>2</sub> (Working Group I 5.5). In 1.5-2°C pathways, the non-CO<sub>2</sub> warming  
8 contribution differs strongly between the near-, medium and long term. Changes to the atmospheric  
9 composition of short-lived climate forcers dominate the warming response in the near term (Working  
10 Group I 6.7). CO<sub>2</sub> reductions are combined with strong reductions in air pollutant emissions due to  
11 rapid reduction in fossil fuel combustion and in some cases the assumption of stringent air quality  
12 policies (Rao et al. 2017b; Smith et al. 2020c). As air pollutants exert a net cooling effect, their  
13 reduction drives up non-CO<sub>2</sub> warming in the near term, which can be attenuated by the simultaneous  
14 reduction of methane and black carbon (Smith et al. 2020b; Shindell and Smith 2019) (Working  
15 Group I 6.7). After 2030, the reduction in methane concentrations and associated reductions in  
16 tropospheric ozone levels tend to dominate so that a peak and decline in non-CO<sub>2</sub> forcing and non-  
17 CO<sub>2</sub> induced warming can occur before net zero CO<sub>2</sub> is reached (Figure 3.29) (Rogelj et al. 2018a)  
18 The more stringent the reductions in methane and other short-lived warming agents like black carbon,  
19 the lower this peak and the earlier the decline of non-CO<sub>2</sub> warming, leading to a reduction of warming  
20 rates and overall warming in the near to medium term (Smith et al. 2020b; Harmsen et al. 2020). This  
21 is important for keeping warming below a tight warming limit that is already reached around mid-  
22 century as is the case in 1.5°C pathways (Xu and Ramanathan 2017). Early and deep reductions of  
23 methane emissions, and other short-lived warming agents like black carbon, provide space for residual  
24 CO<sub>2</sub>-induced warming until the point of net zero CO<sub>2</sub> emissions is reached (purple lines in Figure  
25 3.29). Such emissions reductions have also been advocated due to co-benefits for, e.g., reducing air  
26 pollution (Rao et al. 2016; Shindell et al. 2017a, 2018; Shindell and Smith 2019; Rauner et al. 2020a;  
27 Vandyck et al. 2020).



1  
2 **Figure 3.29: Illustration of emissions and climate response in four mitigation pathways with different**  
3 **assumptions about near term policy developments, global warming limit and non-CO<sub>2</sub> warming**  
4 **contribution drawn from Riahi et al. (2021). Shown are (a) CO<sub>2</sub> emissions trajectories, (b) cumulative**  
5 **CO<sub>2</sub> emissions, (c) effective non-CO<sub>2</sub> radiative forcing, and (d) the resulting estimate of the 67<sup>th</sup> percentile**  
6 **of global mean temperature response relative to 1850-1900. Light blue lines show a scenario that acts**  
7 **immediately on a remaining carbon budget of 900 GtCO<sub>2</sub> from 2020 without allowing net negative CO<sub>2</sub>**  
8 **emissions, i.e., temporary budget overshoot (COFFEE 1.1, Scenario EN\_NPi2020\_900). Orange and black**  
9 **lines show scenarios drawn from the same model that follow the NDCs until 2030 and thereafter**  
10 **introduce action to stay within the same budget – in one case excluding net negative CO<sub>2</sub> emissions like**  
11 **before (orange lines; COFFEE 1.1, Scenario EN-INDCi2030\_900) and in the other allowing for a**  
12 **temporary overshoot of the carbon budget until 2100 (black lines; COFFEE 1.1, Scenario EN-**  
13 **INDCi2030\_900f). Light blue lines describe a scenario following the NDCs until 2030, and then aiming for**  
14 **a higher budget of 2300 GtCO<sub>2</sub> without overshoot (AIM/CGE 2.2, Scenario EN-INDCi2030\_1200). It is**  
15 **drawn from another model which projects a lower anthropogenic non-CO<sub>2</sub> forcing contribution and**  
16 **therefore achieves about the same temperature outcome as the other two non-overshoot scenarios despite**  
17 **the higher CO<sub>2</sub> budget. Grey funnels include the trajectories from all scenarios that likely limit warming**  
18 **to 2°C (Category C3). Historical CO<sub>2</sub> emissions until 2019 are from Chapter SM.2.1 EDGAR v6.0.**

19 The relationship between long-term climate goals and near term action is further constrained by  
20 social, technological, economic and political factors (Aghion et al. 2019; Mercure et al. 2019; van  
21 Sluisveld et al. 2018b; Cherp et al. 2018; Jewell and Cherp 2020; Trutnevte et al. 2019b). These  
22 factors influence path dependency and transition speed (Vogt-Schilb et al. 2018; Pahle et al. 2018).  
23 While detailed integrated assessment modelling of global mitigation pathways accounts for  
24 technology inertia (Bertram et al. 2015a; Mercure et al. 2018) and technology innovation and  
25 diffusion (Wilson et al. 2013; van Sluisveld et al. 2018a; Luderer et al. 2021), there are limitations in  
26 capturing socio-technical and political drivers of innovation, diffusion and transition processes  
27 (Keppo et al. 2021; Gambhir et al. 2019; Hirt et al. 2020; Köhler et al. 2019). Mitigation pathways  
28 show a wide range of transition speeds that have been interrogated in the context of socio-technical

1 inertia (Gambhir et al. 2017; Kefford et al. 2018; Kriegler et al. 2018a; Brutschin et al. 2021) vs.  
2 accelerating technological change and self-enforcing socio-economic developments (Creutzig et al.  
3 2017; Zenghelis 2019) (Section 3.8). Diagnostic analysis of detailed IAMs found a lag of 8-20 years  
4 between the convergence of emissions pricing and the convergence of emissions response after a  
5 period of differentiated emission prices (Harmsen et al. 2021). This provides a measure of the inertia  
6 to changing policy signals in the model response. It is about half the timescale of 20-40 years  
7 observed for major energy transitions (Grubb et al. 2021). Hence, the mitigation pathways assessed  
8 here capture socio-technical inertia in reducing emissions, but the limited modelling of socio-political  
9 factors may alter the extent and persistence of this inertia.

### 10 11 **3.5.2 Implications of near-term emission levels for keeping long-term climate goals within** 12 **reach**

13 The implications of near-term climate action for long-term climate outcomes can be explored by  
14 comparing mitigation pathways with different near-term emissions developments aiming for the same  
15 climate target (Vrontisi et al. 2018; Riahi et al. 2015; Roelfsema et al. 2020). A particular example is  
16 the comparison of cost-effective pathways with immediate action to limit warming to 1.5-2°C with  
17 mitigation pathways pursuing more moderate mitigation action until 2030. After the adoption of the  
18 Paris Agreement, near term action was often modelled to reflect conditional and unconditional  
19 elements of originally submitted NDCs (2015-2019) (Fawcett et al. 2015; Fujimori et al. 2016a;  
20 Kriegler et al. 2018a; Vrontisi et al. 2018; Roelfsema et al. 2020). The most recent modelling studies  
21 also include submission of updated NDCs or announcements of planned updates in the first half of  
22 2021 (Network for Greening the Financial System 2021; Riahi et al. 2021). Emissions levels under  
23 current NDCs (see footnote 15) are assessed to range between 47–57 GtCO<sub>2</sub>-eq in 2030 (Chapter  
24 4.2.2). This assessed range corresponds well to 2030 emissions levels in 2°C mitigation pathways in  
25 the literature that are designed to follow the original or current NDCs until 2030<sup>19</sup>. For the 139  
26 scenarios of this kind that are collected in the AR6 scenario database and that still likely limit  
27 warming to 2°C, the 2030 emissions range is 52.5 (44.5-57) GtCO<sub>2</sub>-eq (based on native model  
28 reporting) and 52 (46.5-56) GtCO<sub>2</sub>-eq, respectively (based on harmonized emissions data for climate  
29 assessment (Annex III part II section 2.4); median and 5<sup>th</sup> to 95<sup>th</sup> percentile). This close match allows  
30 a robust assessment of the implications of implementing current NDCs for post-2030 mitigation  
31 efforts and warming outcomes based on the literature and the AR6 scenarios database.

32 The assessed emission ranges from implementing the unconditional (unconditional and conditional)  
33 elements of current NDCs implies an emissions gap to cost-effective mitigation pathways of 20-26  
34 (16-24) GtCO<sub>2</sub>-eq in 2030 for limiting warming to 1.5°C with no or limited overshoot and 10-17 (7-  
35 14) GtCO<sub>2</sub>-eq in 2030 for likely limiting warming to 2°C (Chapter 4, Cross-Chapter Box 2 in chapter  
36 2). The emissions gap gives rise to a number of mitigation challenges (Rogelj et al. 2013a; Kriegler et  
37 al. 2013a, 2018b,a; Riahi et al. 2015; Luderer et al. 2013, 2018; Fujimori et al. 2016b; Fawcett et al.  
38 2015; Strefler et al. 2018; Winning et al. 2019; UNEP 2020; SEI et al. 2020): (i) larger transitional  
39 challenges post-2030 to still remain under the warming limit (, in particular higher CO<sub>2</sub> emissions  
40 reduction rates and technology transition rates required during 2030-2050; (ii) larger lock-in into  
41 carbon-intensive infrastructure and increased risk of stranded fossil fuel assets (3.5.2.2); and (iii)  
42 larger reliance on CDR to reach net zero CO<sub>2</sub> more rapidly and compensate excess emissions in the  
43 second half of the century (3.5.2.1). All these factors exacerbate socio-economic strain of

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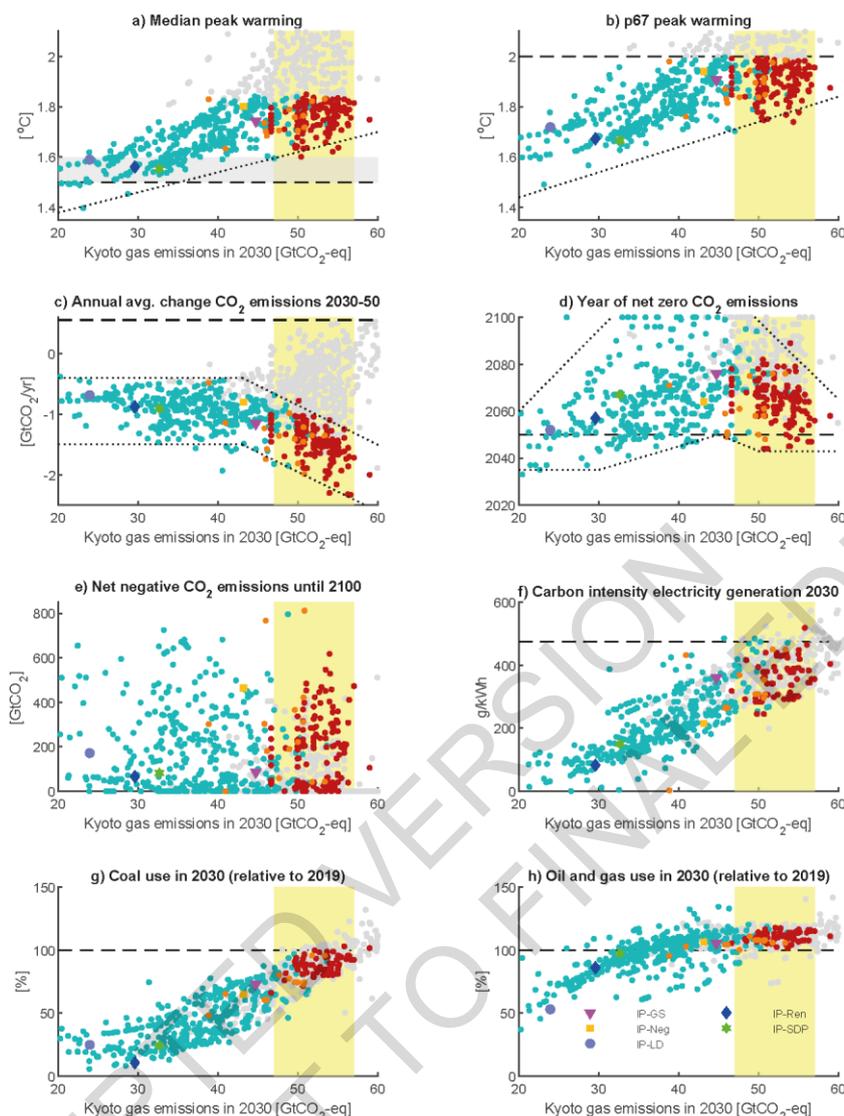
FOOTNOTE <sup>19</sup> The intended design of mitigation pathways in the literature can be deduced from underlying publications and study protocols. This information was collected as part of this assessment to establish a categorization of policy assumptions underpinning the mitigation pathways collected in the AR6 scenario database (3.2; Annex III Part II section 3.2).

1 implementing the transition, leading to an increased risk of overshooting the warming and a higher  
2 risk of climate change impacts (Drouet et al. 2021).

3 The challenges are illustrated in Table 3.6 and Figure 3.30, surveying global mitigation pathways in  
4 the literature that were collected in the AR6 scenarios database. There is a clear trend of increasing  
5 peak warming with increasing 2030 GHG emission levels (Figure 3.30a+b). In particular, there is no  
6 mitigation pathway designed to follow the NDCs until 2030 in 2030 that can limit warming to 1.5°C  
7 with no or limited overshoot. Our assessment confirms the finding of the IPCC Special Report on  
8 1.5°C Warming for the case of current NDCs, including updates until 11 October 2021 that were  
9 assessed in the literature, that pathways following the NDCs until 2030 “*would not limit global*  
10 *warming to 1.5°C, even if supplemented by very challenging increases in the scale and ambition of*  
11 *emissions reductions after 2030*” (SR1.5 SPM). This assessment is now more robust than in SR1.5 as  
12 it is based on a larger set of 1.5-2°C pathways with better representation of current trends and plans  
13 covering a wider range of post-2030 emissions developments. In particular, a recent multi-model  
14 study limiting peak cumulative CO<sub>2</sub> emissions for a wide range of carbon budgets and immediate vs  
15 NDC-type action until 2030 established a feasibility frontier for the existence of such pathways across  
16 participating models (Riahi et al. 2021).

17 2030 emissions levels in the NDC range also tighten the remaining space to likely limit warming 2°C.  
18 As shown in Figure 3.30b, the 67<sup>th</sup> percentile of peak warming reaches values above 1.7°C warming  
19 in pathways with 2030 emissions levels in this range. To still have a likely chance to stay below 2°C,  
20 the global post-2030 GHG emission reduction rates would need to be abruptly raised in 2030 from 0-  
21 0.8 GtCO<sub>2</sub>-eq yr<sup>-1</sup> to an average of 1.3-2.1 GtCO<sub>2</sub>-eq yr<sup>-1</sup> during the period 2030-2050 (Figure 3.30c),  
22 around 70% of that in immediate mitigation pathways confirming findings in the literature (Winning  
23 et al. 2019). Their average reduction rate of 0.6-1.4 GtCO<sub>2</sub> yr<sup>-1</sup> would already be unprecedented at the  
24 global scale and with a few exceptions national scale for an extended period of time (Riahi et al.  
25 2015). For comparison, the impact of COVID-19 on the global economy is projected to lead to a  
26 decline of ca. 2.5-3 GtCO<sub>2</sub> of global CO<sub>2</sub> emissions from fossil fuel and industry in 2020  
27 (Friedlingstein et al. 2020) (Chapter 2.2).

28 The increased post-2030 transition challenge in mitigation pathways with moderate near term action is  
29 also reflected in the timing of reaching net zero CO<sub>2</sub> emissions (Figure 3.30d and Table 3.6) (Cross-  
30 Chapter Box 3 in this chapter). As 2030 emission levels and the cumulated CO<sub>2</sub> emissions until 2030  
31 increase, the remaining time for dropping to net zero CO<sub>2</sub> and staying within the remaining carbon  
32 budget shortens (Figure 3.29). This gives rise to an inverted v-shape of the lower bound on the year of  
33 reaching net zero as a function of 2030 emissions levels. Reaching low in 2030 facilitates reaching net  
34 zero early (left leg of the inverted v), but staying high until 2030 also requires to reach net zero CO<sub>2</sub>  
35 faster to compensate for higher emissions early on (right leg of the inverted v). Overall, there is a  
36 considerable spread of the timing of net zero CO<sub>2</sub> for any 2030 emissions level due to variation in the  
37 timing of spending the remaining carbon budget and the non-CO<sub>2</sub> warming contribution (Cross-  
38 Chapter Box 3 in this chapter).



1  
 2 **Figure 3.30: Relationship between level of global GHG emissions in 2030 and selected indicators as listed**  
 3 **in the panel titles for scenarios collected in the AR6 scenario database. Emissions data based on**  
 4 **harmonized emissions used for the climate assessment. All scenarios likely to limit warming to 2°C or**  
 5 **below are coloured blue or red (see p67 peak warming in panel b). The large majority of blue coloured**  
 6 **scenarios act immediately on the temperature target, while red coloured scenarios depict all those that**  
 7 **were designed to follow the NDCs or lesser action until 2030 and orange coloured scenarios comprise a**  
 8 **small set of pathways with additional regulatory action beyond NDCs (3.5.3). Grey coloured scenarios**  
 9 **exceed the 2°C (p67), either by temporary overshoot or towards the end of the century. Large markers**  
 10 **denote the 5 illustrative mitigation pathways (legend in Panel h; Section 3.2). Shaded yellow areas depict**  
 11 **the estimated range of 2030 emissions from current NDCs (Chapter 4.2.2). Dotted lines are inserted in**  
 12 **some panels to highlight trends in the dependency of selected output variables on 2030 GHG emissions**  
 13 **levels (see text)**

14 There is also a profound impact on the underlying transition of energy and land use (Table 3.6 and  
 15 Figure 3.30f-h). Scenarios following NDCs until 2030 show a much smaller reduction in fossil fuel  
 16 use, only half of the growth in renewable energy use, and a smaller reduction in CO<sub>2</sub> and CH<sub>4</sub> land  
 17 use emissions in 2030 compared to immediate action scenarios. This is then followed by a much faster  
 18 reduction of land use emissions and fossil fuels, and a larger increase of nuclear energy, bioenergy  
 19 and non-biomass renewable energy during the medium term in order to get close to the levels of the

1 immediate action pathways in 2050. This is combined with a larger amount of net negative CO<sub>2</sub>  
 2 emissions that are used to compensate the additional emissions before 2030. The faster transition  
 3 during 2030-2050 is taking place from a greater investment in fossil fuel infrastructure and lower  
 4 deployment of low carbon alternatives in 2030, adding to the socio-economic challenges to realize the  
 5 higher transition rates (Section 3.5.2.2). Therefore, these pathways also show higher mitigation costs,  
 6 particularly during the period 2030-2050, than immediate action scenarios (3.6.1, Figure 3.34d) (Liu  
 7 et al. 2016; Vrontisi et al. 2018; Kriegler et al. 2018a).. Given these circumstances and the fact the  
 8 modelling of socio-political and institutional constraints is limited in integrated assessment models  
 9 (Keppo et al. 2021; Gambhir et al. 2019; Hirt et al. 2020; Köhler et al. 2019), the feasibility of  
 10 realizing these scenarios is assessed to be lower (Gambhir et al. 2017; Napp et al. 2017; Brutschin et  
 11 al. 2021) (cf. Section 3.8), increasing the risk of an overshoot of climate goals.

13 **Table 3.6: Comparison of key scenario characteristics for four scenario classes (see Table 3.2): (i)**  
 14 **immediate action to limit warming to 1.5°C with no or limited overshoot, (ii) near term action following**  
 15 **the NDCs until 2030 and returning warming to below 1.5°C (50% chance) by 2100 with high overshoot,**  
 16 **(iii) immediate action to likely limit warming to 2°C, and (iv) near term action following the NDCs until**  
 17 **2030 followed by post-2030 action to likely limit warming to 2°C. The classes (ii) and (iv) comprise the**  
 18 **large majority of scenarios indicated by red dots, and the classes (i) and (iii) the scenarios depicted by**  
 19 **blue dots in Figure 3.30. Shown are median and interquartile ranges (in brackets) for selected global**  
 20 **indicators. Emissions ranges are based on harmonized emissions data for the climate assessment with the**  
 21 **exception of land use CO<sub>2</sub> emissions for which uncertainty in historic estimates is large. Numbers are**  
 22 **rounded to the nearest 5.**

Global indicators	1.5°C	1.5°C by 2100	Likely < 2°C	
	Immediate action, with no or limited overshoot (C1, 97 scenarios)	NDCs until 2030, with overshoot before 2100 (subset of 42 scenarios in C2)	Immediate action (C3a, 204 scenarios)	NDCs until 2030 (C3b; 97 scenarios)
Kyoto GHG emissions in 2030 (% rel to 2019)	-45 (-50,-40)	-5 (-5,0)	-25 (-35,-20)	-5 (-10,0)
in 2050 (% rel to 2019)	-85 (-90,-80)	-75 (-85,-70)	-65 (-70,-60)	-70 (-70,-60)
CO <sub>2</sub> emissions change in 2030 (% rel to 2019)	-50 (-60,-40)	-5 (-5,0)	-25 (-35,-20)	-5 (-5,0)
in 2050 (% rel to 2019)	-100 (-105,-95)	-85 (-95,-80)	-70 (-80,-65)	-75 (-80,-65)
Net land use CO <sub>2</sub> emissions in 2030 (% rel to 2019)	-100 (-105,-95)	-30 (-60,-20)	-90 (-105,-75)	-20 (-80,-20)
in 2050 (% rel to 2019)	-150 (-200,-100)	-135 (-165,-120)	-135 (-185,-100)	-130 (-145,-115)
CH <sub>4</sub> emissions in 2030 (% rel to 2019)	-35 (-40,-30)	-5 (-5,0)	-25 (-35,-20)	-10 (-15,-5)
in 2050 (% rel to 2019)	-50 (-60,-45)	-50 (-60,-45)	-45 (-50,-40)	-50 (-65,-45)
Cumulative CCS until 2100 (GtCO <sub>2</sub> )	665 (520,900)	670 (535,865)	605 (490,895)	535 (440,725)
of which BECCS (GtCO <sub>2</sub> )	330 (250,560)	365 (280,590)	350 (240,455)	270 (240,400)
Cumulative net negative CO <sub>2</sub> emissions until 2100 (GtCO <sub>2</sub> )	190 (0,385)	320 (250,440)	10 (0,120)	70 (0,200)
Primary energy from coal in 2030 (% rel to 2019)	-75 (-80,-65)	-10 (-20,-5)	-50 (-65,-35)	-15 (-20,-10)
in 2050 (% rel to 2019)	-95 (-100,-80)	-90 (-100,-85)	-85 (-100,-65)	-80 (-90,-70)
Primary energy from oil in 2030 (% rel to 2019)	-10 (-25,0)	5 (5,10)	0 (-10,10)	10 (5,10)
in 2050 (% rel to 2019)	-60 (-75,-40)	-50 (-65,-30)	-30 (-45,-15)	-40 (-55,-20)

Primary energy from gas in 2030 (% rel to 2019)	-10 (-30,0)	15 (10,25)	10 (0,15)	15 (10,15)
in 2050 (% rel to 2019)	-45 (-60,-20)	-45 (-55,-25)	-10 (-35,15)	-30 (-45,-5)
Primary energy from nuclear in 2030 (% rel to 2019)	40 (5,70)	10 (0,25)	35 (5,50)	10 (0,30)
in 2050 (% rel to 2019)	90 (10,305)	100 (40,135)	85 (30,200)	75 (30,120)
Primary energy from biomass in 2030 (% rel to 2019)	75 (55,130)	45 (20,75)	60 (35,105)	45 (10,80)
in 2050 (% rel to 2019)	290 (215,430)	230 (170,440)	240 (130,355)	260 (95,435)
Primary energy from non-biomass renewables in 2030 (% rel to 2019)	225 (150,270)	100 (85,145)	150 (115,190)	115 (85,130)
in 2050 (% rel to 2019)	725 (540,955)	665 (515,925)	565 (415,765)	625 (545,705)
Carbon intensity of electricity in 2030 (% rel to 2019)	-75 (-85,-70)	-30 (-40,-30)	-60 (-70,-50)	-35 (-40,-30)
in 2050 (% rel to 2019)	-100 (-100,-100)	-100 (-100,-100)	-95 (-100,-95)	-100 (-100,-95)
Carbon intensity of non-electric final energy consumption in 2030 (% rel to 2019)	-40 (-50,-35)	0 (0,5)	-20 (-30,-15)	0 (0,0)
in 2050 (% rel to 2019)	-80 (-85,-75)	-70 (-75,-70)	-60 (-65,-55)	-65 (-70,-55)

### 3.5.2.1 Overshoot and net negative CO<sub>2</sub> emissions

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

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

1 Obtaining net negative CO<sub>2</sub> emissions requires massive deployment of carbon dioxide removal (CDR)  
2 in the second half of the century, on the order of 220 (160-370) GtCO<sub>2</sub> for each 0.1°C degree of  
3 cooling (based on the assessment of the likely range of the transient response to cumulative CO<sub>2</sub>  
4 emissions in WGI Chap. 5.5, not taking into account potential asymmetries in the temperature  
5 response to CO<sub>2</sub> emissions and removals). CDR is assessed in detail in Chapter 12.3 of this report (see  
6 also Cross-Chapter Box 8 in Chapter 12). Here we only point to the finding that CDR ramp-up rates  
7 and absolute deployment levels are tightly limited by techno-economic, social, political, institutional  
8 and sustainability constraints (Smith et al. 2016; Boysen et al. 2017; Nemet et al. 2018; Fuss et al.  
9 2018, 2020; Hilaire et al. 2019; Jia et al. 2019) (Chapter 12.3). CDR therefore cannot be deployed  
10 arbitrarily to compensate any degree of overshoot. A fraction of models was not able to compute  
11 pathways that would follow the mitigation ambition in unconditional and conditional NDCs until  
12 2030 and return warming to below 1.5°C by 2100 (Luderer et al. 2018; Roelfsema et al. 2020; Riahi  
13 et al. 2021). There exists a three-way trade-off between near-term emissions developments until 2030,  
14 transitional challenges during 2030-50, and long-term CDR deployment post 2050 (Sanderson et al.  
15 2016; Holz et al. 2018; Strefler et al. 2018). For example, Strefler et al. (2018) find that if CO<sub>2</sub>  
16 emission levels stay around 40 GtCO<sub>2</sub> until 2030, within the range of what is projected for current  
17 unconditional and conditional NDCs, rather than being halved to 20 GtCO<sub>2</sub> until 2030, CDR  
18 deployment in the second half of the century would have to increase by 50%-100%, depending on  
19 whether the 2030-2050 CO<sub>2</sub> emissions reduction rate is doubled from 6% to 12% or kept at 6% per  
20 year. This three-way trade-off has also been identified at the national level (Pan et al. 2020).

21  
22 In addition to enabling a temporary budget overshoot by net negative CO<sub>2</sub> emissions in the second  
23 half of the century, CDR can also be used to compensate – on an annual basis - residual CO<sub>2</sub>  
24 emissions from sources that are difficult to eliminate and to reach net zero CO<sub>2</sub> emissions more  
25 rapidly if deployed before this point (Kriegler et al. 2013b; Rogelj et al. 2018a). This explains its  
26 continued deployment in pathways that exclude overshoot and net negative CO<sub>2</sub> emissions (Riahi  
27 et al. 2021). However, given the timescales that would likely be needed to ramp-up CDR to Gigaton  
28 scale (Nemet et al. 2018), it can be expected to only make a limited contribution to reaching net zero  
29 CO<sub>2</sub> as fast as possible. In the vast majority (95%) of 1.5-2°C mitigation pathways assessed in this  
30 report, cumulative CDR deployment did not exceed 100 GtCO<sub>2</sub> until mid-century. This adds to the  
31 risk of excessively relying on CDR to compensate for weak mitigation action until 2030 by either  
32 facilitating massive net CO<sub>2</sub> emissions reduction rates during 2030-2050 or allowing a high temporary  
33 overshoot of 1.5°C until the end of the century. If international burden sharing considerations are  
34 taken into account, the CDR penalty for weak action could increase further, in particular for  
35 developed countries (Fyson et al. 2020). Further assessment of CDR deployment in 1.5-2°C  
36 mitigation pathways is found in Section 3.4.7.

### 37 38 **3.5.2.2 Carbon lock-in and stranded assets**

39 There already exists a substantial and growing carbon lock-in today, as measured by committed  
40 emissions associated with existing long-lived infrastructure {Chapter 2.7, Figure 2.31}. If existing  
41 fossil-fuel infrastructure would continue to be operated as historically, they would entail CO<sub>2</sub>  
42 emissions exceeding the carbon budget for 1.5°C {Chapter 2.7.2, Figure 2.32}. However, owner-  
43 operators and societies may choose to retire existing infrastructure earlier than in the past, and  
44 committed emissions are thus contingent on the competitiveness of non-emitting alternative  
45 technologies and climate policy ambition. Therefore, in mitigation pathways, some infrastructure may  
46 become stranded assets. Stranded assets have been defined as “assets that have suffered from  
47 unanticipated or premature write-downs, devaluations or conversion to liabilities” (Caldecott 2017).

48 A systematic map of the literature on carbon lock-in has synthesized quantification of stranded-assets  
49 in the mitigation pathways literature, and showed that (i) coal power plants are the most exposed to

1 risk of becoming stranded, (ii) delayed mitigation action increases stranded assets and (iii) sectoral  
2 distribution and amount of stranded assets differ between countries (Fisch-Romito et al. 2020). There  
3 is high agreement that existing fossil fuel infrastructure would need to be retired earlier than  
4 historically, used less, or retrofitted with CCS, to stay within the remaining carbon budgets of limiting  
5 warming to 1.5°C or 2°C (Johnson et al. 2016; Kefford et al. 2018; Pfeiffer et al. 2018; Cui et al.  
6 2019; Fofrich et al. 2020; Rogelj et al. 2018a). Studies estimate that cumulative early retired power  
7 plant capacities by 2060 can be up to 600 GW for gas and 1700 GW for coal (Iyer et al. 2015a;  
8 Kefford et al. 2018), that only 42% of the total capital stock of both operating and planned coal-fired  
9 powers plants can be utilized to be compatible with the 2°C target (Pfeiffer et al. 2018), and that coal-  
10 fired power plants in scenarios consistent with keeping global warming below 2°C or 1.5°C retire one  
11 to three decades earlier than historically has been the case (Cui et al. 2019; Fofrich et al. 2020). After  
12 coal, electricity production based on gas is also projected to be phased out, with some capacity  
13 remaining as back-up (van Soest et al. 2017a). Kefford et al. (2018) find USD541 billion worth of  
14 stranded fossil fuel power plants could be created by 2060, with China and India the most exposed.

15 Some publications have suggested that stranded long-lived assets may be even more important outside  
16 of the power sector. While stranded power sector assets by 2050 could reach up to USD1.8 trillion in  
17 scenarios consistent with a 2°C target, Saygin et al. (2019) found a range of USD5-11 trillion in the  
18 buildings sectors. Muldoon-Smith and Greenhalgh (2019) have even estimated a potential value at  
19 risk for global real estate assets up to USD21 trillion. More broadly, the set of economic activities that  
20 are potentially affected by a low carbon transition is wide and includes also energy-intensive  
21 industries, transport and housing, as reflected in the concept of climate policy relevant sectors  
22 introduced in Battiston et al. (2017). The sectoral distribution and amount of stranded assets differ  
23 across countries (Fisch-Romito et al. 2020). Capital for fossil fuel production and distribution  
24 represents a larger share of potentially stranded assets in fossil fuel producing countries such as the  
25 United States and Russia. Electricity generation would be a larger share of total stranded assets in  
26 emerging countries because this capital is relatively new compared to its operational lifetime.  
27 Conversely, buildings could represent a larger part of stranded capital in more developed countries  
28 such as the United States, EU or even Russia because of high market value and low turnover rate.

29 Many quantitative estimates of stranded assets along mitigation pathways have focused on fossil fuel  
30 power plants in pathways characterized by mitigation ambition until 2030 corresponding to the  
31 current NDCs followed by strengthened action afterwards to limit warming to 2°C or lower (Bertram  
32 et al. 2015a; Iyer et al. 2015b; Lane et al. 2016; Farfan and Breyer 2017; van Soest et al. 2017a;  
33 Luderer et al. 2018; Kriegler et al. 2018a; Cui et al. 2019; Saygin et al. 2019; SEI et al. 2020).  
34 Pathways following current NDCs until 2030 do not show a significant reduction of coal, oil and gas  
35 use (Figure 3.30f-h, Table 3.6) compared to immediate action pathways. Stranded coal power assets  
36 are evaluated to be higher by a factor of 2-3 if action is strengthened after 2030 rather than now (Iyer  
37 et al. 2015b; Cui et al. 2019). There is high agreement that the later climate policies are implemented,  
38 the higher the expected stranded assets and the societal, economic and political strain of strengthening  
39 action. Associated price increases for carbon-intensive goods and transitional macro-economic costs  
40 have been found to scale with the emissions gap in 2030 (Kriegler et al. 2013a). At the aggregate level  
41 of the whole global economy, Rozenberg et al. (2015) showed that each year of delaying the start of  
42 mitigation decreases the required CO<sub>2</sub> intensity of new production by 20-50 gCO<sub>2</sub>/USD. Carbon lock-  
43 in can have a long-lasting effect on future emissions trajectories after 2030. Luderer et al. (2018)  
44 compared cost-effective pathways with immediate action to limit warming to 1.5-2°C with pathways  
45 following the NDCs until 2030 and adopting the pricing policy of the cost-effective pathways  
46 thereafter and found that the majority of additional CO<sub>2</sub> emissions from carbon lock-in occurs after  
47 2030, reaching a cumulative amount of 290 (160–330) GtCO<sub>2</sub> by 2100 (2.7.2). Early action and  
48 avoidance of investments in new carbon-intensive assets can minimize these risks.

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

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

### 13 14 **3.5.2.3 Global accelerated action towards long-term climate goals**

15 A growing literature explores long-term mitigation pathways with accelerated near-term action going  
16 beyond the NDCs (Jiang et al. 2017; Roelfsema et al. 2018; Graichen et al. 2017; Kriegler et al.  
17 2018a; van Soest et al. 2021a; Fekete et al. 2021). Global accelerated action pathways are designed to  
18 transition more gradually from current policies and planned implementation of NDCs onto a 1.5-2°C  
19 pathway and at the same time alleviate the abrupt transition in 2030 that would be caused by  
20 following the NDCs until 2030 and strengthening towards limiting warming to 2°C thereafter (Section  
21 3.5.2). Therefore they have sometimes been called bridging scenarios / pathways in the literature (IEA  
22 2011; Spencer et al. 2015; van Soest et al. 2021a). They rely on regionally differentiated regulatory  
23 and pricing policies to gradually strengthening regional and sectoral action beyond the mitigation  
24 ambition in the NDCs. There are limitations to this approach. The tighter the warming limit, the more  
25 is disruptive action becoming inevitable to achieve the speed of transition that would be required  
26 (Kriegler et al. 2018a). Cost effective pathways already have abrupt shifts in deployments,  
27 investments and prices at the time a stringent warming limit is imposed reflecting the fact that the  
28 overall response to climate change has so far been misaligned with long-term climate goals (Geiges et  
29 al. 2019; Rogelj et al. 2016; Fawcett et al. 2015; Schleussner et al. 2016b). Disruptive action can help  
30 to break lock-ins and enable transformative change (Vogt-Schilb et al. 2018).

31  
32 The large literature on accelerating climate action was assessed in the IPCC Special Report on 1.5°C  
33 Warming (de Coninck et al. 2018) and is taken up in this report primarily in Chapters 4, 13, and 14.  
34 Accelerating climate action and facilitating transformational change requires a perspective on socio-  
35 technical transitions (Geels et al. 2016b; Geels 2018; Geels et al. 2016a), a portfolio of policy  
36 instruments to manage technological and environmental change (Goulder and Parry 2008; Fischer and  
37 Newell 2008; Acemoglu et al. 2012, 2016), a notion of path dependency and policy sequencing  
38 (Meckling et al. 2017; Pahle et al. 2018; Pierson 2000) and the evolvement of poly-centric governance  
39 layers of institutions and norms in support of the transformation (Messner 2015; Leach et al. 2007;  
40 Dietz et al. 2003). This subsection is focused on an assessment of the emerging quantitative literature  
41 on global accelerated action pathways towards 1.5-2°C, which to a large extent abstracts from the  
42 underlying processes and uses a number of stylized approaches to generate these pathways. A  
43 representative of accelerated action pathways has been identified as one of the illustrative mitigation  
44 pathways in this assessment (GS, Figure 3.31).

45  
46 One approach relies on augmenting initially moderate emissions pricing policies with robust  
47 anticipation of ratcheting up climate action in the future (Spencer et al. 2015). If announcements of  
48 strong future climate policies are perceived to be credible, they can help to prevent carbon lock-in as  
49 investors anticipating high future costs of GHG emissions would reduce investment into fossil fuel  
50 infrastructure, such as coal power plants (Bauer et al. 2018b). However, the effectiveness of such

1 announcements strongly hinges on their credibility. If investors believe that policy makers could drop  
2 them if anticipatory action did not occur, they may not undertake such action.

3  
4 Another approach relies on international cooperation to strengthen near term climate action. These  
5 studies build on international climate policy architectures that could incentivize a coalition of like-  
6 minded countries to raise their mitigation ambition beyond what is stated in their current NDC  
7 (Graichen et al. 2017). Examples are the idea of climate clubs characterized by harmonized carbon  
8 and technology markets (Pihl 2020; Nordhaus 2015; Keohane et al. 2017; Paroussos et al. 2019) and  
9 the Powering Past Coal Alliance (Jewell et al. 2019). Paroussos et al. (2019) find economic benefits of  
10 joining a climate club despite the associated higher mitigation effort, in particular due to access to  
11 technology and climate finance. Graichen et al. (2017) find an additional reduction of 5-11 GtCO<sub>2</sub>eq  
12 compared to the mitigation ambition in the NDCs from the successful implementation of international  
13 climate initiatives. Other studies assess benefits from international transfers of mitigation outcomes  
14 (Stua 2017; Edmonds et al. 2021). Edmonds et al. (2021) find economic gains from sharing NDC  
15 emissions reduction commitments compared to purely domestic implementation of NDCs. If  
16 reinvested in mitigation efforts, the study projects an additional reduction of 9 billion tonnes of CO<sub>2</sub> in  
17 2030.

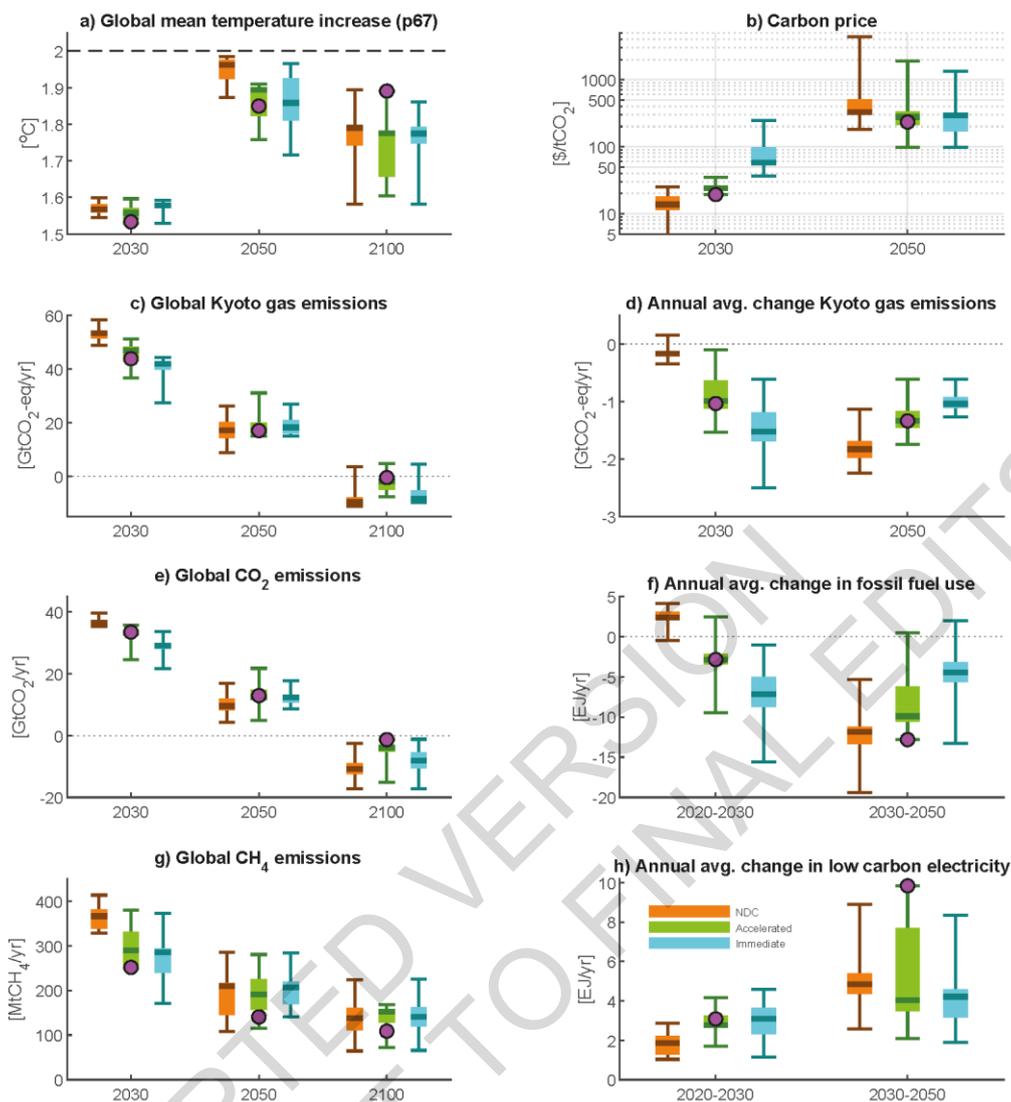
18  
19 The most common approach relies on strengthening regulatory policies beyond current policy trends,  
20 also motivated by the finding that such policies have so far been employed more often than  
21 comprehensive carbon pricing (Roelfsema et al. 2018; Kriegler et al. 2018a; van Soest et al. 2021a;  
22 Fekete et al. 2021; IEA 2021a). Some studies have focused on generic regulatory policies such as low  
23 carbon support policies, fossil fuel sunset policies, and resource efficiency policies (Bertram et al.  
24 2015b; Hatfield-Dodds et al. 2017). Bertram et al. (2015b) found that a moderate carbon price  
25 combined with a coal moratorium and ambitious low carbon support policies can limit efficiency  
26 losses until 2030 if emissions pricing is raised thereafter to limit warming to 2°C. They also showed  
27 that all three components are needed to achieve this outcome. Hatfield-Dodds et al. (2017) found that  
28 resource efficiency can lower 2050 emissions by an additional 15-20% while boosting near-term  
29 economic growth. The International Energy Agency (IEA 2021a) developed a detailed net zero  
30 scenario for the global energy sector characterized by a rapid phase out of fossil fuels, a massive clean  
31 energy and electrification push, and the stabilization of energy demand, leading to 10 GtCO<sub>2</sub> lower  
32 emissions from energy use in 2030 than in a scenario following the announced pledges.

33  
34 The Paris Agreement has spurred the formulation of NDCs for 2030 and mid-century strategies  
35 around the world (cf. Chapter 4). This is giving researchers a rich empirical basis to formulate  
36 accelerated policy packages taking national decarbonisation pathways as a starting point (van Soest et  
37 al. 2017b; Waisman et al. 2019; Graichen et al. 2017; Jiang et al. 2017). The concept is to identify  
38 good practice policies that had demonstrable impact on pushing low carbon options or reducing  
39 emissions in a country or region and then consider a wider roll-out of these policies taking into  
40 account regional specificities (den Elzen et al. 2015; Kuramochi et al. 2018; Roelfsema et al. 2018;  
41 Kriegler et al. 2018a; Fekete et al. 2015, 2021). A challenge for this approach is to account for the fact  
42 that policy effectiveness varies with different political environments in different geographies. As a  
43 result, a global roll-out of good practice policies to close the emissions gap will still be an idealized  
44 benchmark, but it is useful to understand how much could be gained from it.

45  
46 Accelerated action pathways derived with this approach show considerable scope for narrowing the  
47 emissions gap between pathways reflecting the ambition level of the NDCs and cost-effective  
48 mitigation pathways in 2030. Kriegler et al. (2018a) find around 10 GtCO<sub>2</sub>eq lower emissions  
49 compared to original NDCs from a global roll-out of good practice plus net zero policies and a  
50 moderate increase in regionally differentiated carbon pricing. Fekete et al. (2021) show that global

1 replication of sector progress in five major economies would reduce GHG emissions in 2030 by about  
2 20% compared to a current policy scenario. These findings were found in good agreement with a  
3 recent model comparison study based on results from 9 integrated assessment models (van Soest et al.  
4 2021a). Based on these three studies, implementing accelerated action in terms of a global roll out of  
5 regulatory and moderate pricing policies is assessed to lead to global GHG emissions of 47 (38-51)  
6 GtCO<sub>2</sub>-eq in 2030 (median and 5<sup>th</sup> to 95<sup>th</sup> percentile based on 10 distinct modelled pathways). This  
7 closes the implementation gap for the NDCs, and in addition falls below the emissions range implied  
8 by implementing unconditional and conditional elements of NDCs by 3-9 GtCO<sub>2</sub>-eq. However, it  
9 does not close the emissions gap to immediate action pathways likely limiting warming to 2°C, and,  
10 based on our assessment in Section 3.5.2, emission levels above 40 GtCO<sub>2</sub>-eq in 2030 still have a very  
11 low prospect for keeping limiting warming to 1.5°C with no or limited overshoot in reach.  
12

13 Figure 3.31 shows the intermediate position of accelerated action pathways derived by van Soest et al.  
14 (2021a) between pathways that follow the NDCs until 2030 and immediate action pathways likely  
15 limiting warming to 2°C. Accelerated action is able to reduce the abrupt shifts in emissions, fossil fuel  
16 use and low carbon power generation in 2030 and also limits peak warming more effectively than  
17 NDC pathways. But primarily due to the moderate carbon price assumptions (Fig. 3.31b), the  
18 reductions in emissions and particular fossil fuel use are markedly smaller than what would be  
19 obtained in the case of immediate action. The assessment shows that accelerated action until 2030 can  
20 have significant benefits in terms of reducing the mitigation challenges from following the NDCs  
21 until 2030. But putting a significant value on GHG emissions reductions globally remains a key  
22 element of moving onto 1.5-2°C pathways. The vast majority of pathways that limit warming to 2°C  
23 or below, independently of their differences in near term emission developments, converge to a global  
24 mitigation regime putting such a significant value on GHG emission reductions in all regions and  
25 sectors.



1  
3  
4 **Figure 3.31: Comparison of (i) pathways with immediate action likely limiting warming to 2°C**  
5 **(Immediate, light blue), (ii) pathways following the NDCs until 2030 and aiming to likely stay below 2°C**  
6 **thereafter (NDC; orange) and (iii) pathways accelerating near term action until 2030 beyond NDC**  
7 **ambition levels and aiming to likely stay below 2°C thereafter (Accelerated) for selected indicators as**  
8 **listed in the panel titles, based on pathways from van Soest et al. (2021a). Low carbon electricity**  
9 **comprises renewable and nuclear power. Indicator ranges are shown as boxplots (full range, interquartile**  
10 **range, and median) for the years 2030, 2050 and 2100 (absolute values) and for the periods 2020-2030,**  
11 **2030-2050 (change indicators). Ranges are based on nine models participating in (van Soest et al. 2021a)**  
12 **with only 7 models reporting emissions and climate results and 8 models reporting carbon prices. The**  
13 **purple dot denotes the illustrative mitigation pathway GS that was part of the study by van Soest et al.**

### 15 3.6 Economics of long-term mitigation and development pathways, 16 including mitigation costs and benefits

17 A complete appraisal of economic effects and welfare effects at different temperature levels would  
18 include the macroeconomic impacts of investments in low-carbon solutions and structural change  
19 away from emitting activities, co-benefits and adverse side effects of mitigation, (avoided) climate

1 damages, as well as (reduced) adaptation costs, with high temporal, spatial and social heterogeneity  
2 using a harmonized framework. If no such complete appraisal in a harmonized framework exists, key  
3 elements are emerging from the literature, and assessed in the following subsections: on aggregated  
4 economy-wide global mitigation costs (section 3.6.1), on the economic benefits of avoiding climate  
5 impacts (section 3.6.2), on economic benefits and costs associated with mitigation co-benefits and co-  
6 harms (section 3.6.3) and on the distribution of economic implications between economic sectors and  
7 actors (section 3.6.4).

### 8 9 **3.6.1 Economy-wide implications of mitigation**

#### 10 **3.6.1.1 Global economic effects of mitigation and carbon values in mitigation pathways**

#### 11 **START BOX HERE**

#### 12 **Box 3.5 Concepts and modelling frameworks used for quantifying macro-economic effects of mitigation**

13  
14  
15 Most studies that have developed mitigation pathways have used a Cost-effectiveness analysis (CEA)  
16 framework, which aim at comparing the costs of different mitigation strategies designed to meet a  
17 given climate change mitigation goal (e.g., an emission-reduction target or a temperature stabilization  
18 target) but does not represent economic impacts from climate change itself, nor the associated  
19 economic benefits of avoided impacts. Other studies use modelling frameworks that represent the  
20 feedback of damages from climate change on the economy in a Cost-benefit analysis (CBA)  
21 approach, which balances mitigation costs and benefits. This second type of studies is represented in  
22 section 3.6.2.

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

44 If GDP or consumption in mitigation pathways are below the reference scenario levels, they are  
45 reported as losses or macro-economic costs. Such cost estimates give an indication on how economic  
46 activity slows relative to the reference scenario; they do not necessarily describe, in absolute terms, a  
47 reduction of economic output or consumption levels relative to previous years along the pathway.  
48 Aggregate mitigation costs depend strongly on the modelling framework used and the assumptions

1 about the reference scenario against which mitigation costs are measured, in particular whether the  
2 reference scenario is, or not, on the efficiency frontier of the economy. If the economy is assumed to  
3 be at the efficiency frontier in the reference scenario, mitigation inevitably leads to actual costs, at  
4 least in the short run until the production frontier evolves with technical and structural change.  
5 Starting from a reference scenario that is not on the efficiency frontier opens the possibility to  
6 simultaneously reduce emissions and obtain macroeconomic gains, depending on the design and  
7 implementation of mitigation policies. A number of factors can result in reference scenarios below the  
8 efficiency frontier, for instance distorting labour taxes and/or fossil fuel subsidies, misallocation or  
9 under-utilization of production factors such as involuntary unemployment, imperfect information or  
10 non-rational behaviours. Although these factors are pervasive, the modelling frameworks used to  
11 construct mitigation pathways are often limited in their ability to represent them (Köberle et al. 2021).  
12 The absolute level of economic activity and welfare also strongly depends on the socioeconomic  
13 pathway assumptions regarding inter alia evolutions in demography, productivity, education levels,  
14 inequality and technical change and innovation. The GDP or consumption indicators reported in the  
15 database of scenarios, and synthesized below, represent the absolute level of aggregate economic  
16 activity or consumption but do not reflect welfare and well-being (Roberts et al. 2020), that notably  
17 depend on human needs satisfaction, distribution within society and inequality (see section 3.6.4).  
18 Chapter 1 and Annex III give further elements on the economic concepts and on the modelling  
19 frameworks, including their limitations, used in this report, respectively.

#### 20 **END BOX HERE**

21  
22 Estimates for the marginal abatement cost of carbon in mitigation pathways vary widely, depending  
23 on the modelling framework used and socioeconomic, technological and policy assumptions.  
24 However, it is robust across modelling frameworks that the marginal abatement cost of carbon  
25 increases for lower temperature categories, with a higher increase in the short-term than in the longer-  
26 term (Figure 3.32, left panel) (*high confidence*). The marginal abatement cost of carbon increases non-  
27 linearly with the decrease of CO<sub>2</sub> emissions level, but the uncertainty in the range of estimates also  
28 increases (Figure 3.33). Mitigation pathways with low-energy consumption patterns exhibit lower  
29 carbon values (Méjean et al. 2019; Meyer et al. 2021). In the context of the COVID-19 pandemic  
30 recovery, Kikstra et al. (2021a) also show that a low energy demand recovery scenario reduces carbon  
31 prices for a 1.5°C consistent pathway by 19% compared to a scenario with energy demand trends  
32 restored to pre-pandemic levels.

33  
34 For optimization modelling frameworks, the time profile of marginal abatement costs of carbon  
35 depends on the discount rate, with lower discount rates implying higher carbon values in the short  
36 term but lower values in the long term (Emmerling et al. 2019) (see also Discounting in glossary and  
37 Annex III part I section 2). In that case, the discount rate also influences the shape of the emissions  
38 trajectory, with low discount rates implying more emission reduction in the short-term and, for low  
39 temperature categories, limiting CDR and temperature overshoot.

40  
41 Pathways that correspond to NDCs in 2030 and strengthen action after 2030 imply higher marginal  
42 abatement costs of carbon in the longer run than pathways with stronger immediate global mitigation  
43 action (Figure 3.32, right panel) (*high confidence*).  
44

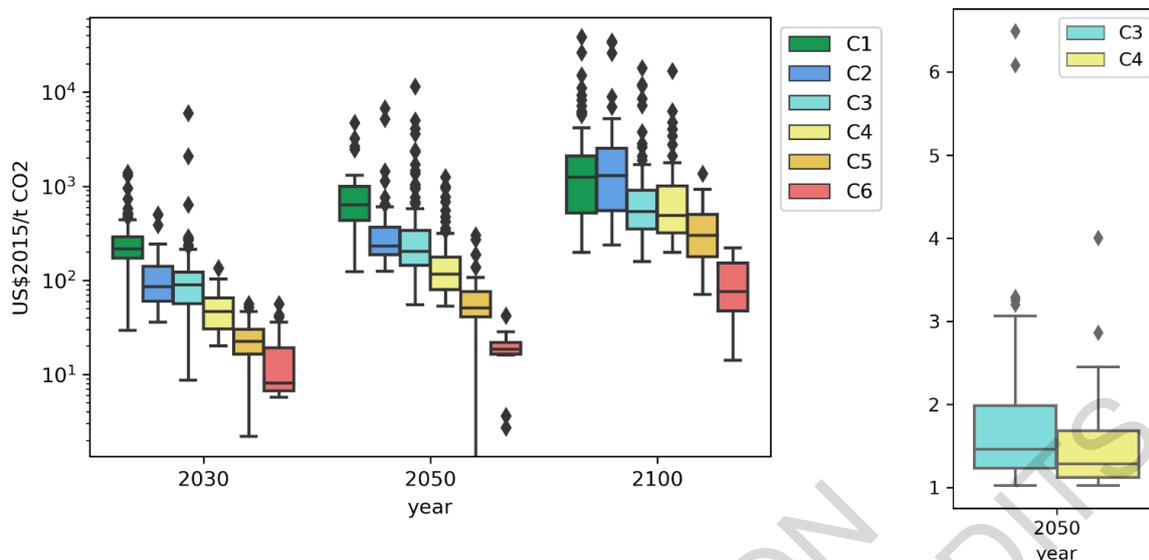


Figure 3.32: Marginal abatement cost of carbon in 2030, 2050 and 2100 for mitigation pathways with immediate global mitigation action (left panel), and ratio in 2050 between pathways that correspond to NDC in 2030 and strengthen action after 2030 and pathways with immediate global mitigation action, for C3 and C4 temperature categories (right panel).

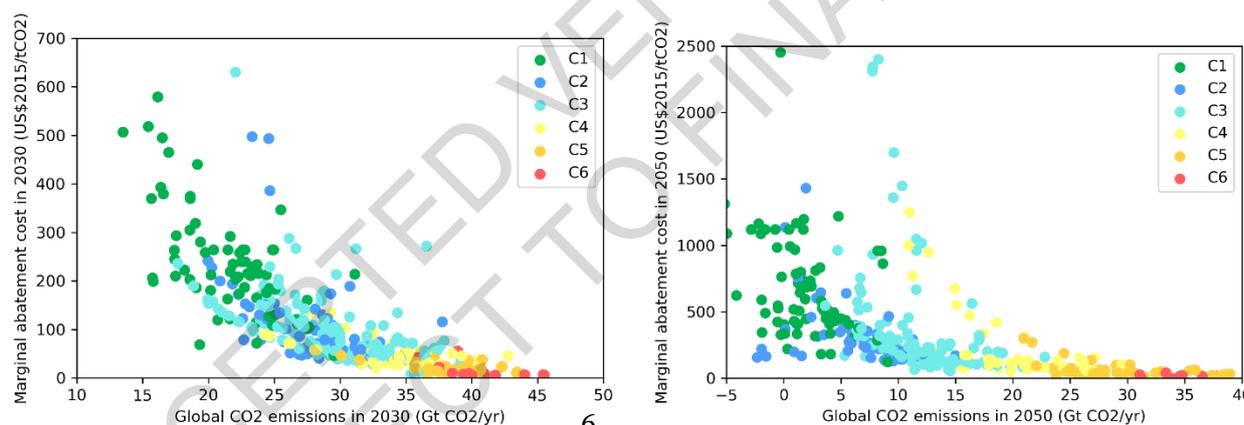


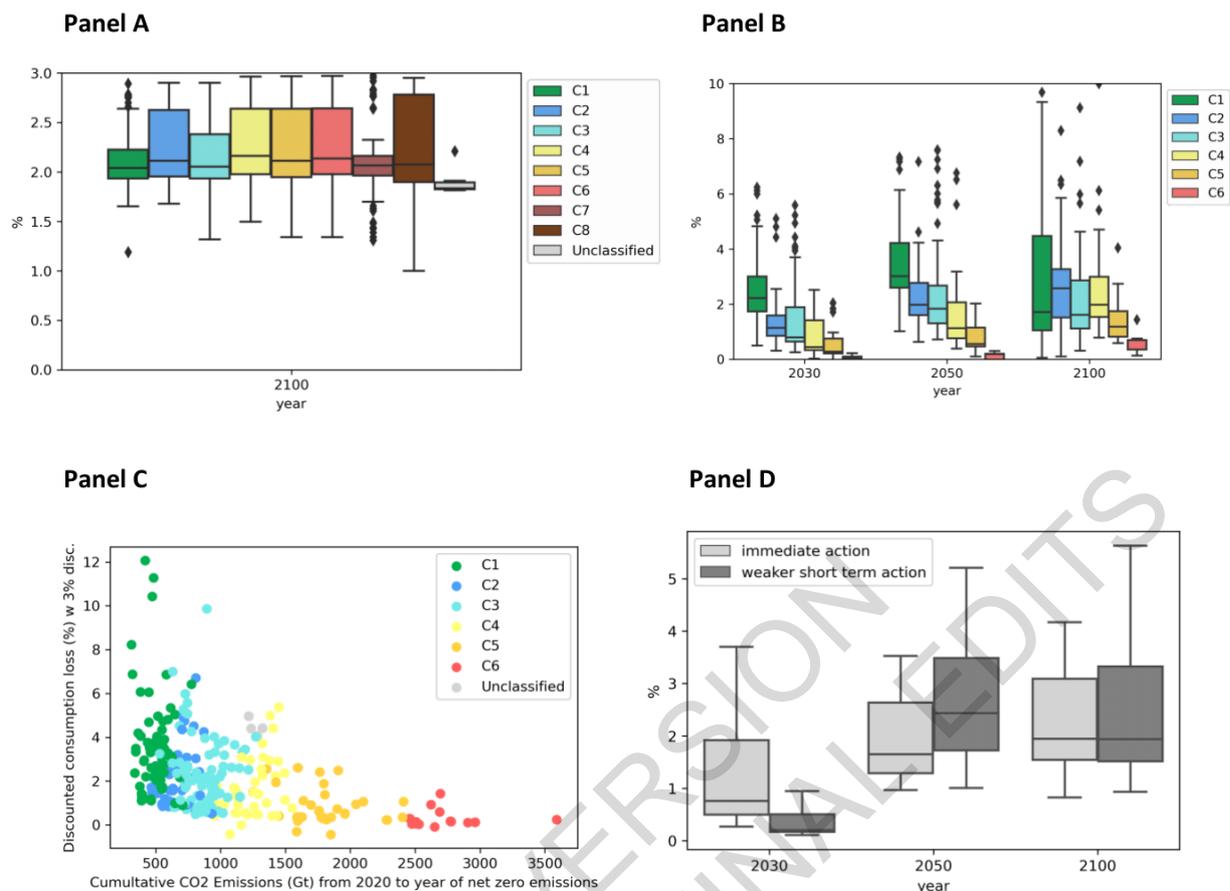
Figure 3.33: Marginal abatement cost of carbon with respect to CO<sub>2</sub> emissions for mitigation pathways with immediate global mitigation action, in 2030 (left panel) and 2050 (right panel).

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

1 However, the possibility for increased economic activity following mitigation action, and conversely  
2 the risk of large negative economic effects, are not excluded. Some studies find that mitigation  
3 increases the speed of economic growth compared to baseline scenarios (Pollitt and Mercure 2018;  
4 Mercure et al. 2019). These studies are based on a macroeconomic modelling framework that  
5 represent baselines below the efficiency frontier, based on non-equilibrium economic theory, and  
6 assume that mitigation is undertaken in such a way that green investments do not crowd-out  
7 investment in other parts of the economy – and therefore offers an economic stimulus. In the context  
8 of the recovery from the COVID-19 crisis, it is estimated that a green investment push, would initially  
9 boost the economy while also reducing GHG emissions (IMF 2020; Pollitt et al. 2021). Conversely,  
10 several studies find that only a GDP non-growth/degrowth or post-growth approach allow to reach  
11 climate stabilization below 2°C (Hardt and O’Neill 2017; D’Alessandro et al. 2020; Hickel and Kallis  
12 2020; Nieto et al. 2020), or to minimize the risks of reliance on high energy-GDP decoupling, large-  
13 scale CDR and large-scale renewable energy deployment (Keyßer and Lenzen 2021). Similarly,  
14 feedbacks of financial system risk to amplify shocks induced by mitigation policy and lead to higher  
15 impact on economic activity (Stolbova et al. 2018).

16  
17 Mitigation cost increases with the stringency of mitigation (Figure 3.34, panels b and c) (Hof et al.  
18 2017; Vrontisi et al. 2018), but are reduced when energy demand is moderated through energy  
19 efficiency and lifestyle changes (Fujimori et al. 2014; Bibas et al. 2015; Liu et al. 2018; Méjean et al.  
20 2019), when sustainable transport policies are implemented (Zhang et al. 2018c), and when  
21 international technology cooperation is fostered (Schultes et al. 2018; Paroussos et al. 2019).  
22 Mitigation costs also depend on assumptions on availability and costs of technologies (Clarke et al.  
23 2014; Bosetti et al. 2015; Dessens et al. 2016; Creutzig et al. 2018; Napp et al. 2019; Giannousakis et  
24 al. 2021), on the representation of innovation dynamics in modelling frameworks (Hoekstra et al.  
25 2017; Rengs et al. 2020) (see also chapter 16), as well as the representation of investment dynamics  
26 and financing mechanisms (Iyer et al. 2015c; Mercure et al. 2019; Battiston et al. 2021). In particular,  
27 endogenous and induced innovation reduce technology cost over time, create path-dependencies and  
28 reduce the macroeconomic cost of reaching a mitigation target (see also 1.7.1.2). Mitigation costs also  
29 depend on the socioeconomic assumptions (van Vuuren et al. 2020; Hof et al. 2017).

30



1  
2  
3 **Figure 3.34: Panel (a): Mean annual global consumption growth rate over 2020-2100 for the mitigation**  
4 **pathways in the AR6 scenarios database. Panel (b): Global GDP loss compared to baselines (not**  
5 **accounting for climate change damages) in 2030, 2050 and 2100 for mitigation pathways with immediate**  
6 **global action. Panel (c): Total discounted consumption loss (with a 3% discount rate) in mitigation**  
7 **scenarios with respect to their corresponding baseline (not accounting for climate change damages) as a**  
8 **function of cumulative CO<sub>2</sub> emissions until date of net zero CO<sub>2</sub>. Panel (d): Comparison of GDP losses**  
9 **compared to baselines (not accounting for climate change damages) in 2030, 2050 and 2100 for pairs of**  
10 **scenarios depicting immediate action pathways and delayed action pathways.**

11 Mitigation pathways with early emissions reductions represent higher mitigation costs in the short run  
12 but bring long-term gains for the economy compared to delayed transition pathways (*high*  
13 *confidence*). Pathways with earlier mitigation action bring higher long-term GDP than pathways  
14 reaching the same end-of-century temperature with weaker early action (Figure 3.34, panel d).  
15 Comparing counterfactual history scenarios, Sanderson and O'Neill (2020) also find that delayed  
16 mitigation action leads to higher peak costs. Rogelj et al. (2019b) and Riahi et al. (2021) also show  
17 that pathways with earlier timing of net zero CO<sub>2</sub> lead to higher transition costs but lower long term  
18 mitigation costs, due to dynamic effects arising from lock-in avoidance and learning effects. For  
19 example, Riahi et al (2021) find that for a 2°C target, the GDP losses (compared to a reference  
20 scenario without impacts from climate change) in 2100 are 5-70% lower in pathways that avoid net  
21 negative CO<sub>2</sub> emissions and temperature overshoot than in pathways with overshoot. Accounting also  
22 for climate change damage, van der Wijst et al. (2021a) show that avoiding net negative emissions  
23 leads to a small increase in total discounted mitigation costs over 2020-2100, between 5% and 14% in  
24 their medium assumptions, but does not increase mitigation costs when damages are high and when  
25 using a low discount rate, and becomes economically attractive if damages are not fully reversible.  
26 The modelled cost-optimal balance of mitigation action over time strongly depends on the discount  
27 rate used to compute or evaluate mitigation pathways: lower discount rates favour earlier mitigation,

1 reducing both temperature overshoot and reliance on net negative carbon emissions (Emmerling et al.  
2 2019; Riahi et al. 2021). Mitigation pathways with weak early action corresponding to NDCs in 2030  
3 and strengthening action after 2030 to reach end-of-century temperature targets imply limited  
4 mitigation costs in 2030, compared to immediate global action pathways, but faster increase in costs  
5 post-2030, with implications for intergenerational equity (Aldy et al. 2016; Liu et al. 2016; Vrontisi et  
6 al. 2018). Emissions trading policies reduce global aggregate mitigation costs, in particular in the  
7 context of achieving NDCs (Fujimori et al. 2015, 2016a; Edmonds et al. 2021; Böhringer et al. 2021),  
8 and change the distribution of mitigation costs between regions and countries (see section 3.6.1.2).

### 9 **3.6.1.2 Regional mitigation costs and effort-sharing regimes**

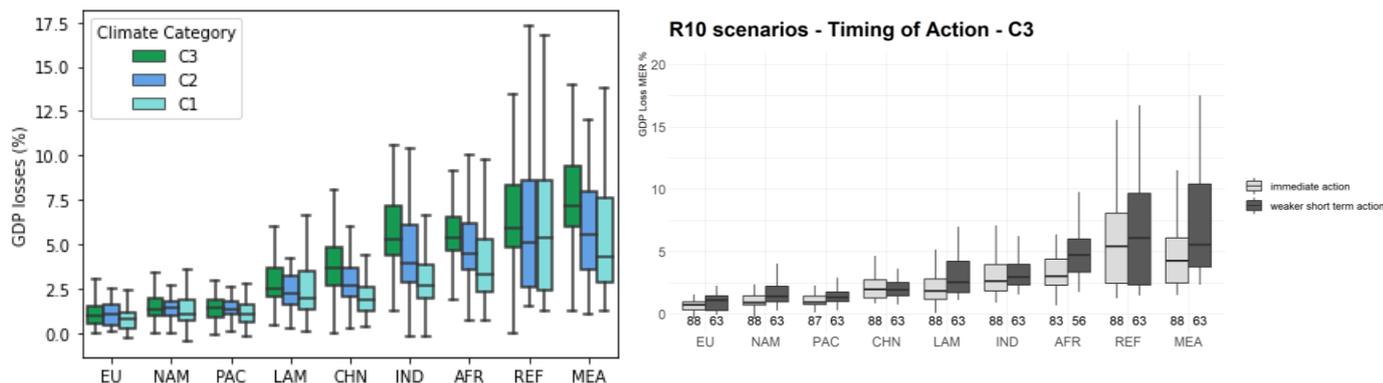
11 The economic repercussions of mitigation policies vary across countries (Hof et al. 2017; Aldy et al.  
12 2016): regional variations exist in institutions, economic and technological development, and  
13 mitigation opportunities. For a globally uniform carbon price, carbon intensive and energy exporting  
14 countries bear the highest economic costs because of a deeper transformation of their economies and  
15 of trade losses in the fossil markets (Stern et al. 2012; Tavoni et al. 2015; Böhringer et al. 2021). This  
16 finding is confirmed in

17 Figure 3.35. Since carbon intensive countries are often poorer, uniform global carbon prices raises  
18 equity concerns (Tavoni et al. 2015). On the other hand, the climate economic benefits of mitigating  
19 climate change will be larger in poorer countries (Cross-Working Group Box 1). This reduces policy  
20 regressivity but does not eliminate it (Taconet et al. 2020; Gazzotti et al. 2021). Together with co-  
21 benefits, such as health benefits of improved air quality, the economic benefits of mitigating climate  
22 change are likely to outweigh mitigation costs in many regions (Li et al. 2018, 2019; Scovronick et al.  
23 2021).

25 Regional policy costs depend on the evaluation framework (Budolfson et al. 2021), policy design,  
26 including revenue recycling, and on international coordination, especially among trade partners. By  
27 fostering technological change and finance, climate cooperation can generate economic benefits, both  
28 in large developing economies such as China and India (Paroussos et al. 2019) and industrialized  
29 countries such as Europe (Vrontisi et al. 2020). International coordination is a major driver of regional  
30 policy costs. Delayed participation in global mitigation efforts raises participation costs, especially in  
31 carbon intensive economies (

32 Figure 3.35, right panel). Trading systems and transfers can deliver cost savings and improve equity  
33 (Rose et al. 2017a). On the other hand, measures that reduce imports of energy intensive goods such  
34 as carbon border tax adjustment may imply costs outside of the policy jurisdiction and have  
35 international equity repercussions, depending on how they are designed (Böhringer et al. 2012, 2017;  
36 Cosbey et al. 2019) (see also 13.6.6).

38 An equitable global emission trading scheme would require very large international financial  
39 transfers, in the order of several hundred billion USD per year (Tavoni et al. 2015; van den Berg et al.  
40 2020; Bauer et al. 2020). The magnitude of transfers depends on the stringency of the climate goals  
41 and on the burden sharing principle. Equitable burden sharing compliant with the Paris Agreement  
42 leads to negative carbon allowances for developed countries as well as China by mid-century (van den  
43 Berg et al. 2020), more stringent than cost-optimal pathways. International transfers also depend on  
44 the underlying socio-economic development (Leimbach and Giannousakis 2019), as these drive the  
45 mitigation costs of meeting the Paris Agreement (Rogelj et al. 2018b). By contrast, achieving equity  
46 without international markets would result in a large discrepancy in regional carbon prices, up to a  
47 factor (Bauer et al. 2020). The efficiency-sovereignty trade-off can be partly resolved by allowing for  
48 limited differentiation of regional carbon prices: moderate financial transfers substantially reduce  
49 inefficiencies by narrowing the carbon price spread (Bauer et al. 2020).

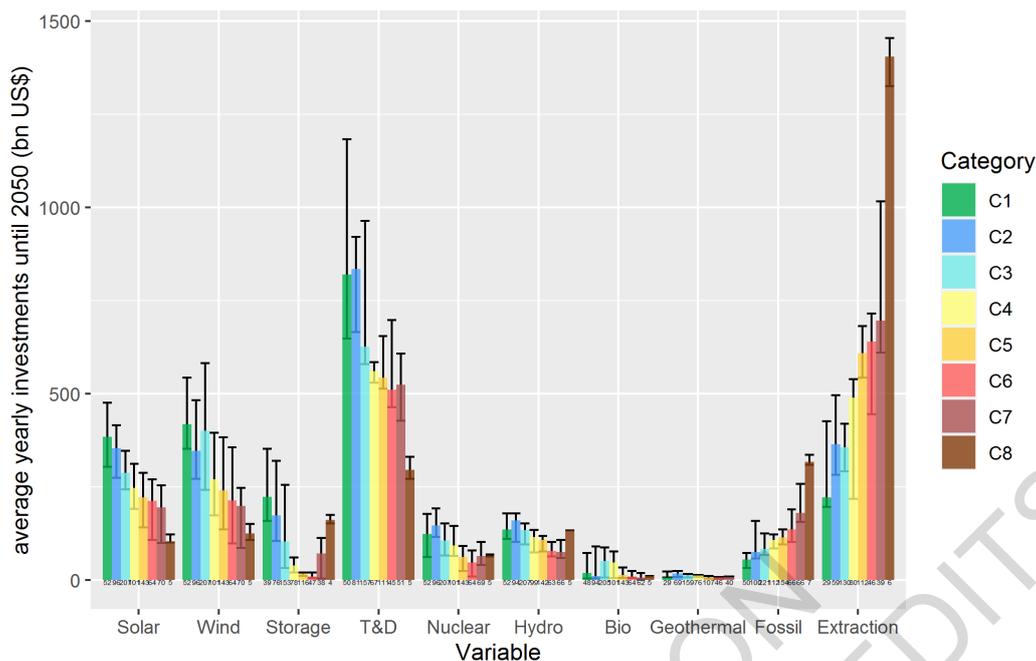


1  
2  
3 **Figure 3.35: Left panel: Regional mitigation costs in the year 2050 (expressed as GDP losses between**  
4 **mitigation scenarios and corresponding baselines, not accounting for climate change damages), under the**  
5 **assumption of immediate global action with uniform global carbon pricing and no international transfers,**  
6 **by climate categories for the 2°C and 1.5°C (with and without overshoot) categories. Right panel: Policy**  
7 **costs in 2050 (as in panel a) for 1.5-2°C climate categories for scenario pairs that represent either**  
8 **immediate global action (‘immediate’) or delayed global action (‘delayed’) with weaker action in the**  
9 **short-term, strengthening to reach the same end-of-century temperature target.**

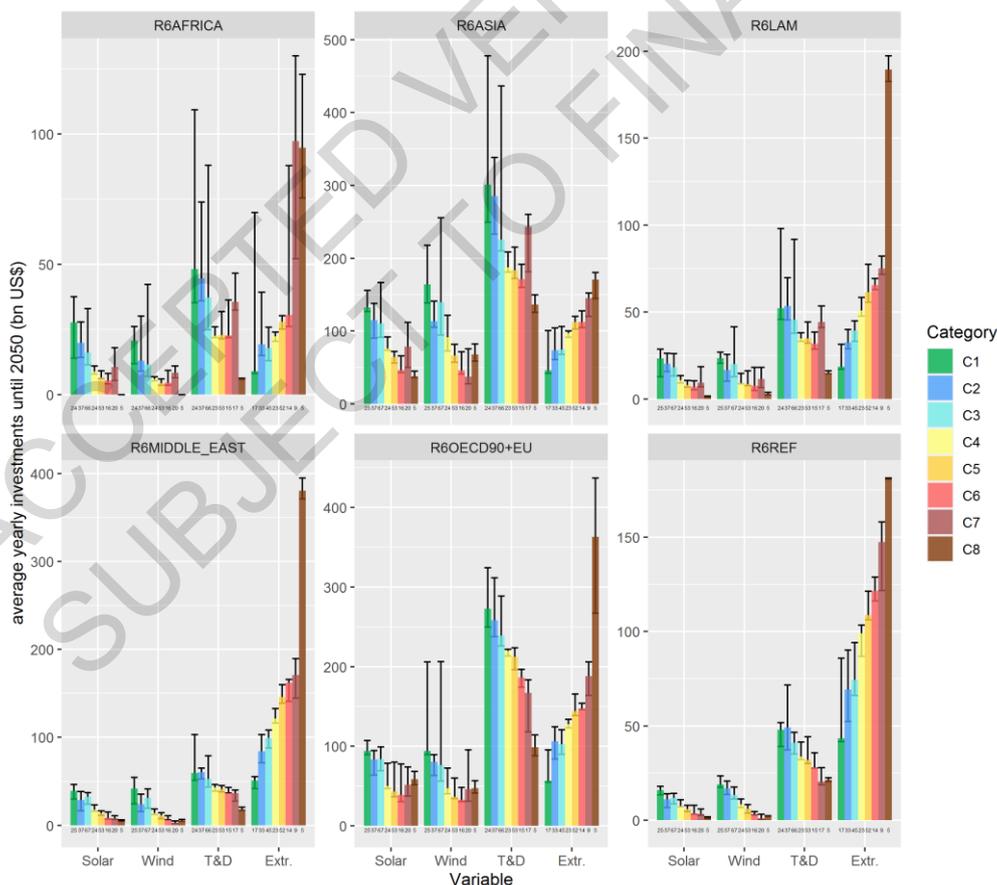
### 10 3.6.1.3 Investments in mitigation pathways

11 Figure 3.36 and Figure 3.37 show increased investment needs in the energy sector in lower  
12 temperature categories, and a major shift away from fossil generation and extraction towards  
13 electricity, including for system enhancements for electricity transmission, distribution and storage,  
14 and low-carbon technologies. Investment needs in the electricity sector are USD2.3 trillion 2015 yr<sup>-1</sup>  
15 over 2023-2050 on average for C1 pathways, USD2.0 trillion for C2 pathways, USD1.7 trillion for  
16 C3, USD1.2 trillion for C4 and USD0.9-1.1 billion for C5/C6/C7 (mean values for pathways in each  
17 temperature categories). The regional pattern of power sector investments broadly mirrors the global  
18 picture. However, the bulk of investment requirements are in medium- and low-income regions.  
19 These results from the AR6 scenarios database corroborate the findings from McCollum et al.  
20 (2018a), Zhou et al. (2019) and Bertram et al. (2021).

21  
22  
23 In the context of the COVID-19 pandemic recovery, (Kikstra et al. 2021a) show that a low energy  
24 demand recovery scenario reduces energy investments required until 2030 for a 1.5°C consistent  
25 pathway by 9% (corresponding to reducing total required energy investment by USD1.8 trillion)  
26 compared to a scenario with energy demand trends restored to pre-pandemic levels.  
27



1  
2 **Figure 3.36: Global average yearly investments from 2023-2052 for 9 electricity supply subcomponents**  
3 **and for extraction of fossil fuels (in billion USD2015), in pathways by temperature categories. T&D:**  
4 **transmission and distribution of electricity. Bars show the median values (number of pathways at the**  
5 **bottom), and whiskers the interquartile ranges.**



6  
7 **Figure 3.37: Average yearly investments from 2023-2052 for the four subcomponents of the energy**  
8 **system representing the larger amounts (in billion USD2015), by aggregate regions, in pathways by**  
9 **temperature categories. T&D: transmissions and distribution of electricity. Extr.: extraction of fossil**

1 **fuels. Bars show the median values (number of pathways at the bottom), and whiskers the interquartile**  
2 **ranges.**

3  
4 Few studies extend the scope of the investment needs quantification beyond the energy sector. Fisch-  
5 Romito and Guivarch (2019) and Ó Broin and Guivarch (2017) assess investment needs for  
6 transportation infrastructures and find lower investment needs in low-carbon pathways, due to a  
7 reduction in transport activity and a shift towards less road construction, compared to high-carbon  
8 pathways. Rozenberg and Fay (2019) estimate the funding needs to close the service gaps in water  
9 and sanitation, transportation, electricity, irrigation, and flood protection in thousands of scenarios,  
10 showing that infrastructure investment paths compatible with full decarbonization in the second half  
11 of the century need not cost more than more-polluting alternatives. Investment needs are estimated  
12 between 2 percent and 8 percent of GDP, depending on the quality and quantity of services targeted,  
13 the timing of investments, construction costs, and complementary policies.

14  
15 Chapter 15 also reports investment requirements in global mitigation pathways in the near-term,  
16 compares them to recent investment trends, and assesses financing issues.

### 17 18 **3.6.2 Economic benefits of avoiding climate changes impacts**

#### 19 20 **START BOX HERE**

#### 21 22 **Cross-Working Group Box 1: Economic benefits from avoided climate impacts along long-term** 23 **mitigation pathways**

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28 Hasegawa (Japan), Alexandre C. Köberle (Brazil/ United Kingdom), Elmar Kriegler (Germany),  
29 David McCollum (the United States of America), Aurélie Méjean (France), Brian O’Neill (the United  
30 States of America), Franziska Piontek (Germany), Julia Steinberger (United Kingdom/Switzerland),  
31 Massimo Tavoni (Italy)

32  
33 Mitigation reduces the extent of climate change and its impacts on ecosystems, infrastructure, and  
34 livelihoods. This box summarizes elements from the WGII report on aggregate climate change  
35 impacts and risks, putting them into the context of mitigation pathways. AR6 Working Group II  
36 provides an assessment of current lines of evidence regarding potential climate risks with future  
37 climate change, and therefore, the avoided risks from mitigating climate change. Regional and  
38 sectoral climate risks to physical and social systems are assessed (WGII Chapters 2-15). Over 100 of  
39 these are identified as Key Risks (KRs) and further synthesized by WGII Chapter 16 into eight  
40 overarching Representative Key Risks (RKRs) relating to low-lying coastal systems; terrestrial and  
41 ocean ecosystems; critical physical infrastructure, networks and services; living standards; human  
42 health; food security; water security; and peace and mobility (WGII 16.5.2). The RKR assessment  
43 finds that risks increase with global warming level, and also depend on socioeconomic development  
44 conditions, which shape exposure and vulnerability, and adaptation opportunities and responses.  
45 “Reasons For Concern”, another WGII aggregate climate impacts risk framing, are also assessed to  
46 increase with climate change, with increasing risk for unique and threatened systems, extreme weather  
47 events, distribution of impacts, global aggregate impacts, and large-scale singular events (WGII  
48 Chapter 16). For human systems, in general, the poor and disadvantaged are found to have greater  
49 exposure level and vulnerability for a given hazard. With some increase in global average warming

1 from today expected regardless of mitigation efforts, human and natural systems will be exposed to  
2 new conditions and additional adaptation will be needed (WGII Chapter 18). The range of dates for  
3 when a specific warming level could be reached depends on future global emissions, with significant  
4 overlap of ranges across emissions scenarios due to climate system response uncertainties (WGI  
5 Tables 4.2 and 4.5). The speed at which the climate changes is relevant to adaptation timing,  
6 possibilities, and net impacts.

7  
8 WGII also assesses the growing literature estimating the global aggregate economic impacts of  
9 climate change and the social cost of carbon dioxide and other greenhouse gases (Cross-Working Box  
10 Economic: Estimating Global Economic Impacts from Climate Change and the Social Cost of  
11 Carbon”, in WGII Chapter 16). The former represents aggregate estimates that inform assessment of  
12 the economic benefits of mitigation. This literature is characterized by significant variation in the  
13 estimates, including for today's level of global warming, due primarily to fundamental differences in  
14 methods, but also differences in impacts included, representation of socioeconomic exposure,  
15 consideration of adaptation, aggregation approach, and assumed persistence of damages. WGII's  
16 assessment identifies different approaches to quantification of aggregated economic impacts of  
17 climate change, including: physical modelling of impact processes, such as projected mortality rates  
18 from climate risks such as heat, vector- or waterborne diseases that are then monetized; structural  
19 economic modelling of impacts on production, consumption, and markets for economic sectors and  
20 regional economies; and statistical estimation of impacts based on observed historical responses to  
21 weather and climate. WGII finds that variation in estimated global economic impacts increases with  
22 warming in all methodologies, indicating higher risk in terms of economic impacts at higher  
23 temperatures (*high confidence*). Many estimates are nonlinear with marginal economic impacts  
24 increasing with temperature, although some show declining marginal economic impacts with  
25 temperature, and functional forms cannot be determined for all studies. WGII's assessment finds that  
26 the lack of comparability between methodologies does not allow for identification of robust ranges of  
27 global economic impact estimates (*high confidence*). Further, WGII identifies evaluating and  
28 reconciling differences in methodologies as a research priority for facilitating use of the different lines  
29 of evidence (*high confidence*). However, there are estimates that are higher than AR5, indicating that  
30 global aggregate economic impacts could be higher than previously estimated (*low confidence* due to  
31 the lack of comparability across methodologies and lack of robustness of estimates) (Cross-Working  
32 Box Economic).

33  
34 Conceptually, the difference in aggregate economic impacts from climate change between two given  
35 temperature levels represents the aggregate economic benefits arising from avoided climate change  
36 impacts due to mitigation action. A subset of the studies whose estimates were evaluated by WGII (5  
37 of 15) are used to derive illustrative estimates of aggregate economic benefits in 2100 arising from  
38 avoided climate change (Howard and Sterner 2017; Burke et al. 2018; Pretis et al. 2018; Kahn et al.  
39 2019; Takakura et al. 2019). Burke et al. (2018), Pretis et al. (2018) and Kahn et al. (2019) are  
40 examples of statistical estimation of historical relationships between temperature and economic  
41 growth, whereas Takakura et al. (2019) is an example of structural modelling, which evaluates  
42 selected impact channels (impacts on agriculture productivity, undernourishment, heat-related  
43 mortality, labour productivity, cooling/heating demand, hydroelectric and thermal power generation  
44 capacity and fluvial flooding) with a general equilibrium model. Howard and Sterner (2017) and  
45 Rose et al. (2017b) estimate damage functions that can be used to compute the economic benefits of  
46 mitigation from avoiding a given temperature level for a lower one. Howard and Sterner (2017)  
47 estimate a damage function from a meta-analysis of aggregate economic impact studies, while Rose et  
48 al. (2017b) derive global functions by temperature and socioeconomic drivers from stylized aggregate  
49 Cost-Benefit-Analysis integrated assessment models using diagnostic experiments. Cross-Working  
50 Group Box 1 Figure 1 summarizes the global aggregate economic benefits in 2100 of avoided climate

1 change impacts from individual studies corresponding to shifting from a higher temperature category  
2 (above 3°C, below 3°C or below 2.5°C) to below 2°C, as well as from below 2°C to below 1.5°C.  
3 Benefits are positive and increase with the temperature gap for any given study, and this result is  
4 robust across socioeconomic scenarios. The Figure provides evidence of a wide range of  
5 quantifications, and illustrates the important differences associated with methods. Panel a puts the  
6 studies used to calculate aggregate economic benefits arising from avoided impacts into the context of  
7 the broader set of studies assessed in WGII (WGII Cross-Working Group Box Economic, 16.6.2).  
8 However, economic benefits in 2100 arising from avoided impacts cannot be directly computed from  
9 damage estimates across this broader set of studies, due to inconsistencies - different socioeconomic  
10 assumptions, scenario designs, and counterfactual reference scenarios across studies. Furthermore,  
11 these types of estimates cannot be readily compared to mitigation cost estimates. The comparison  
12 would require a framework that ensures consistency in assumptions and dynamics and allows for  
13 consideration of benefits and costs along the entire pathway.

14  
15 **Cross-Working Group Box 1 Figure 1: Global aggregate economic benefits of mitigation from avoided**  
16 **climate change impacts in 2100 corresponding to shifting from a higher temperature category (4°C**  
17 **(3.75°C-4.25°C), 3°C(2.75°C-3.25°C) or above 2°C (2°C-2.5°C)) to below 2°C (1.5°C-2°C), as well as from**  
18 **below 2°C to below 1.5°C (1°C-1.5°C), from the five studies discussed in the text. Panel a is adapted from**  
19 **WGII CWGB ECONOMIC Figure 1, showing global aggregate economic impact estimates (% global**  
20 **GDP loss relative to GDP without additional climate change) by temperature change level. All estimates**  
21 **are shown in grey. Estimates used for the computation of estimated benefits in 2100 in Panel b are**  
22 **coloured for the selected studies, which provide results for different temperature change levels. See the**  
23 **WGII Chapter 16 box for discussion and assessment of the estimates in Panel a and the differences in**  
24 **methodologies. For B18 and T19, median estimates in the cluster are considered. Shape distinguishes the**  
25 **baseline scenarios. Temperature ranges are highlighted. HS17 estimates are based on their preferred**  
26 **model - 50th percentile of non-catastrophic damage. Panel b shows the implied aggregate economic**  
27 **benefits in 2100 of a lower temperature increase. Economic benefits for point estimates are computed as a**  
28 **difference, while economic benefits from the curve HS17 are computed as ranges from the segment**  
29 **differences.**  
30

31 Aggregate benefits from avoided impacts expressed in GDP terms, as in Figure 1, do not encompass  
32 all avoided climate risks, adaptation possibilities, and does not represent their influence on well-being  
33 and welfare (WGII Cross-Working Group Box Economic). Methodological challenges for economic  
34 impact estimates include representing uncertainty and variability, capturing interactions and spill  
35 overs, considering distributional effects, representing micro and macro adaptation processes,  
36 specifying non-gradual damages and non-linearities, and improving understanding of potential long-  
37 run growth effects. In addition, the economic benefits aggregated at the global scale provide limited  
38 insights into regional heterogeneity. Global economic impact studies with regional estimates find  
39 large differences across regions in absolute and percentage terms, with developing and transitional  
40 economies typically more vulnerable. Furthermore, (avoided) impacts for poorer households and  
41 poorer countries can represent a smaller share in aggregate quantifications expressed in GDP terms or  
42 monetary terms, compared to their influence on well-being and welfare (Hallegatte et al. 2020;  
43 Markhvida et al. 2020). Finally, as noted by WGII, other lines of evidence regarding climate risks,  
44 beyond monetary estimates, should be considered in decision-making, including key risks and  
45 Reasons for Concern.

46  
47 **END CCB HERE**  
48

49 Cost-benefit analyses (CBA) aim to balance all costs and benefits in a unified framework (Nordhaus,  
50 2008). Estimates of economic benefits from avoided climate change impacts depend on the types of  
51 damages accounted for, the assumed exposure and vulnerability to these damages as well as the  
52 adaptation capacity, which in turn are based on the development pathway assumed (Cross-Working

1 Group Box 1). CBA integrated assessment models raised critics, in particular for omitting elements of  
2 dynamic realism, such as inertia, induced innovation and path dependence, in their representation of  
3 mitigation (Grubb et al. 2021), and for underestimating damages from climate change, missing non-  
4 monetary damages, the uncertain and heterogeneous nature of damages and the risk of catastrophic  
5 damages (Stern 2013, 2016; Stern and Stiglitz 2021; Diaz and Moore 2017; Pindyck 2017; NASEM  
6 2017; Stoerk et al. 2018). Emerging literature has started to address those gaps, and integrated into  
7 cost-benefit frameworks the account of heterogeneity of climate damage and inequality (Dennig et al.  
8 2015; Budolfson et al. 2017; Fleurbaey et al. 2019; Kornek et al. 2021), damages with higher  
9 persistence, including damages on capital and growth (Dietz and Stern 2015; Moore and Diaz 2015;  
10 Moyer et al. 2014; Guivarch and Pottier 2018; Piontek et al. 2019; Ricke et al. 2018), risks of tipping  
11 points (Cai et al. 2015, 2016; Lontzek et al. 2015; Lemoine and Traeger 2016; van der Ploeg and de  
12 Zeeuw 2018; Cai and Lontzek 2019; Nordhaus 2019; Yumashev et al. 2019; Taconet et al. 2021) and  
13 damages to natural capital and non-market goods (Tol 1994; Sterner and Persson 2008; Bastien-  
14 Olvera and Moore 2020; Drupp and Hänsel 2021).

15  
16 Each of these factors, when accounted for in a CBA framework, tends to increase the welfare benefit  
17 of mitigation, thus leading to stabilization at lower temperature in optimal mitigation pathways. The  
18 limitations in CBA modelling frameworks remain significant, their ability to represent all damages  
19 incomplete, and the uncertainty in estimates remains large. However, emerging evidence suggests  
20 that, even without accounting for co-benefits of mitigation on other sustainable development  
21 dimensions (see section 3.6.3 for elements on co-benefits), global benefits of pathways *likely* to limit  
22 warming to 2°C outweigh global mitigation costs over the 21st century: depending on the study, the  
23 reason for this result lies in assumptions of economic damages from climate change in the higher end  
24 of available estimates (Moore and Diaz 2015; Ueckerdt et al. 2019; Brown and Saunders 2020;  
25 Glanemann et al. 2020), in the introduction of risks of tipping-points (Cai and Lontzek 2019), in the  
26 consideration of damages to natural capital and non-market goods (Bastien-Olvera and Moore 2020)  
27 or in the combination of updated representations of carbon cycle and climate modules, updated  
28 damage estimates and/or updated representations of economic and mitigation dynamics (Dietz and  
29 Stern 2015; Hänsel et al. 2020; Wei et al. 2020; van der Wijst et al. 2021b). In the above studies that  
30 perform a sensitivity analysis, this result is found to be robust to a wide range of assumptions on  
31 social preferences (in particular on inequality aversion and pure rate of time preference) and holds  
32 except if assumptions of economic damages from climate change are in the lower end of available  
33 estimates and the pure rate of time preference is in the higher range of values usually considered  
34 (typically above 1.5%). However, although such pathways bring net benefits over time (in terms of  
35 aggregate discounted present value), they involve distributional consequences and transition costs  
36 (Brown and Saunders 2020; Brown et al. 2020) (see also sections 3.6.1.2 and 3.6.4).

37  
38 The standard discounted utilitarian framework dominates CBA, thus often limiting the analysis to the  
39 question of discounting. CBA can be expanded to accommodate a wider variety of ethical values to  
40 assess mitigation pathways (Fleurbaey et al. 2019). The role of ethical values with regard to inequality  
41 and the situation of the worse-off (Adler et al. 2017), risk (van den Bergh and Botzen 2014; Drouet et  
42 al. 2015), and population size (Scovronick et al. 2017; Méjean et al. 2020) has been explored. In most  
43 of these studies, the optimal climate policy is found to be more stringent than the one obtained using a  
44 standard discounted utilitarian criterion.

45  
46 Comparing economic costs and benefits of mitigation raises a number of methodological and  
47 fundamental difficulties. Monetizing the full range of climate change impacts is extremely hard, if not  
48 impossible (WGII chapter 16), as is aggregating costs and benefits over time and across individuals  
49 when values are heterogeneous (AR5, WGIII chapter 3; this assessment, Chapter 1). Other approaches  
50 should thus be considered in supplement for decision making (Chapter 1, section 1.7), in particular

1 cost-effectiveness approaches that analyse how to achieve a defined mitigation objective at least cost  
2 or while also reaching other societal goals (Kooimey 2013; Kaufman et al. 2020; Köberle et al. 2021;  
3 Stern and Stiglitz 2021). In cost effectiveness studies too, incorporating benefits from avoided climate  
4 damages influences the results and leads to more stringent mitigation in the short-term (Drouet et al.  
5 2021; Schultes et al. 2021).

### 6 7 **3.6.3 Aggregate economic implication of mitigation co-benefits and trade-offs**

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

13  
14 Systematic reviews of the literature on co-benefits and trade-offs from mitigation actions have shown  
15 that only a small portion of articles provide economic quantifications (Deng et al. 2017; Karlsson et  
16 al. 2020). Most economic quantifications use monetary valuation approaches. Improved air quality,  
17 and associated health effects, are the co-benefit category dominating the literature (Markandya et al.  
18 2018; Vandyck et al. 2018; Scovronick et al. 2019; Howard et al. 2020; Karlsson et al. 2020b; Rauner  
19 et al. 2020a,b), but some studies cover other categories, including health effects from diet change  
20 (Springmann et al. 2016b) and biodiversity impacts (Rauner et al. 2020a). Regarding health effects  
21 from air quality improvement and from diet change, co-benefits are shown to be of the same order of  
22 magnitude as mitigation costs (Thompson et al. 2014; Springmann et al. 2016a,b; Markandya et al.  
23 2018; Scovronick et al. 2019b; Howard et al. 2020; Rauner et al. 2020a,b; Liu et al. 2021; Yang et al.  
24 2021). Co-benefits from improved air quality are concentrated sooner in time than economic benefits  
25 from avoided climate change impacts (Karlsson et al. 2020), such that when accounting both for  
26 positive health impacts from reduced air pollution and for negative climate effect of reduced cooling  
27 aerosols, optimal greenhouse gas mitigation pathways exhibit immediate and continual net economic  
28 benefits (Scovronick et al. 2019a). However, WGI chapter 6 (section 6.7.3) shows a delay in air  
29 pollution reduction benefits when they come from climate change mitigation policies compared with  
30 air pollution reduction policies.

31  
32 Achieving co-benefits is not automatic but results from coordinated policies and implementation  
33 strategies (Clarke et al. 2014; McCollum et al. 2018a). Similarly, avoiding trade-offs requires targeted  
34 policies (van Vuuren et al. 2015; Bertram et al. 2018). There is limited evidence of such pathways, but  
35 the evidence shows that pathways mitigation pathways designed to reach multiple sustainable  
36 development goals instead of focusing exclusively on emissions reductions, result in limited  
37 additional costs compared to the increased benefits (Cameron et al. 2016; McCollum et al. 2018b;  
38 Fujimori et al. 2020a; Sognaes et al. 2021).

### 39 40 **3.6.4 Structural change, employment and distributional issues along mitigation pathways**

41  
42 Beyond aggregate effects at the economy wide level, mitigation pathways have heterogeneous  
43 economic implications for different sectors and different actors. Climate-related factors are only one  
44 driver of the future structure of the economy, of the future of employment, and of future inequality  
45 trends, as overarching trends in demographics, technological change (innovation, automation, etc.),  
46 education and institutions will be prominent drivers. For instance, Rao et al. (2019b) and Benveniste  
47 et al. (2021) have shown that income inequality projections for the 21st century vary significantly,  
48 depending on socioeconomic assumptions related to demography, education levels, social public  
49 spending and migrations. However, the sections below focus on climate-related factors, both climate

1 mitigation actions themselves and the climate change impacts avoided along mitigation pathways,  
2 effects on structural change, including employment, and distributional effects.

#### 3 4 **3.6.4.1 Economic structural change and employment in long-term mitigation pathways**

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

9  
10 Mitigation affects work through multiple channels, which impacts geographies, sectors and skill  
11 categories differently (Fankhaeser et al. 2008; Bowen et al. 2018; Malerba and Wiebe 2021).  
12 Aggregate employment impacts of mitigation pathways mainly depend on the aggregate  
13 macroeconomic effect of mitigation (see 3.6.1, 3.6.2) and of mitigation policy design and  
14 implementation (Freire-González 2018) (section 4.2.6.3). Most studies that quantify overall  
15 employment implications of mitigation policies are conducted at the national or regional scales  
16 (section 4.2.6.3), or sectoral scales (e.g., see chapter 6 for energy sector jobs). The evidence is limited  
17 at the multi-national or global scale, but studies generally find small differences in aggregate  
18 employment in mitigation pathways compared to baselines: the sign of the difference depends on the  
19 assumptions and modelling frameworks used and the policy design tested, with some studies or policy  
20 design cases leading to small increases in employment (Chateau and Saint-Martin 2013; Pollitt et al.  
21 2015; Barker et al. 2016; Garcia-Casals et al. 2019; Fujimori et al. 2020a; Vrontisi et al. 2020;  
22 Malerba and Wiebe 2021) and other studies or policy design cases leading to small decreases  
23 (Chateau and Saint-Martin 2013; Vandyck et al. 2016). The small variations in aggregate employment  
24 hide substantial reallocation of jobs across sectors, with jobs creation in some sectors and jobs  
25 destruction in others. Mitigation action through thermal renovation of buildings, installation and  
26 maintenance of low-carbon generation, the build-out of public transit lead to jobs creation, while jobs  
27 are lost in fossil fuel extraction, energy supply and energy intensive sectors in mitigation pathways  
28 (von Stechow et al. 2015, 2016; Barker et al. 2016; Fuso Nerini et al. 2018; Perrier and Quirion 2018;  
29 Pollitt and Mercure 2018; Dominish et al. 2019; Garcia-Casals et al. 2019). In the energy sector, jobs  
30 losses in the fossil fuel sector are found to be compensated by gains in wind and solar jobs, leading to  
31 a net increase in energy sector jobs in 2050 in a mitigation pathway compatible with stabilization of  
32 the temperature increase below 2°C (Pai et al. 2021). Employment effects also differ by geographies,  
33 with energy-importing regions benefiting from net job creations but energy-exporting regions  
34 experiencing very small gains or suffering from net job destruction (Barker et al. 2016; Pollitt and  
35 Mercure 2018; Garcia-Casals et al. 2019; Malerba and Wiebe 2021). Coal phase-out raises acute  
36 issues of just transition for the coal-dependent countries (Spencer et al. 2018; Jakob et al. 2020)  
37 (section 4.5 and Box 6.2).

38  
39 Mitigation action also affects employment through avoided climate change impacts. Mitigation  
40 reduces the risks to human health and associated impacts on labour and helps protect workers from  
41 the occupational health and safety hazards imposed by climate change (Kjellstrom et al. 2016, 2018,  
42 2019 ; Levi et al. 2018; Day et al. 2019) (see WGII chapter 16).

#### 43 44 **3.6.4.2 Distributional implications of long-term mitigation pathways**

45 Mitigation policies can have important distributive effects between and within countries, either  
46 reducing or increasing economic inequality and poverty, depending on policy instruments design and  
47 implementation (see section 3.6.1.2 for an assessment of the distribution of mitigation costs across  
48 regions in mitigation pathways, section 3.7, Box 3.6 and chapter 4 section 4.2.2.6 for an assessment of  
49 the fairness and ambition of NDCs, and section 4.5 for an assessment of national mitigation pathways  
50 along the criteria of equity, including just transition, as well as chapter 17, section 17.4.5 for equity in

1 a just transition). For instance, emissions taxation has important distributive effects, both between and  
2 within income groups (Klenert et al. 2018; Cronin et al. 2018b; Pizer and Sexton 2019; Douenne  
3 2020; Steckel et al. 2021). These effects are more significant in some sectors, such as transport, and  
4 depend on country-specific consumption structures (Dorband et al. 2019; Fullerton and Muehlegger  
5 2019; Ohlendorf et al. 2021). However, revenues from emissions taxation can be used to lessen their  
6 regressive distributional impacts or even turn the policy into a progressive policy reducing inequality  
7 and/or leading to gains for lower income households (Cameron et al. 2016; Jakob and Steckel 2016;  
8 Fremstad and Paul 2019; Fujimori et al. 2020b; Böhringer et al. 2021; Steckel et al. 2021; Soergel et  
9 al. 2021b; Budolfson et al. 2021). Mitigation policies may affect the poorest through effects on energy  
10 and food prices (Hasegawa et al. 2015; Fujimori et al. 2019). Markkanen and Anger-Kraavi (2019)  
11 and Lamb et al. (2020) synthesize evidence from the existing literature on social co-impacts of  
12 climate change mitigation policy and their implications for inequality. They show that most policies  
13 can compound or lessen inequalities depending on contextual factors, policy design and policy  
14 implementation, but that negative inequality impacts of climate policies can be mitigated (and  
15 possibly even prevented), when distributive and procedural justice are taken into consideration in all  
16 stages of policy making, including policy planning, development and implementation, and when  
17 focusing on the carbon intensity of lifestyles, sufficiency and equity, wellbeing and decent living  
18 standards for all (see also 13.6).

19  
20 Mitigation pathways also affect economic inequalities between and within countries, and poverty,  
21 through the reduction of climate change impacts that fall more heavily on low-income countries,  
22 communities and households and exacerbate poverty (WGII chapters 8 and 16). Higher levels of  
23 warming are projected to generate higher inequality between countries as well as within them (WGII  
24 chapter 16). Through avoiding impacts, mitigation thus reduces economic inequalities and poverty  
25 (*high confidence*).

26  
27 A few studies consider both mitigation policies distributional impacts and avoided climate change  
28 impacts on inequalities along mitigation pathways. Rezai et al. (2018) find that unmitigated climate  
29 change impacts increase inequality, whereas mitigation has the potential to reverse this effect.  
30 Considering uncertainty in socioeconomic assumptions, emission pathways, mitigation costs,  
31 temperature response, and climate damage, Taconet et al. (2020) show that the uncertainties  
32 associated with socioeconomic assumptions and damage estimates are the main drivers of future  
33 inequalities between countries and that in most cases mitigation policies reduce future inequalities  
34 between countries. Gazzotti et al. (2021) show that inequality persists in 2°C consistent pathways due  
35 to regressivity of residual climate damages. However, the evidence on mitigation pathways  
36 implications for global inequality and poverty remains limited, and the modelling frameworks used  
37 have limited ability to fully represent the different dimensions of inequality and poverty and all the  
38 mechanisms by which mitigation affects inequality and poverty (Rao et al. 2017a; Emmerling and  
39 Tavoni 2021; Jafino et al. 2021).

## 40 41 42 **3.7 Sustainable development, mitigation and avoided impacts**

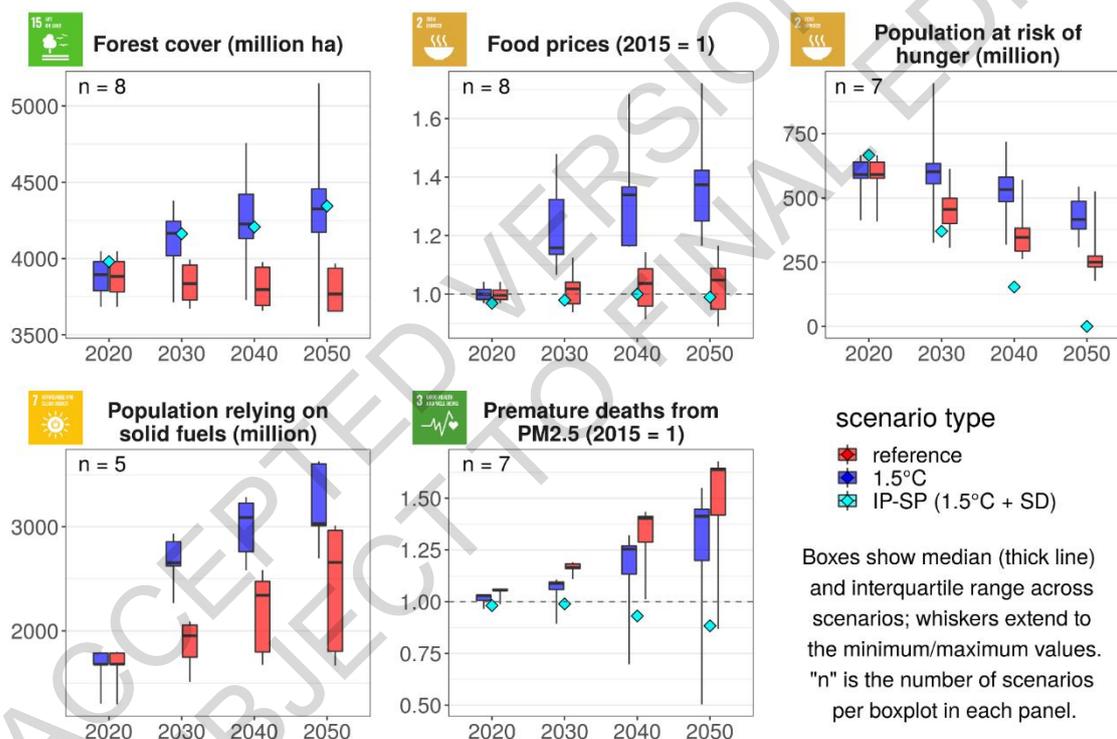
### 43 **3.7.1 Synthesis findings on mitigation and sustainable development**

44 Rapid and effective climate mitigation is a necessary part of sustainable development (*high*  
45 *confidence*) (see Cross-Chapter Box 5 in Chapter 4), but the latter can only be realized if climate  
46 mitigation becomes integrated with sustainable development policies (*high confidence*). Targeted  
47 policy areas must include healthy nutrition, sustainable consumption and production, inequality and  
48 poverty alleviation, air quality and international collaboration (*high confidence*). Lower energy

1 demand enables synergies between mitigation and sustainability, with lower reliance on CDR (*high*  
2 *confidence*).

3  
4 This section covers the long-term interconnection of SD and mitigation, taking forward the holistic  
5 vision of SD described in the SDGs (Brandi 2015; Leal Filho et al. 2018). Recent studies have  
6 explored the aggregated impact of mitigation for multiple sustainable development dimensions  
7 (Hasegawa et al. 2014; Bertram et al. 2018; Grubler et al. 2018; McCollum et al. 2018b; Fuso Nerini  
8 et al. 2018; van Vuuren et al. 2019; Soergel et al. 2021a). For instance, Figure 3.38 shows selected  
9 mitigation co-benefits and trade-offs based on a subset of models and scenarios, since so far many  
10 IAMs do not have a comprehensive coverage of sustainable development goals (Rao et al. 2017a; van  
11 Soest et al. 2019). Figure 3.38 shows that mitigation likely leads to increased forest cover (SDG 15)  
12 and reduced mortality from ambient PM<sub>2.5</sub> pollution (SDG 3) compared to reference scenarios.  
13 However, mitigation policies can also cause higher food prices and an increased population at risk of  
14 hunger (SDG 2) and relying on solid fuels (SDG 3 and SDG 7) as side effects. These trade-offs can be  
15 compensated through targeted support measures and/or additional SD policies (Cameron et al. 2016;  
16 Bertram et al. 2018; Fujimori et al. 2019; Soergel et al. 2021a).

17



18

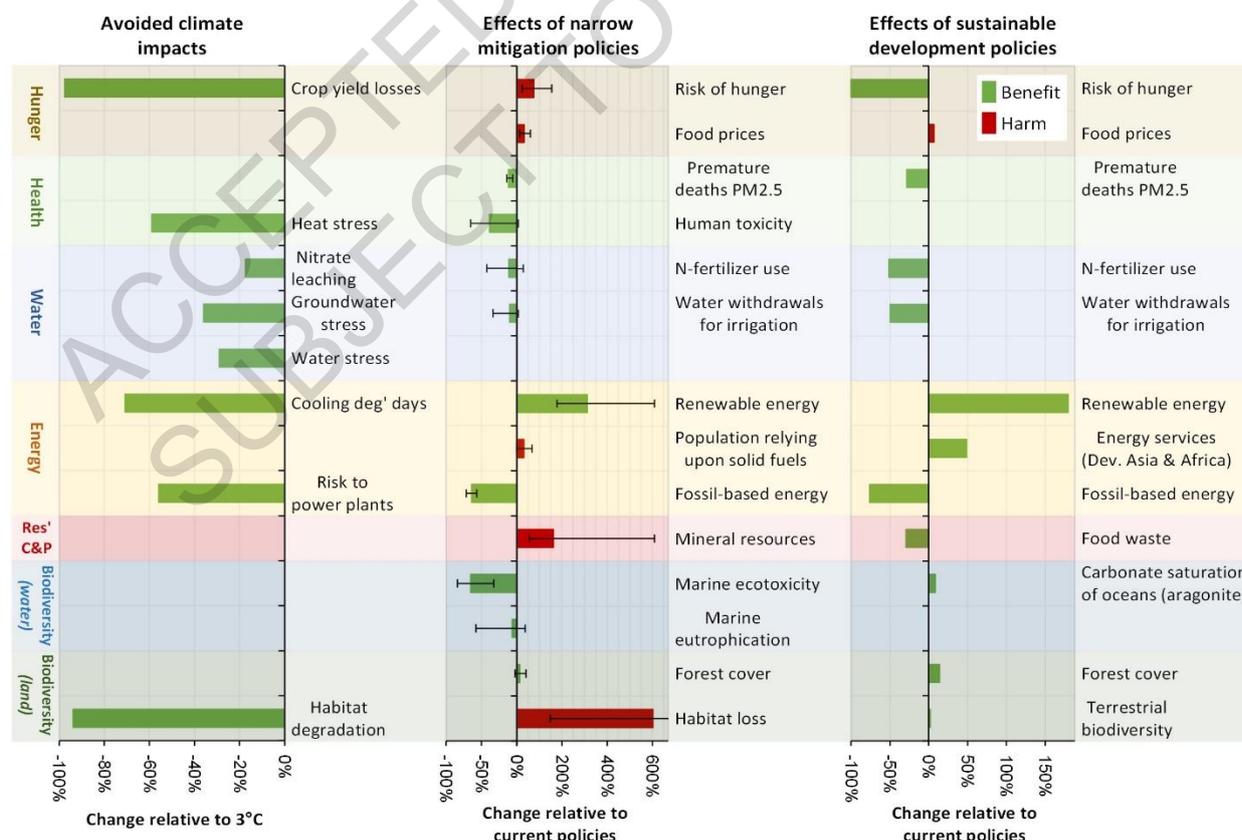
19 **Figure 3.38: Effect of climate change mitigation on different dimensions of sustainable development:**  
20 **shown are mitigation scenarios compatible with 1.5°C target (blue) and reference scenarios (red). Blue**  
21 **boxplots contain scenarios that include narrow mitigation policies from different studies (see below). This**  
22 **is compared to a sustainable development scenario (SP, Soergel et al. (2021a), cyan diamonds) integrating**  
23 **mitigation and SD policies (e.g., zero hunger in 2050 by assumption). Scenario sources for boxplots: single**  
24 **scenarios from i) Fujimori et al. (2020a); ii) Soergel et al. (2021a); multi-model scenario set from CD-**  
25 **LINKS (McCollum et al. 2018b; Roelfsema et al. 2020; Fujimori et al. 2019). For associated methods, see**  
26 **also Cameron et al. (2016), Rafaj et al. (2021). The reference scenario for (Fujimori et al. 2020a) is no-**  
27 **policy baseline; for all other studies, it includes current climate policies. In the “Food prices” and “Risk**  
28 **of hunger” panels, scenarios from CD-LINKS include a price cap of 200 USD/tCO<sub>2</sub>eq for land-use**  
29 **emissions (Fujimori et al. 2019). For the other indicators, CD-LINKS scenarios without price cap**  
30 **Roelfsema et al. (2020) are used due to SDG indicator availability. In the “Premature deaths” panel, a**  
31 **well-below 2°C scenario from Fujimori et al. (2020a) is used in place of a 1.5°C scenario due to data**  
32 **availability, and all scenarios are indexed to their 2015 values due to a spread in reported levels between**  
33 **models. SDG icons were created by the United Nations.**

1  
 2 The synthesis of the interplay between climate mitigation and sustainable development is shown in  
 3 Figure 3.39. The left panel shows the reduction in population affected by climate impacts at 1.5°C  
 4 compared to 3°C according to sustainability domains (Byers et al. 2018). Reducing warming reduces  
 5 the population impacted by all impact categories shown (*high confidence*). The left panel does not  
 6 take into account any side effects of mitigation efforts or policies to reduce warming: only reductions  
 7 in climate impacts. This underscores that mitigation is an integral basis for comprehensive SD (Watts  
 8 et al. 2015).

9  
 10 The middle and right panels of Figure 3.39 show the effects of 1.5°C mitigation policies compared to  
 11 current national policies: narrow mitigation policies (averaged over several models, middle panel),  
 12 and policies integrating sustainability considerations (right panel of Figure 3.39, based on the  
 13 Illustrative Mitigation Pathway “Shifting Pathways” (*SP*) (Soergel et al. 2021a)). Policies integrating  
 14 sustainability and mitigation (right panel) have far fewer trade-offs (red bars) and more co-benefits  
 15 (green bars) than narrow mitigation policies (middle panel). Note that neither middle nor right panels  
 16 include climate impacts.

17  
 18 Areas of co-benefits include human health, ambient air pollution and other specific kinds of pollution,  
 19 while areas of trade-off include food access, habitat loss and mineral resources (*medium confidence*).  
 20 For example, action consistent with 1.5°C in the absence of energy demand reduction measures  
 21 require large quantities of CDR, which, depending on the type used, are likely to negatively impact  
 22 both food availability and areas for biodiversity (Fujimori et al. 2018; Ohashi et al. 2019; Roelfsema  
 23 et al. 2020).

24  
 25 Mitigation to 1.5°C reduces climate impacts on sustainability (left). Policies integrating sustainability  
 26 and mitigation (right) have far fewer trade-offs than narrow mitigation policies (middle).  
 27



28

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

### 13 *3.7.1.1 Policies combining mitigation and sustainable development*

14  
 15 These findings indicate that holistic policymaking integrating sustainability objectives alongside  
 16 mitigation will be important in attaining sustainable development goals (van Vuuren et al. 2015, 2018;  
 17 Bertram et al. 2018; Fujimori et al. 2018; Hasegawa et al. 2018; Liu et al. 2020a; Honegger et al.  
 18 2021; Soergel et al. 2021a). Mitigation policies which target direct sector-level regulation, early  
 19 mitigation action, and lifestyle changes have beneficial sustainable development outcomes across air  
 20 pollution, food, energy and water (Bertram et al. 2018).

21  
 22 These policies include ones around stringent air quality (Kinney 2018; Rafaj et al. 2018; Soergel et al.  
 23 2021a); efficient and safe demand-side technologies, especially cook stoves (Cameron et al. 2016);  
 24 lifestyle changes (Bertram et al. 2018; Grubler et al. 2018; Soergel et al. 2021a); industrial and  
 25 sectoral policy (Bertram et al. 2018); agricultural and food policies (including food waste) (van  
 26 Vuuren et al. 2019; Soergel et al. 2021a); international cooperation (Soergel et al. 2021a); as well as  
 27 economic policies described in section 3.6. Recent research shows that mitigation is compatible with  
 28 reductions in inequality and poverty (see Box 3.6 on poverty and inequality).

29  
 30 Lower demand – e.g., for energy and land-intensive consumption such as meat – represents a  
 31 synergistic strategy for achieving ambitious climate mitigation without compromising sustainable  
 32 development goals (Grubler et al. 2018; van Vuuren et al. 2018; Bertram et al. 2018; Kikstra et al.  
 33 2021b; Soergel et al. 2021a) (*high confidence*). This is especially true for reliance on BECCS (Hickel  
 34 et al. 2021; Keyßer and Lenzen 2021). Options that reduce agricultural demand (e.g., dietary change,  
 35 reduced food waste) can have co-benefits for adaptation through reductions in demand for land and  
 36 water (IPCC 2019a; Grubler et al. 2018; Bertram et al. 2018; Soergel et al. 2021a).

37  
 38 While the impacts of climate change on agricultural output are expected to increase the population at  
 39 risk of hunger, there is evidence suggesting population growth will be the dominant driver of hunger  
 40 and undernourishment in Africa in 2050 (Hall et al. 2017). Meeting SDG5 relating to gender equality  
 41 and reproductive rights could substantially lower population growth, leading to a global population  
 42 lower than the 95% prediction range of the UN projections (Abel et al. 2016). Meeting SDG5 (gender  
 43 equality, including via voluntary family planning (O’Sullivan 2018)) could thus minimise the risks to  
 44 SDG2 (hunger) that are posed by meeting SDG13 (climate action).

## 45 **START BOX HERE**

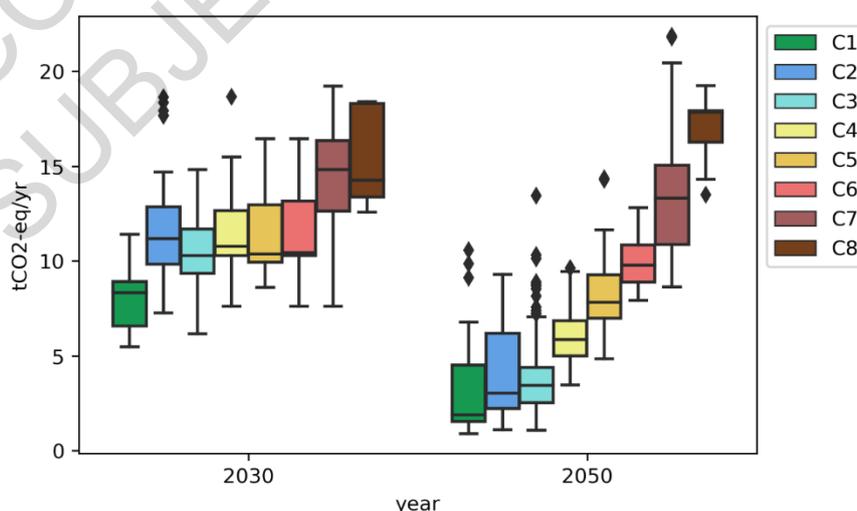
### 46 **Box 3.6 Poverty and Inequality**

47  
 48 There is high confidence (*medium evidence, high agreement*) that the eradication of extreme poverty  
 49 and universal access to energy can be achieved without resulting in significant greenhouse gas  
 50 emissions (Tait and Winkler 2012; Pachauri 2014; Chakravarty and Tavoni 2013; Rao 2014; Pachauri  
 51 et al. 2013; Hubacek et al. 2017b; Pobleto-Cazenave et al. 2021). There is also high agreement in the

1 literature that a focus on wellbeing and decent living standards for all can reduce disparities in access  
 2 to basic needs for services concurrently with climate mitigation (Chapter 5, 5.2). Mitigation pathways  
 3 in which national redistribution of carbon pricing revenues is combined with international climate  
 4 finance, achieve poverty reduction globally (Fujimori et al. 2020b; Soergel et al. 2021b). Carbon  
 5 pricing revenues in mitigation pathways consistent with limiting temperature increase to 2°C could  
 6 also contribute to finance investment needs for basic infrastructure (Jakob et al. 2016) and SDGs  
 7 achievement (Franks et al. 2018).

8  
 9 Several studies conclude that reaching higher income levels globally, beyond exiting extreme poverty,  
 10 and achieving more qualitative social objectives and well-being, are associated with higher emissions  
 11 (Ribas et al. 2017, 2019; Scherer et al. 2018; Fischetti 2018; Hubacek et al. 2017b). Studies give  
 12 divergent results on the effect of economic inequality reduction on emissions, with either an increase  
 13 or a decrease in emissions (Berthe and Elie 2015; Lamb and Rao 2015; Grunewald et al. 2017;  
 14 Hubacek et al. 2017a,b; Jorgenson et al. 2017; Knight et al. 2017; Mader 2018; Rao and Min 2018;  
 15 Liu et al. 2019; Sager 2019; Baležentis et al. 2020; Liobikienė 2020; Liobikienė and Rimkuvienė  
 16 2020; Liu et al. 2020b; Millward-Hopkins and Oswald 2021). However, the absolute effect of  
 17 economic inequality reduction on emissions remains moderate, under the assumptions tested. For  
 18 instance, (Sager 2019) finds that a full redistribution of income leading to equality among US  
 19 households in a counterfactual scenario for 2009 would raise emissions by 2.3%; and (Rao and Min  
 20 2018) limit to 8% the maximum plausible increase in emissions that would accompany the reduction  
 21 of the global Gini coefficient from its current level of 0.55 to a level of 0.3 by 2050. Similarly,  
 22 reduced income inequality would lead to a global energy demand increase of 7% (Oswald et al. 2021).  
 23 Reconciling mitigation and inequality reduction objectives requires policies that take into account  
 24 both objectives at all stages of policy making (Markkanen and Anger-Kraavi 2019), including  
 25 focusing on the carbon intensity of lifestyles (Scherer et al. 2018), attention to sufficiency and equity  
 26 (Fischetti 2018) and targeting the consumption of the richest and highest emitting households (Otto et  
 27 al. 2019).

28  
 29 In modelled mitigation pathways, inequality in per capita emissions between regions are generally  
 30 reduced over time, and the reduction is generally more pronounced in lower temperature pathways  
 31 (Box 3.6 Figure 1). Already in 2030, if Nationally Determined Contributions from the Paris  
 32 Agreement are fully achieved, inequalities in per capita GHG emissions between countries would be  
 33 reduced (Benveniste et al. 2018).



35  
 36 **Box 3.6 Figure 1: Difference in per capita emissions of Kyoto gases between the highest emitting and the**  
 37 **lowest emitting of the 10 regions, in 2030 and 2050, by temperature category of pathways**

1  
2 Through avoiding impacts of climate change, which fall more heavily on low-income countries,  
3 communities and households and exacerbate poverty, mitigation reduces inequalities and poverty (see  
4 section 3.6.4.2).

## 5 6 **END BOX HERE**

7  
8 The remainder of this section covers specific domains of sustainable development: food (3.7.2), water  
9 (3.7.3), energy (3.7.4), health (3.7.5), biodiversity (3.7.6) and multisector - Cities, infrastructure,  
10 industry, production & consumption (3.7.7). These represent the areas with the strongest research  
11 connecting mitigation to sustainable development. The links to individual SDGs are given within  
12 these sections. Each domain covers the benefits of avoided climate impacts and the implications  
13 (synergies and trade-offs) of mitigation efforts.

### 14 15 **3.7.2 Food**

16 The goal of SDG2 is to achieve “zero-hunger” by 2030. According to the UN (2015), over 25% of the  
17 global population currently experience food insecurity and nearly 40% of these experience severe  
18 food insecurity, a situation worsened by the covid pandemic (Paslakis et al. 2021).

#### 19 20 **3.7.2.1 Benefits of avoided climate impacts along mitigation pathways**

21 Climate change will reduce crop yields, increase food insecurity, and negatively influence nutrition  
22 and mortality (*high confidence*) (AR6 WGII Chapter 5). Climate mitigation will thus reduce these  
23 impacts, and hence reduce food insecurity (*high confidence*). The yield reduction of global food  
24 production will increase food insecurity and influence nutrition and mortality (Springmann et al.  
25 2016a; Hasegawa et al. 2014). For instance, (Springmann et al. 2016a) estimate that climate change  
26 could lead to 315,000-736,000 additional deaths by 2050, though these could mostly be averted by  
27 stringent mitigation efforts. Reducing warming reduces the impacts of climate change, including  
28 extreme climates, on food production and risk of hunger (Hasegawa et al. 2014, 2021b).

#### 29 30 **3.7.2.2 Implications of mitigation efforts along pathways**

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

38  
39 Mitigating climate change while ensuring that food security is not adversely affected requires a range  
40 of different strategies and interventions (*high confidence*). (Fujimori et al. 2018) explore possible  
41 economic solutions to these unintended impacts of mitigation (e.g., agricultural subsidies, food aid,  
42 and domestic reallocation of income) with an additional small (<0.1%) change in global GDP.  
43 Targeted food-security support is needed to shield impoverished and vulnerable people from the risk  
44 of hunger that could be caused by the economic effects of policies narrowly focussed on climate  
45 objectives. Introducing more biofuels and careful selection of bioenergy feedstocks could also reduce  
46 negative impacts (FAO WFP, WHO 2017). Reconciling bioenergy demands with food and  
47 biodiversity, as well as competition for land and water, will require changes in food systems –  
48 agricultural intensification, open trade, less consumption of animal-products and reduced food losses  
49 – and advanced biotechnologies (Henry et al. 2018; Xu et al. 2019).

1 There are many other synergistic measures for climate mitigation and food security. Agricultural  
2 technological innovation can improve the efficiency of land use and food systems, thus reducing the  
3 pressure on land from increasing food demand (Foley et al. 2011; Humpenöder et al. 2018; Popp et al.  
4 2014; Obersteiner et al. 2016; Doelman et al. 2019). Furthermore, decreasing consumption of animal  
5 products could contribute to SDG3.4 by reducing the risk of non-communicable diseases (Garnett  
6 2016).

7  
8 Taken together, climate changes will reduce crop yields, increase food insecurity and influence  
9 nutrition and mortality (*high confidence*) (see 3.7.2.1). However, if measures are not properly  
10 designed, mitigating climate change will also negatively impact on food consumption and security.  
11 Additional solutions to negative impacts associated with climate mitigation on food production and  
12 consumption include a transition to a sustainable agriculture and food system that is less resource  
13 intensive, more resilient to a changing climate, and in line with biodiversity and social targets (Kayal  
14 et al. 2019).

### 16 3.7.3 Water

17 Water is relevant to SDG 6 (clean water and sanitation), SDG 15 (ecosystem protection and water  
18 systems), and SDG Targets 12.4 and 3.9 (water pollution and health). This section discusses water  
19 quantity, water quality, and water-related extremes. See 3.7.5 for water-related health effects.

#### 21 3.7.3.1 Benefits of avoided climate impacts along mitigation pathways

22 Global precipitation, evapotranspiration, runoff and water availability increase with warming  
23 (Hanasaki et al. 2013; Greve et al. 2018) (see also WGII Chapter 4). Climate change also affects the  
24 occurrence of and exposure to hydrological extremes (*high confidence*) (Arnell and Lloyd-Hughes  
25 2014; Asadieh and Krakauer 2017; Dottori et al. 2018; IPCC 2019a; Naumann et al. 2018; Do et al.  
26 2020) (see also WGII Chapter 4). Climate models project increases in precipitation intensity (*high*  
27 *confidence*), local flooding (*medium confidence*), and drought risk (*very high confidence*) (Arnell and  
28 Lloyd-Hughes 2014; Asadieh and Krakauer 2017; Dottori et al. 2018; IPCC 2019a) (see also WGII  
29 Chapter 4).

30  
31 The effect of climate change on water availability and hydrological extremes varies by region (*high*  
32 *confidence*) due to differences in the spatial patterns of projected precipitation changes (Hanasaki et  
33 al. 2013; Koutroulis et al. 2019; Schewe et al. 2014; Schlosser et al. 2014; Asadieh and Krakauer  
34 2017; Dottori et al. 2018; Naumann et al. 2018) (see also WGII Chapter 4). Global exposure to water  
35 stress is projected to increase with increased warming, but increases will not occur in all regions  
36 (Arnell and Lloyd-Hughes 2014; Gosling and Arnell 2016; Hanasaki et al. 2013; IPCC 2019a;  
37 Schewe et al. 2014).

38  
39 Limiting warming could reduce water-related risks (*high confidence*) (O'Neill et al. 2017b; Byers et  
40 al. 2018; Hurlbert et al. 2019) (see also WGII Chapter 4) and the population exposed to increased  
41 water stress (Arnell and Lloyd-Hughes 2014; Gosling and Arnell 2016; Hanasaki et al. 2013; IPCC  
42 2019a; Schewe et al. 2014).

43  
44 The effect of climate change on water depends on the climate model, the hydrological model, and the  
45 metric (*high confidence*) stress (Arnell and Lloyd-Hughes 2014; Gosling and Arnell 2016; Hanasaki  
46 et al. 2013; IPCC 2019a; Schewe et al. 2014; Schlosser et al. 2014). However, the effect of  
47 socioeconomic development could be larger than the effect of climate change (*high confidence*)  
48 (Arnell and Lloyd-Hughes 2014; Schlosser et al. 2014; Graham et al. 2020).

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

### 3.7.3.2 *Implications of mitigation efforts along pathways*

6 The effect of mitigation on water demand depends on the mitigation technologies deployed (*high*  
7 *confidence*) (Bonsch et al. 2016; Chaturvedi et al. 2013a,b; Jakob and Steckel 2016; Hejazi et al.  
8 2014; Kyle et al. 2013; Fujimori et al. 2017; Maïzi et al. 2017; Mouratiadou et al. 2016; Parkinson et  
9 al. 2019; Bijl et al. 2018; Cui et al. 2018; Graham et al. 2018; Hanasaki et al. 2013). Some mitigation  
10 options could increase water consumption (volume removed and not returned) while decreasing  
11 withdrawals (total volume of water removed, some of which may be returned) (Kyle et al. 2013;  
12 Mouratiadou et al. 2016; Fricko et al. 2016; Parkinson et al. 2019). Bioenergy and BECCS can  
13 increase water withdrawals and water consumption (*high confidence*) (Bonsch et al. 2016; Chaturvedi  
14 et al. 2013a; Hejazi et al. 2014; Jakob and Steckel 2016; Kyle et al. 2013; Fujimori et al. 2017; Maïzi  
15 et al. 2017; Mouratiadou et al. 2016; Parkinson et al. 2019; Yamagata et al. 2018; Séférian et al. 2018)  
16 (see also WGII Chapter 4). DACCS (Fuhrman et al. 2020) and CCS (Kyle et al. 2013; Fujimori et al.  
17 2017) could increase water demand; however, the implications of CCS depend on the cooling  
18 technology and when capture occurs (Magneschi et al. 2017; Maïzi et al. 2017; Giannaris et al. 2020).  
19 Demand-side mitigation (e.g., dietary change, reduced food waste, reduced energy demand) can  
20 reduce water demand (Bajželj et al. 2014; Aleksandrowicz et al. 2016; Springmann et al. 2018; Green  
21 et al. 2018). Introducing specific measures (e.g., environmental flow requirements, improved  
22 efficiency, priority rules) can reduce water withdrawals (Bertram et al. 2018; Bijl et al. 2018;  
23 Parkinson et al. 2019).

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

### 3.7.4 **Energy**

30 Energy is relevant to SDG7 on sustainable and affordable energy access. Access to sufficient levels of  
31 reliable, affordable and renewable energy is essential for sustainable development. Currently, over 1  
32 billion people still lack access to electricity (Ribas et al. 2019).

#### 3.7.4.1 *Benefits of avoided climate impacts along mitigation pathways*

35 Climate change alters the production of energy through changes in temperature (hydropower, fossil  
36 fuel, nuclear, solar, bioenergy, transmission and pipelines), precipitation (hydropower, fossil fuel,  
37 nuclear, bioenergy), windiness (wind, wave), and cloudiness (solar) (*high confidence*). Increases in  
38 temperature reduce efficiencies of thermal power plants (e.g., fossil fuel and nuclear plants) with air-  
39 cooled condensers by 0.4–0.7% °C increase in ambient temperature (Cronin et al. 2018a; Yalaw, S. G.  
40 et al. 2020; Simioni and Schaeffer 2019). Potentials and costs for renewable energy technologies are  
41 also affected by climate change, though with considerable regional variation and uncertainty (Gernaat  
42 et al. 2021). Biofuel yields could increase or decrease depending on the level of warming, changes in  
43 precipitation, and the effect of CO<sub>2</sub> fertilization (Calvin et al. 2013; Kyle et al. 2014; Gernaat et al.  
44 2021). Coastal energy facilities could potentially be impacted by sea-level rise (Brown et al. 2014).

46 The energy sector uses large volumes of water (Fricko et al. 2016), making it highly vulnerable to  
47 climate change (Tan and Zhi 2016) (*high confidence*). Thermoelectric and hydropower sources are the  
48 most vulnerable to water stress (van Vliet et al. 2016). Restricted water supply to these power sources  
49 can affect grid security and affordable energy access (Koch et al. 2014; Ranzani et al. 2018; Zhang et  
50 al. 2018d). The hydropower facilities from high mountain areas of Central Europe, Iceland, Western

1 US/Canada, and Latin America (Hock et al. 2019) as well as Africa and China (Bartos and Chester  
2 2015; Eyer and Wichman 2018; Tarroja et al. 2016; Savelsberg et al. 2018; Ranzani et al. 2018;  
3 Zhang et al. 2018d; Conway et al. 2017; Zhou et al. 2018; Gaupp et al. 2015; Wang et al. 2019; Byers  
4 et al. 2018) have experienced changes in seasonality and availability.

#### 6 **3.7.4.2 Implications of mitigation efforts along pathways**

7 Extending energy access to all in line with SDG7 is compatible with strong mitigation consistent with  
8 the Paris agreement (*high confidence*). The Low Energy Demand (LED) scenario projects that these  
9 twin goals can be achieved by relying heavily on energy efficiency and rapid social transformations  
10 (Grubler et al. 2018). The IEA's Sustainable Development Scenario (IEA 2020a) achieves  
11 development outcomes but with higher average energy use, and bottom-up modelling suggests that  
12 decent living standards could be provided to all in 2040-2050 with roughly 150 EJ, or 40% of current  
13 final energy use (Kikstra et al. 2021b; Millward-Hopkins et al. 2020). The trade-offs between climate  
14 mitigation and increasing energy consumption of the world's poorest are negligible (Rao and Min  
15 2018; Scherer et al. 2018).

16  
17 The additional energy demand to meet the basic cooling requirement in Global South is estimated to  
18 be much larger than the electricity needed to provide basic residential energy services universally via  
19 clean and affordable energy, as defined by SDG7 (IEA 2019; Mastrucci et al. 2019) (*high*  
20 *confidence*). If conventional air conditioning systems are widely deployed to provide cooling, energy  
21 use could rise significantly (van Ruijven et al. 2019; Falchetta and Mistry 2021; Bezerra et al. 2021),  
22 thus creating a positive feedback further increasing cooling demand. However, the overall emissions  
23 are barely altered by the changing energy demand composition with reductions in heating demand  
24 occurring simultaneously (Isaac and van Vuuren 2009; Labriet et al. 2015; McFarland et al. 2015;  
25 Clarke et al. 2018). Some mitigation scenarios show price increases of clean cooking fuels, slowing  
26 the transition to clean cooking fuels (SDG 7.1) and leaving a billion people in 2050 still reliant on  
27 solid fuels in South Asia (Cameron et al. 2016).

28  
29 In contrast, future energy infrastructure could improve reliability, thus lowering dependence on high-  
30 carbon, high-air pollution backup diesel generators (Farquharson et al. 2018) that are often used to  
31 cope with unreliable power in developing countries (Maruyama Rentschler et al. 2019). There can be  
32 significant reliability issues where mini-grids are used to electrify rural areas (Numminen and Lund  
33 2019). A stable, sustainable energy transition policy that considers national sustainable development  
34 in the short- and long-term is critical in driving a transition to an energy future that addresses the  
35 trilemma of energy security, equity, and sustainability (La Viña et al. 2018).

### 37 **3.7.5 Health**

38  
39 SDG 3 aims to ensure healthy lives and promote well-being for all at all ages. Climate change is  
40 increasingly causing injuries, illnesses, malnutrition, threats to mental health and well-being, and  
41 deaths (see WGII Chapter 7). Mitigation policies and technologies to reduce GHG emissions are often  
42 beneficial for human health on a shorter time scale than benefits in terms of slowing climate change  
43 (Limaye et al. 2020). The financial value of health benefits from improved air quality alone is  
44 projected to exceed the costs of meeting the goals of the Paris Agreement (Markandya et al. 2018).

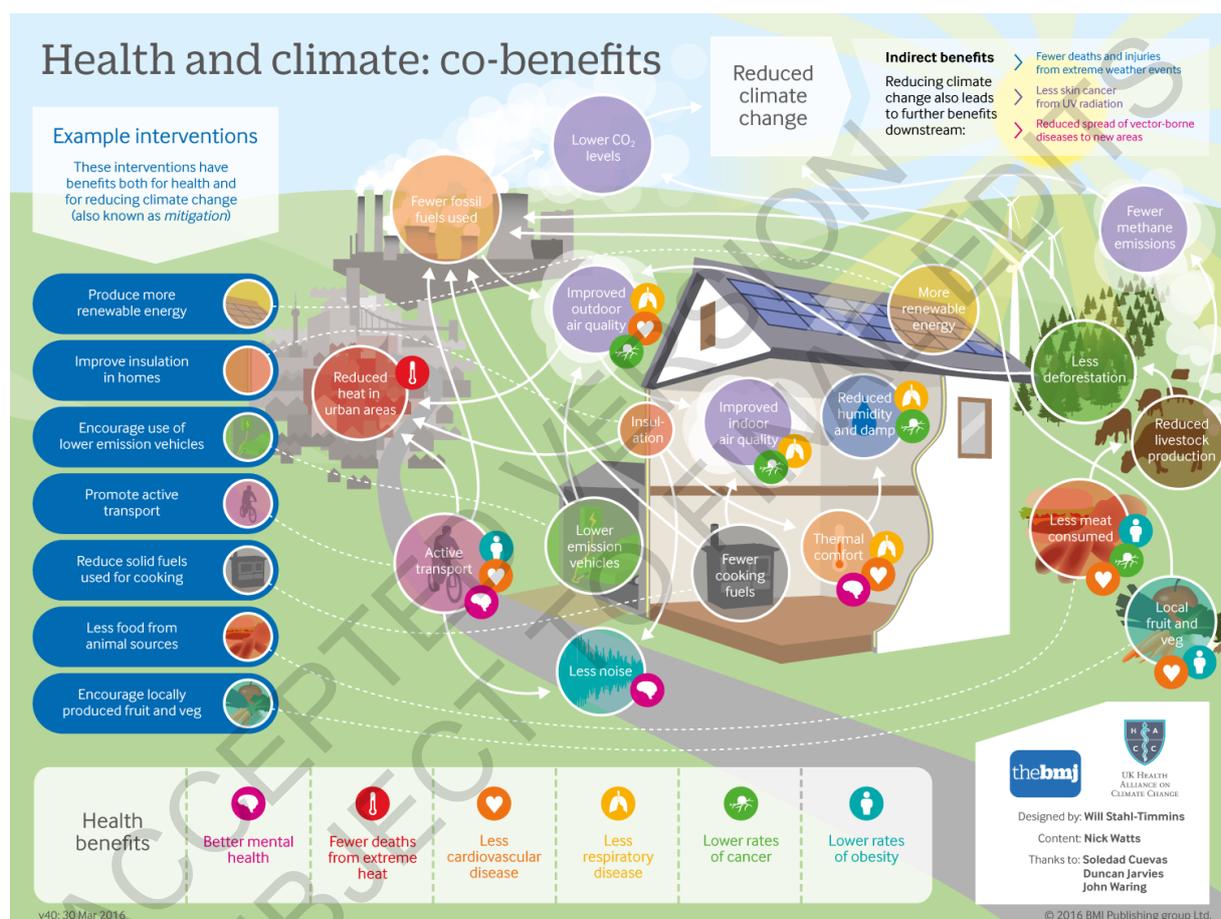
#### 46 **3.7.5.1 Benefits of avoided climate impacts along mitigation pathways**

47  
48 The human health chapter of the WGII contribution to the AR6 concluded that climate change is  
49 increasingly affecting a growing number of health outcomes, with negative net impacts at the global  
50 scale and positive only in a few limited situations. There are few estimates of economic costs of

1 increases in climate-sensitive health outcomes. In the U.S. in 2012, the financial burden in terms of  
 2 deaths, hospitalizations, and emergency department visits for ten climate-sensitive events across 11  
 3 states were estimated to be USD 10.0 (2.7 – 24.6) billion in 2018 dollars (Limaye et al. 2019).

### 3.7.5.2 Implications of mitigation efforts along pathways

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



14 **Figure 3.40: Diagram showing the co-benefits between health and mitigation (Iacobucci 2016)**

16 The avoided health impacts associated with climate change mitigation can substantially offset  
 17 mitigation costs at the societal level (Chang et al. 2017; Ščasný et al. 2015; Schucht et al. 2015;  
 18 Markandya et al. 2018). Models of health co-benefits show that a 1.5 C pathway could result in 152  
 19 +/- 43 million fewer premature deaths worldwide between 2020 and 2100 in comparison to a  
 20 business-as-usual scenario, particularly due to reductions in exposure to PM2.5 (Shindell et al. 2018;  
 21 Rauner et al. 2020a; Rafaj et al. 2021). Some of the most substantial health, wellbeing, and equity  
 22 benefits associated with climate action derive from investing in basic infrastructure: sanitation, clean  
 23 drinking water, clean energy, affordable healthy diets, clean public transport, and improved air quality  
 24 from transformative solutions across economic sectors including agriculture, energy, transport and  
 25 buildings (Chang et al. 2017).

1  
2 The health co-benefits of the NDCs for 2040 were compared for two scenarios, one consistent with  
3 the goal of the Paris Agreement and the SDGs and the other also placing health as a central focus of  
4 the policies (i.e., health in all climate policies scenario) (Hamilton et al. 2021), for Brazil, China,  
5 Germany, India, Indonesia, Nigeria, South Africa, the UK, and the USA. Modelling of the energy,  
6 food and agriculture, and transport sectors, and associated risk factors related to mortality, suggested  
7 the sustainable pathways scenario could result in annual reductions of 1.18 million air pollution-  
8 related deaths, 5.86 million diet-related deaths, and 1.15 million deaths due to physical inactivity.  
9 Adopting the more ambitious health in all climate policies scenario could result in further reductions  
10 of 462,000 annual deaths attributable to air pollution, 572,000 annual deaths attributable to diet, and  
11 943,000 annual deaths attributable to physical inactivity. These benefits were attributable to the  
12 mitigation of direct greenhouse gas emissions and the commensurate actions that reduce exposure to  
13 harmful pollutants, as well as improved diets and safe physical activity.  
14

15 Cost-benefit analyses for climate mitigation in urban settings that do not account for health may  
16 underestimate the potential cost savings and benefits (Hess et al. 2020). The net health benefits of  
17 controlling air pollution as part of climate mitigation efforts could reach trillions of dollars annually,  
18 depending on the air quality policies adopted globally (Markandya et al. 2018; Scovronick et al.  
19 2019b). Air pollution reductions resulting from meeting the Paris Agreement targets were estimated to  
20 provide health co-benefits-to-mitigation ratios of between 1.4 and 2.5 (Markandya et al. 2018). In  
21 Asia, the benefit of air pollution reduction through mitigation measures were estimated to reduce  
22 premature mortality by 0.79 million, with an associated health benefit of USD2.8 trillion versus  
23 mitigation costs of USD840 billion, equating to 6% and 2% of GDP, respectively (Xie et al. 2018).  
24 Similarly, stabilizing radiative forcing to 3.4 W/m<sup>2</sup> in South Korea could cost USD1.3-8.5 billion in  
25 2050 and could lead to a USD23.5 billion cost reduction from the combined benefits of avoided  
26 premature mortality, health expenditures, and lost work hours (Kim et al. 2020). The health co-  
27 benefits related to physical exercise and reduced air pollution largely offset the costs of implementing  
28 low CO<sub>2</sub> emitting urban mobility strategies in three Austrian cities (Wolkingner et al. 2018).  
29

30 Just in the United States of America, over the next 50 years, a 2°C pathway could prevent roughly 4.5  
31 million premature deaths, about 3.5 million hospitalizations and emergency room visits, and  
32 approximately 300 million lost workdays (Shindell 2020). The estimated yearly benefits of USD700  
33 billion were more than the estimated cost of the energy transition.  
34

### 35 **3.7.6 Biodiversity (land and water)**

36  
37 Biodiversity covers Life Below Water (SDG 14) and Life On Land (SDG 15). Ecosystem services are  
38 relevant to the goals of Zero Hunger (SDG 2), Good Health and Well Being (SDG 3), Clean Water  
39 and Sanitation (SDG 6) and Responsible Consumption and Production (SDG 12), as well as being  
40 essential to human existence (Díaz et al. 2019).  
41

#### 42 **3.7.6.1 Benefits of avoided climate impacts along mitigation pathways**

##### 43 **3.7.6.1.1 Terrestrial and freshwater aquatic ecosystems**

44 Climate change is a major driver of species extinction and terrestrial and freshwater ecosystems  
45 destruction (see WGII Chapter 2) (*high confidence*). Analysis shows that approximately half of all  
46 species with long-term records have shifted their ranges in elevation and about two thirds have  
47 advanced their timing of spring events (Parmesan and Hanley 2015). Under 3.2 °C warming, 49% of  
48 insects, 44% of plants and 26% of vertebrates are projected to be at risk of extinction. At 2°C, this  
49 falls to 18% of insects, 16% of plants and 8% of vertebrates and at 1.5°C, to 6% of insects, 8% of  
50

1 plants and 4% of vertebrates (Warren et al. 2018). Incidents of migration of invasive species,  
2 including pests and diseases, are also attributable to climate change, with negative impacts on food  
3 security and vector-borne diseases. Moreover, if climate change reduces crop yields, cropland may  
4 expand – a primary driver of biodiversity loss – in order to meet food demand (Molotoks et al. 2020).  
5 Land restoration and halting land degradation under all mitigation scenarios has the potential for  
6 synergy between mitigation and adaptation.  
7

#### 8 *3.7.6.1.2 Marine and coastal ecosystems*

9 Marine ecosystems are being affected by climate change and growing non-climate pressures including  
10 temperature change, acidification, land-sourced pollution, sedimentation, resource extraction and  
11 habitat destruction (*high confidence*) (IPCC 2019b; Bindoff et al. 2019). The impacts of climate  
12 drivers and their combinations vary across taxa (WGII Chapter 3). The danger of warming and  
13 acidification to coral reefs, rocky shores and kelp forests is well established (*high confidence*) (WGII  
14 Chapter 3). Migration towards optimal thermal and chemical conditions (Burrows et al. 2019)  
15 contributes to large scale redistribution of fish and invertebrate populations, and major impacts on  
16 global marine biomass production and maximum sustainable yield (Bindoff et al. 2019).  
17

#### 18 *3.7.6.2 Implications of mitigation efforts along pathways*

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

24 Climate change mitigation actions to reduce or slow negative impacts on ecosystems are likely to  
25 support the achievement of SDGs 2, 3, 6, 12, 14 and 15. Some studies show that stringent and  
26 constant GHG mitigation practices bring a net benefit to global biodiversity even if land-based  
27 mitigation measures are also adopted (Ohashi et al. 2019), as opposed to delayed action which would  
28 require much more widespread use of BECCS. Scenarios based on demand reductions of energy and  
29 land-based production are expected to avoid many such consequences, due to their minimized reliance  
30 on BECCS (Grubler et al. 2018; Conijn et al. 2018; Bowles et al. 2019; Soergel et al. 2021a).  
31 Stringent mitigation that includes reductions in demand for animal-based foods and food-waste could  
32 also relieve pressures on land-use and biodiversity (*high confidence*), both directly by reducing  
33 agricultural land requirements (Leclère et al. 2020) and indirectly by reducing the need for land-based  
34 CDR (van Vuuren et al. 2018).  
35

36 As environmental conservation and sustainable use of the earth's terrestrial species and ecosystems  
37 are strongly related, recent studies have evaluated interconnections among key aspects of land and  
38 show pathway to the global sustainable future of land (Erb et al. 2016; Humpenöder et al. 2018; Popp  
39 et al. 2014; Obersteiner et al. 2016). Most studies agree that many biophysical options exist to achieve  
40 global climate mitigation and sustainable land-use in future. Conserving local biodiversity requires  
41 careful policy design in conjunction with land-use regulations and societal transformation in order to  
42 minimize the conversion of natural habitats.  
43

### 44 **3.7.7 Cities and infrastructure**

45 This subsection focuses upon SDG9, Industry, Innovation and Infrastructure and SDG11, Sustainable  
46 Cities and Communities.  
47

#### 48 *3.7.7.1 Benefits of avoided climate impacts along mitigation pathways*

49 By 2100, urban population will be almost double and more urban areas will be built (Jiang and  
50 O'Neill 2017), although Covid-19 may modify these trends (Kii 2021). Urbanization will amplify

1 projected air temperature changes in cities, including amplifying heat waves (see WGI Chapter 10,  
2 Box 10.3). Benefits of climate mitigation in urban areas include reducing heat, air pollution and  
3 flooding. Industrial infrastructure and production-consumption supply networks also benefit from  
4 avoided impacts.

### 6 **3.7.7.2 Implications of mitigation efforts along pathways**

7 Many co-benefits to urban mitigation actions (see Chapter 8, Section 8.2.1) that improve the  
8 liveability of cities and contribute to achieving SDG11. In particular, compact, urban form, efficient  
9 technologies and infrastructure can play a valuable role in mitigation by reducing energy demand  
10 (Güneralp et al. 2017; Creutzig et al. 2016), thus averting carbon lock-in, while reducing land sprawl  
11 and hence increasing carbon storage and biodiversity (D'Amour et al. 2017). Benefits of mitigation  
12 include air quality improvements from decreased traffic and congestion when private vehicles are  
13 displaced by other modes; health benefits from increases in active travel; and lowered urban heat  
14 island effects from green-blue infrastructures (section 8.2.1).

15  
16 However, increasing urban density or enlarging urban green spaces can increase property prices and  
17 reduce affordability (Section 8.2.1). Raising living conditions for slum dwellers & people living in  
18 informal settlements will require significant materials and energy; however, regeneration can be  
19 conducted in ways that avoid carbon-intense infrastructure lock-in (see Chapter 8 & 9). Cities affect  
20 other regions through supply chains (Marinova et al. 2020).

21  
22 Sustainable production, consumption and management of natural resources are consistent with, and  
23 necessary for, mitigation (Chapters 5 & 11). Demand-side measures can lower requirements for  
24 upstream material and energy use (Chapter 5). In terms of industrial production, transformational  
25 changes across sectors will be necessary for mitigation (Chapter 11, sections 11.3 and 11.4).

26  
27 Addressing multiple SDG arenas requires new systemic thinking in the areas of governance and  
28 policy, such as those proposed by (Sachs et al. 2019).

## 30 **3.8 Feasibility of socio/techno/economic transitions**

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

### 35 **3.8.1 Feasibility frameworks for the low carbon transition and scenarios**

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

47  
48 Regarding scenarios, the feasibility ‘what’ question is the one most commonly dealt with in the  
49 literature, though most of the studies have focused on expanding low carbon system, and yet political

1 constraints might arise mostly from phasing out fossil fuel-based ones (Spencer et al. 2018; Fattouh et  
2 al. 2019). The ‘when and where’ dimension can also be related to the scenario assessment, but only  
3 insofar the models generating them can differentiate time and geographical contextual factors.  
4 Distinguishing mitigation potential by regional institutional capacity has a significant influence on the  
5 costs of stabilizing climate (Iyer et al. 2015c). The ‘whom’ question is the most difficult to capture by  
6 scenarios, given the multitude of actors involved as well as their complex interactions. The focus of  
7 socio-technical transition sciences on the co-evolutionary processes can shed light on the dynamics of  
8 feasibility (Nielsen et al. 2020).

9  
10 The when-where-whom distinction allows depicting a feasibility frontier beyond which  
11 implementation challenges prevent mitigation action (Jewell and Cherp 2020). Even if the current  
12 feasibility frontier appears restraining in some jurisdictions, it is context-dependent and dynamic as  
13 innovation proceeds and institutional capacity builds up (Nielsen et al. 2020). The question is whether  
14 the feasibility frontier can move faster than the pace at which the carbon budget is being exhausted.  
15 Jewell et al. (2019) show that the emission savings from the pledges of premature retirement of coal  
16 plants is 150 times less than globally committed emissions from existing coal power plants. The  
17 pledges come from countries with high institutional capacity and relatively low shares of coal in  
18 electricity. Other factors currently limiting the capacity to steer transitions at the necessary speed  
19 include the electoral market orientation of politicians (Willis 2017), the status quo orientation of  
20 senior public officials (Geden 2016), path dependencies created by 'instrument constituencies' (Béland  
21 and Howlett 2016), or the benefits of deliberate inconsistencies between talk, decisions and actions in  
22 climate policy (Rickards et al. 2014). All in all, a number of different delay mechanisms in both  
23 science and policy have been identified to potentially impede climate goal achievement (Karlsson and  
24 Gilek 2020) - see also Chapter 13.

25  
26 In addition to its contextual and dynamic nature, feasibility is a multi-dimensional concept. The IPCC  
27 1.5°C special report distinguishes 6 dimensions of feasibility: geophysical, environmental-ecological,  
28 technological, economic, socio-cultural and institutional. At the individual option level, different  
29 mitigation strategies face various barriers as well as enablers (see Chapter 6 for the option-level  
30 assessment). However, a systemic transformation involves interconnections of a wide range of  
31 indicators. Model-based assessments are meant to capture the integrative elements of the transition  
32 and of associated feasibility challenges. However, the translation of model-generated pathways into  
33 feasibility concerns (Rogelj et al. 2018b) has developed only recently. Furthermore, multiple forms of  
34 knowledge can be mobilized to support strategic decision-making and complement scenario analysis  
35 (Turnheim and Nykvist 2019). We discuss both approaches next.

### 37 **3.8.2 Feasibility appraisal of low carbon scenarios**

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

#### 43 **3.8.2.1 Model solvability**

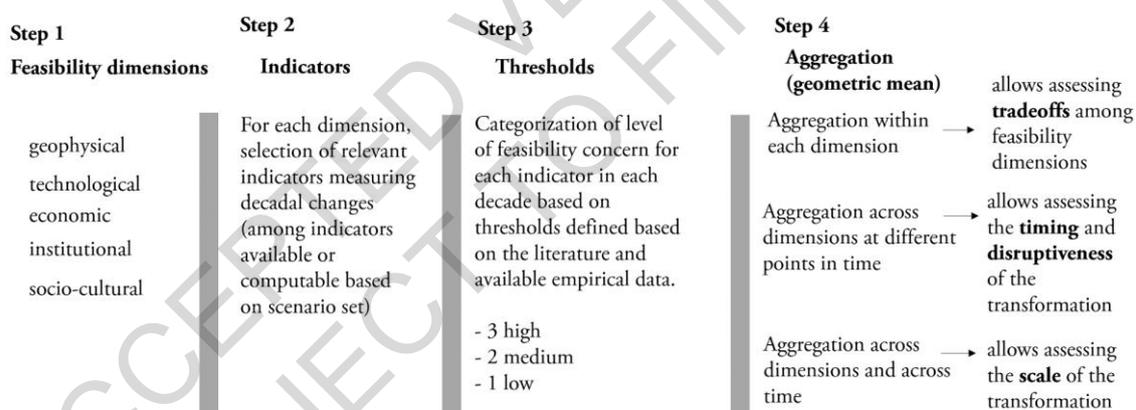
44 In order to be generated, scenarios must be coherent with the constraints and assumptions embedded  
45 in the models (i.e., deployment potential of given technologies, physical and geological limits) and in  
46 the scenario design (i.e., carbon budget). Sometimes, models cannot solve specific scenarios. This  
47 provides a first, coarse indication of feasibility concerns. Specific vetting criteria can be imposed,  
48 such as carbon price values above which scenarios should not be reported, as in Clarke et al. (2009).  
49 However, model solvability raises issues of aggregation in model ensemble. Since model solving is

1 not a random process, but a function of the characteristics of the models, analysing only reported  
2 outcomes leads to statistical biases (Tavoni and Tol 2010).

3  
4 Although model-feasibility differs distinctly from feasibility in the real world, it can indicate the  
5 relative challenges of low carbon scenarios - primarily when performed in a model ensemble of  
6 sufficient size. Riahi et al. (2015) interpreted infeasibility across a large number of models as an  
7 indication of increased risk that the transformation may not be attainable due to technical or economic  
8 concerns. All models involved in a model comparison of 1.5°C targets (Rogelj et al. 2018b) (Table  
9 S1) were able to solve under favourable underlying socio-economic assumptions (SSP1), but none for  
10 the more challenging SSP3. This interpretation of feasibility was used to highlight the importance of  
11 socio-economic drivers for attaining climate stabilization. Gambhir et al. (2017) constrained the  
12 models to historically observed rates of change and found that it would no longer allow to solve for  
13 2°C, highlighting the need for rapid technological change.

### 15 3.8.2.2 Scenario feasibility

16 Evaluating the feasibility of scenarios involves several steps (see Figure 3.41). First, one need to  
17 identify which dimensions of feasibility to focus on. Then, for each dimension, one needs to select  
18 relevant indicators for which sufficient empirical basis exists and which are an output of models (or at  
19 least of a sufficient number of them). Then, thresholds marking different levels of feasibility concerns  
20 are defined based on available literature, expert elicitations and empirical analysis based on  
21 appropriately chosen historical precedents. Finally, scenario feasibility scores are obtained for each  
22 indicator, and where needed aggregated up in time or dimensions, as a way to provide an overall  
23 appraisal of feasibility trade-offs, depending on the timing, disruptiveness and scale of transformation.  
24



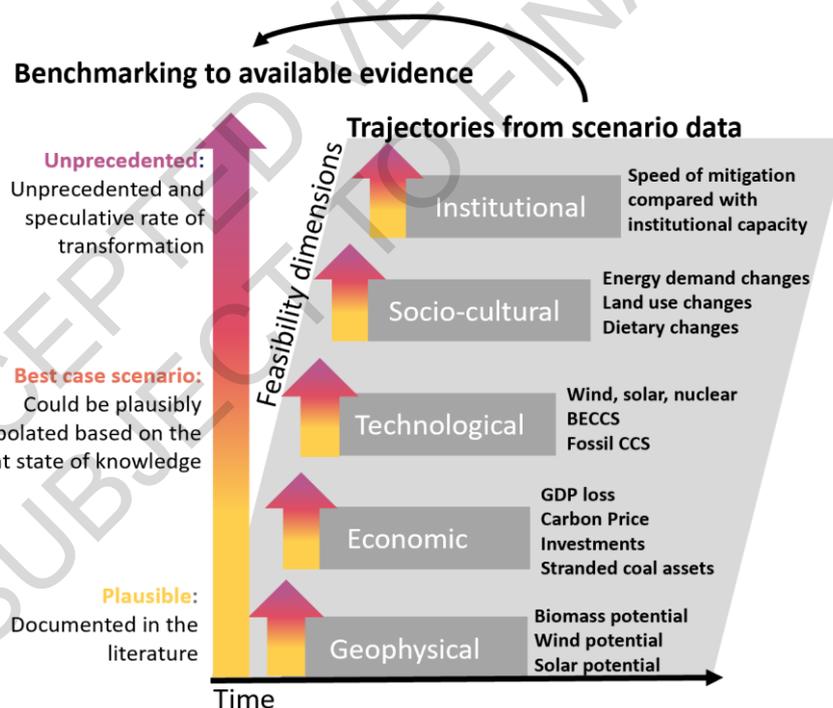
25  
26 **Figure 3.41: Steps involved in evaluating the feasibility of scenarios**

27 Most of the existing literature has focused on the technological dimensions, given the technology  
28 focus of models and the ease of comparison. The literature points to varied findings. Some suggest  
29 that scenarios envision technological progress consistent with historical benchmarks (Loftus et al.  
30 2015; Wilson et al. 2013). Others that scenarios exceed historically observed rates of low carbon  
31 technology deployment and of energy demand transformation globally (Napp et al. 2017; van der  
32 Zwaan et al. 2013; Semieniuk et al. 2021; Cherp et al. 2021), but not for all countries (Cherp et al.  
33 2021). The reason for these discrepancies depends on the unit of analysis and the indicators used.  
34 Comparing a different kind of historical indicators, (van Sluisveld et al. 2015) find that indicators that  
35 look into the absolute change of energy systems remain within the range of historical growth frontiers  
36 for the next decade, but increase to unprecedented levels before mid-century. Expert assessments  
37 provide another way of benchmarking scenarios, though they have shown to be systematically biased  
38 (Wiser et al. 2021) and to underperform empirical methods (Meng et al. 2021). (van Sluisveld et al.  
39 2018a) find that scenarios and experts align for baseline scenarios but differ for low carbon ones.

1 Scenarios rely more on conventional technologies based on existing infrastructure (such as nuclear  
2 and CCS) than what forecasted by experts. Overall, the technology assessment of the feasibility space  
3 highlights that Paris-compliant transformations would have few precedents, but not zero (Cherp et al.  
4 2021).

5  
6 Recent approaches have addressed multiple dimensions of feasibility, an important advancement since  
7 social and institutional aspects are as if not more important than technology ones (Jewell and Cherp  
8 2020). Feasibility corridors of scenarios based on their scale, rate of change and disruptiveness have  
9 been identified (Kriegler et al. 2018b; Warszawski et al. 2021). The reality check shows that many  
10 1.5°C compatible scenarios violate the feasibility corridors. The ones which didn't are associated with  
11 a greater coverage of the available mitigation levers (Warszawski et al. 2021).

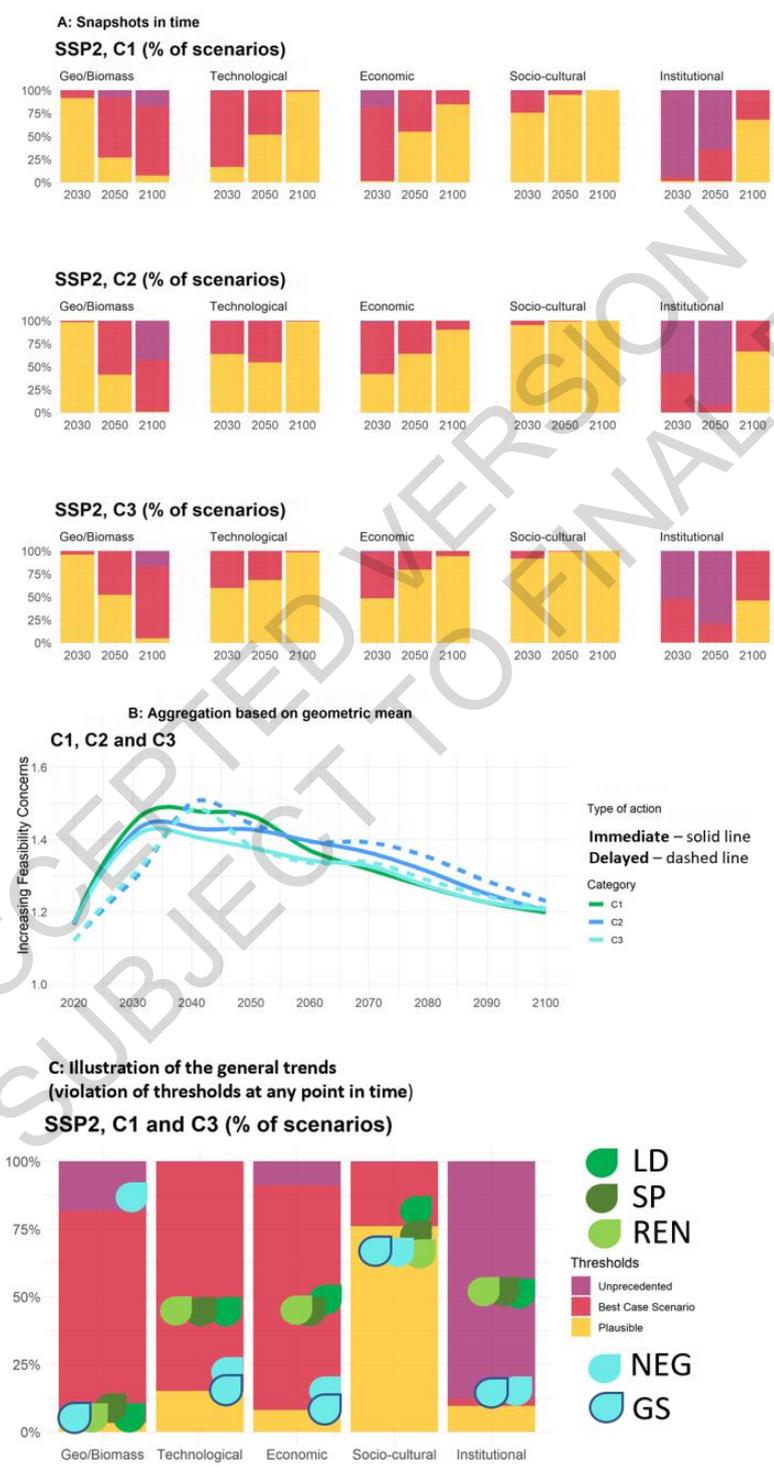
12  
13 Brutschin et al. (2021) proposed an operational framework covering all six dimensions of feasibility.  
14 They developed a set of multi-dimensional metrics capturing the timing, disruptiveness and the scale  
15 of the transformative change within each dimension (as in Kriegler et al. (2018b)). Thresholds of  
16 feasibility risks of different intensity are obtained through the review of the relevant literature and  
17 empirical analysis of historical data. Novel indicators include governance levels (Andrijevic et al.  
18 2020a). The 17 bottom-up indicators are then aggregated up across time and dimension, as way to  
19 highlight feasibility trade-offs. Aggregation is done via compensatory approaches such as the  
20 geometric mean. This is employed, for instance, for the Human Development Index. A conceptual  
21 example of this approach as applied to the IPCC AR6 scenarios database is shown in Figure 3.42 and  
22 further described in the Annex.  
23



24  
25 **Figure 3.42: Example of multi-dimensional feasibility analysis and indicators used in the IPCC AR6**  
26 **scenarios. The approach defines relevant indicators characterizing the key dimensions of feasibility.**  
27 **Indicators capture the timing, scale and disruptiveness challenges. Low, medium and high feasibility**  
28 **concerns are defined based on historical trends and available literature. Details about indicator and**  
29 **thresholds values can be found in Annex III**

30 In Figure 3.43, we show the results of applying the methodology of Brutschin et al. (2021) to the AR6  
31 scenarios database. The charts highlight the dynamic nature of feasibility risks, which are mostly  
32 concentrated in the decades before mid-century except for geophysical risks driven by CO<sub>2</sub> removals

1 later in the century. Different dimensions pose differentiated challenges: for example, institutional  
 2 feasibility challenges appear to be the most relevant, in line with the qualitative literature. Thus,  
 3 feasibility concerns might be particularly relevant in countries with weaker institutional capacity. The  
 4 Figure also highlights the key role of policy and technology, as enabling factors. In particular (Panel  
 5 B), internationally coordinated and immediate emission reductions allow to smooth out feasibility  
 6 concerns and reduce long term challenges compared to delayed policy action, as a result of a more  
 7 gradual transition and lower requirements of CO<sub>2</sub> removals. For the same climate objective, different  
 8 illustrative mitigation pathways entail somewhat different degrees and distributions of implementation  
 9 challenges (panel C).



1 **Figure 3.43: Feasibility characteristics of the Paris-consistent scenarios in AR6 scenarios database,**  
 2 **applying the methodology by : Feasibility corridors for the AR6 scenarios database, applying the**  
 3 **methodology by (Brutschin et al. 2021). Panel A: the fraction of scenarios falling within 3 categories of**  
 4 **feasibility concerns (Plausible, Best Case, Unprecedented), for different times (2030, 2050, 2100), different**  
 5 **climate categories consistent with the Paris Agreement and five dimensions. Panel B: composite feasibility**  
 6 **score (obtained by geometric mean of underlying indicators) over time for scenarios with immediate and**  
 7 **delayed global mitigation efforts, for different climate categories (C1-C2-C3. Note: no C1 scenarios has**  
 8 **delayed participation). Panel C: Fraction of scenarios which in any point in time over the century exceed**  
 9 **the feasibility concerns, for C1 and C3 climate categories. Overlaid are the Illustrative Mitigation**  
 10 **Pathways (LP, SP, Ren: C1 category; Neg, GS: C3 category)**

### 11 3.8.3 Feasibility in the light of socio-technical transitions

12 The limitations associated with quantitative low-carbon transition pathways stem from a predominant  
 13 reliance on techno-economic considerations with a simplified or non-existent representation of the  
 14 socio-political and institutional agreement. Accompanying the required deployment of low carbon  
 15 technologies will be the formation of new socio-technical systems (Bergek et al. 2008). With a socio-  
 16 technical system being defined as a cluster of elements comprising of technology, regulation, user  
 17 practices and markets, cultural meaning, infrastructure, maintenance networks, and supply networks  
 18 (Geels and Geels 2005; Hofman et al. 2004); the interrelationship between technological systems and  
 19 social systems must be comprehensively understood. It is of vital importance that the pro-cess of  
 20 technical change must considered in its institutional and social context so as to ascertain potential  
 21 transition barriers which in turn provide an indication of pathway feasibility. In order to address the  
 22 multitudinous challenges associated with low-carbon transition feasibility and governance, it has been  
 23 opined that the robustness of evaluating pathways may be improved by the bridging of differing  
 24 quantitative-qualitative analytical approaches (Haxeltine et al. 2008; Foxon et al. 2010; Hughes 2013;  
 25 Wangel et al. 2013; Li et al. 2015; Turnheim et al. 2015; Geels et al. 2016a,b, 2018; Moallemi et al.  
 26 2017; De Cian et al. 2018; Li and Strachan 2019). The rationale for such analytical bridging is to  
 27 rectify the issue that in isolation each disciplinary approach only can generate a fragmented  
 28 comprehension of the transition pathway with the consequence being an incomplete identification of  
 29 associated challenges in terms of feasibility. Concerning low-carbon transition pathways generated by  
 30 IAMs, it has been argued that a comprehensive analysis should include social scientific enquiry  
 31 (Geels et al. 2016a, 2018; van Sluisveld et al. 2018b). The normative analysis of IAM pathways  
 32 assists in the generation of a vision or the formulation of a general plan with this being complemented  
 33 by socio-technical transition theory (Geels et al. 2016a). Such an approach thereby allowing for the  
 34 socio-political feasibility and the social acceptance and legitimacy of low-carbon options to be  
 35 considered. Combining computer models and the multi-level perspective can help identify ‘transition  
 36 bottlenecks’ (Geels et al. 2018). Similarly, increased resolution of integrated assessment models’  
 37 actors has led to more realistic narratives of transition in terms of granularity and behaviour  
 38 (McCollum et al. 2017; van Sluisveld et al. 2018b). Increased data availability of actual behaviour  
 39 from smart technology lowers the barriers to representing behavioural change in computer  
 40 simulations, and thus better represent crucial demand side transformations (Creutzig et al. 2018).  
 41 Increasing the model resolution is a meaningful way forward. However, integrating a much broader  
 42 combination of real-life aspects and dynamics into models could lead to an increased complexity that  
 43 could restrict them to smaller fields of applications (De Cian et al. 2018).

44  
 45 Other elements of feasibility relate to social justice, which could be essential to enhance the political  
 46 and public acceptability of the low carbon transition. Reviewing the literature, one study finds that  
 47 employing social justice as an orienting principle can increase the political feasibility of low carbon  
 48 policies (Patterson et al. 2018). Three elements are identified as key: i) protecting vulnerable people  
 49 from climate change impacts, ii), protecting people from disruptions of transformation, iii), enhancing  
 50 the process of envisioning and implementing an equitable post-carbon society.

#### 3.8.4 Enabling factors

There is strong agreement that the climate policy institutional framework as well as technological progress have a profound impact on the attainability of low carbon pathways. Delaying international cooperation reduces the available carbon budget and locks into carbon intensive infrastructure exacerbating implementation challenges (Clarke et al. 2009; Bosetti et al. 2009; Krey and Riahi 2009; Boucher et al. 2009; Keppo and Rao 2007; van Vliet et al. 2009; Knopf et al. 2011; Luderer et al. 2013; Jakob et al. 2012; Aboumahboub et al. 2014; Bertram et al. 2021; Popp et al. 2014; Rogelj et al. 2013a; Riahi et al. 2015; Kriegler et al. 2014a; Gambhir et al. 2017). Similarly, technological availability influences the feasibility of climate stabilization, though differently for different technologies (Iyer et al. 2015a; Kriegler et al. 2014a; Riahi et al. 2015).

One of the most relevant factors affecting mitigation pathways and their feasibility is the rate and kind of socio-economic development. For example, certain socio-economic trends and assumptions about policy effectiveness preclude achieving stringent mitigation futures (Rogelj et al. 2018b). The risk of failure increases markedly in high growth, unequal and/or energy-intensive worlds - such as those characterized by the shared socio-economic pathways SSP3, SSP4 and SSP5. On the other hand, socio-economic development conducive to mitigation relieves the energy sector transformation from relying on large scale technology development: for example, the amount of biomass with CCS in SSP1 is one third of that in SSP5. The reason why socio-economic trends matter so much is that they both affect the CO<sub>2</sub> emissions in counterfactual scenarios as well as the mitigation capacity (Riahi et al. 2017; Rogelj et al. 2018b). Economic growth assumptions are the most important determinant of scenario emissions (Marangoni et al. 2017). De- and post-growth scenarios have been suggested as valuable alternatives to be considered (Hickel et al. 2021; Keyßer and Lenzen 2021), though substantial challenges remain regarding political feasibility (Keyßer and Lenzen 2021).

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

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

## 3.9 Methods of assessment and gaps in knowledge and data

### 3.9.1 AR6 mitigation pathways

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

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

Scenarios are not independent of each other and not representative of all possible outcomes, nor of the underlying scenario generation process; thus, the statistical power of the database is limited. Dependencies in the data generation process originate from various sources. Certain model groups, and types, are over-represented. For example, 8 model teams contributed with 90% of scenarios. Second, not all models can generate all scenarios, and these differences are not random, thereby creating selection bias (Tavoni and Tol 2010). Third, there are strong model dependencies: the modelling scientific community shares code and data, and several IAMs are open source.

### 3.9.2 Models assessed in this chapter

The models assessed in this chapter differ in their sectoral coverage and the level of complexity in each sector. Models tend to have more detail in their representation of energy supply and transportation, than they do for industry (Section 3.4; Annex III). Some models include detailed land use models, while others exclude land models entirely and use supply curves to represent bioenergy potential (Bauer et al. 2018a). IAMs do not include all mitigation options available in the literature (Rogelj et al. 2018b; Smith et al. 2019). For example, most IAM pathways exclude many granular demand-side mitigation options and land-based mitigation options found in more detailed sectoral models; additionally, only a few pathways include CDR options beyond afforestation/reforestation and BECCS. Section 3.4 and Chapter 12 include some results and comparisons to non-IAM models (e.g., bottom-up studies and detailed sectoral models). These sectoral studies often include a more complete set of mitigation options but exclude feedbacks and linkages across sectors which may alter

1 the mitigation potential of a given sector. There is an increasing focus in IAM studies on SDGs  
2 (Section 3.7), with some studies reporting the implications of mitigation pathways on SDGs (e.g.,  
3 Bennich et al. (2020)) and others using achieving SDGs as a constraint on the scenario itself (van  
4 Vuuren et al. 2015; Soergel et al. 2021a). However, IAMs are still limited in the SDGs they represent,  
5 often focusing on energy, water, air pollution and land. On the economic side, the majority of the  
6 models report information on marginal costs (i.e., carbon price). Only a subset provides full economic  
7 implications measured by either economic activity or welfare. Also often missing, is detail about  
8 economic inequality within countries or large aggregate regions.

9  
10 For further details about the models and scenarios, see Annex III.

## 13 **Frequently Asked Questions (FAQs)**

### 14 **FAQ 3.1 – Is it possible to stabilize warming without net negative CO<sub>2</sub> and GHG emissions?**

15 Yes. Achieving net zero CO<sub>2</sub> emissions and sustaining them into the future is sufficient to stabilize  
16 the CO<sub>2</sub>-induced warming signal which scales with the cumulative net amount of CO<sub>2</sub> emissions. At  
17 the same time, the warming signal of non-CO<sub>2</sub> GHGs can be stabilized or reduced by declining  
18 emissions that lead to stable or slightly declining concentrations in the atmosphere. For short-lived  
19 GHGs with atmospheric lifetimes of less than 20 years, this is achieved when residual emissions are  
20 reduced to levels that are lower than the natural removal of these gases in the atmosphere. Taken  
21 together, mitigation pathways that bring CO<sub>2</sub> emissions to net zero and sustain it, while strongly  
22 reducing non-CO<sub>2</sub> GHGs to levels that stabilize or decline their aggregate warming contribution, will  
23 stabilize warming without using net negative CO<sub>2</sub> emissions and with positive overall GHG emissions  
24 when aggregated using GWP100. A considerable fraction of pathways limiting warming to 1.5°C  
25 with no or limited overshoot and likely limiting warming to 2°C, respectively, do not or only  
26 marginally (<10 GtCO<sub>2</sub> cumulative until 2100) deploy net negative CO<sub>2</sub> emissions (26% and 46%,  
27 respectively) and do not reach net zero GHG emissions by the end of the century (48% and 70%,  
28 respectively). This is no longer the case in pathways that return warming to 1.5°C after a high  
29 overshoot (typically > 0.1°C). All of these pathways deploy net negative emissions on the order of  
30 330 (26-623 GtCO<sub>2</sub>) (median and 5<sup>th</sup>-95<sup>th</sup> percentile) and 87% achieve net negative GHGs emissions  
31 in AR6 GWP-100 before the end of the century. Hence, global net negative CO<sub>2</sub> emissions, and net  
32 zero or net negative GHG emissions, are only needed to decline, not to stabilize global warming. The  
33 deployment of carbon dioxide removal (CDR) is distinct from the deployment of net negative CO<sub>2</sub>  
34 emissions, because it is also used to neutralize residual CO<sub>2</sub> emissions to achieve and sustain net zero  
35 CO<sub>2</sub> emissions. CDR deployment can be considerable in pathways without net negative emissions and  
36 all pathways limiting warming to 1.5°C use it to some extent.

### 38 **FAQ 3.2 – How can net zero emissions be achieved and what are the implications of net zero 39 emissions for the climate?**

40 Halting global warming in the long term requires, at a minimum, that no additional CO<sub>2</sub> emissions  
41 from human activities are added to the atmosphere (i.e., CO<sub>2</sub> emissions must reach “net” zero). Given  
42 that CO<sub>2</sub> emissions constitute the dominant human influence on global climate, global net zero CO<sub>2</sub>  
43 emissions are a prerequisite for stabilizing warming at any level. However, CO<sub>2</sub> is not the only  
44 greenhouse gas that contributes to global warming and reducing emissions of other greenhouse gases  
45 alongside CO<sub>2</sub> towards net zero emissions of all GHGs would lower the level at which global  
46 temperature would peak. The temperature implications of net zero GHG emissions depend on the  
47 bundle of gases that is being considered, and the emissions metric used to calculate aggregated GHG  
48 emissions and removals. If reached and sustained, global net zero GHG emissions using the 100-year  
49 Global Warming Potential (GWP-100) will lead to gradually declining global temperature.

1 Not all emissions can be avoided. Achieving net zero CO<sub>2</sub> emissions globally therefore requires deep  
2 emissions cuts across all sectors and regions, along with active removal of CO<sub>2</sub> from the atmosphere  
3 to balance remaining emissions that may be too difficult, too costly or impossible to abate at that time.  
4 Achieving global net zero GHG emissions would require, in addition, deep reductions of non-CO<sub>2</sub>  
5 emissions and additional CO<sub>2</sub> removals to balance remaining non-CO<sub>2</sub> emissions.

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

19 Total GHG emissions are greater than emissions of CO<sub>2</sub> only; reaching net zero CO<sub>2</sub> emissions  
20 therefore occurs earlier, by up to several decades, than net zero GHG emissions in all modelled  
21 pathways. In most modelled pathways that likely limit warming to 2°C above pre-industrial levels and  
22 below in the most cost-effective way, the AFOLU and energy supply sectors reach net zero CO<sub>2</sub>  
23 emissions several decades earlier than other sectors; however, many pathways show much reduced,  
24 but still positive net GHG emissions in the AFOLU sector in 2100.

### 25 26 **FAQ 3.3 – How plausible are high emissions scenarios, and how do they inform policy?**

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

50

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