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 tow 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 Fotnotes 0-2 updated inresponse 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) GtCO2-eq yr-1 by 2030 and 20 (13-26) change to: are associated with net global GHG emissions of 44 (32–55) GtCO2-eq yr-1 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

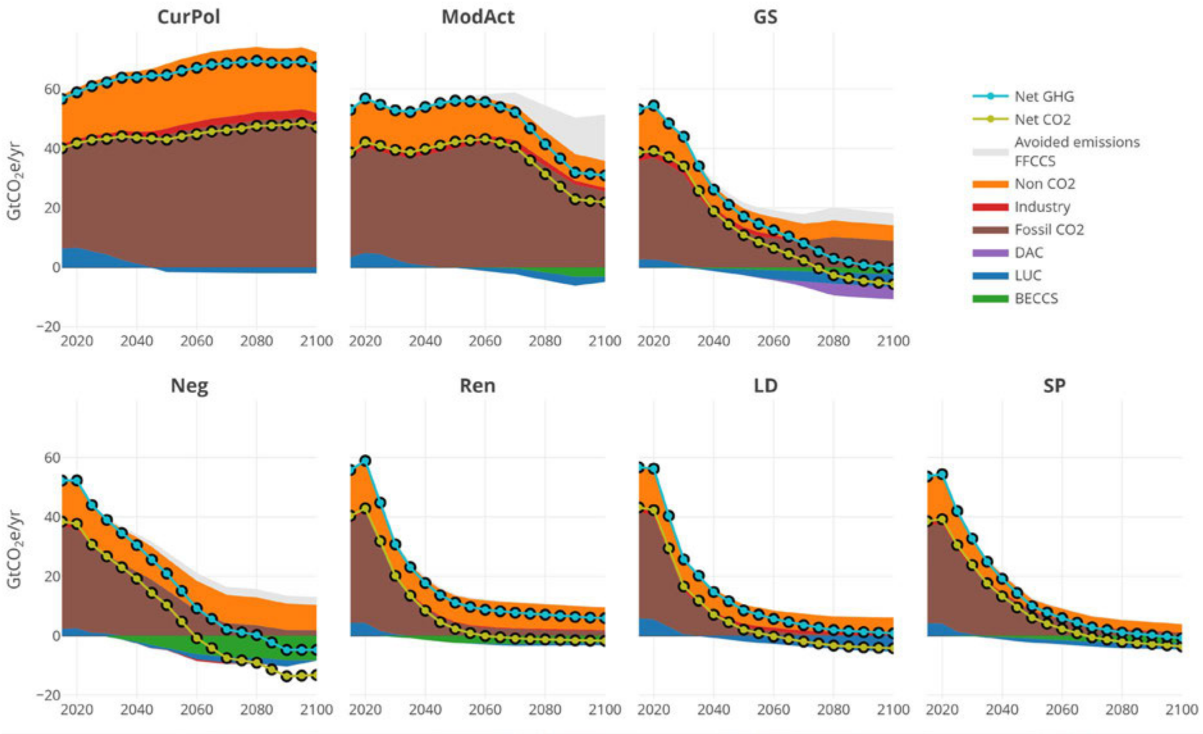
Chapter 3	23	2	Fig 3.7 - updated A new figure to replace existing one
Chapter 3	28	1	Fig 3.10 - updated A new figure to replace existing one
Chapter 3	42	30	Fig 3.14 - updated A new figure to replace existing one
Chapter 3	75	23	Table 3.6 – updated A new figure to replace existing one
Chapter 3	4	16	2.4°C change to: 2.2°C
Chapter 3	4	15	52-60 GtCO2-eq yr-1 by 2030 and to 46-67 change to 54-61 GtCO2-eq yr-1 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 GtCO2-eq yr-1 to an average of 1.4-2.0 GtCO2-eq yr-1 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 GtCO2-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 GtCO2-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) GtCO2-eq (based on native model reporting) and 52.5 (47-56.5) GtCO2-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) GtCO2-eq (based on native model reporting) and 52.5 (47-56.5) GtCO2-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) GtCO2-eq in 2030 for limiting warming to 1.5°C with no or limited overshoot and 10-17 (7-14) GtCO2-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) $GtCO_2$-eq in 2030 for limiting warming to 1.5°C with no or limited overshoot and 10-16 (6-14) $GtCO_2$-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_2 emissions in ... Change in net land use CO_2 emissions in ... Change in CH_4 emissons 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 $GtCO_2$-eq yr^{-1} by 2030 and 13-27 $GtCO_2$ change to with net global GHG emissions of 32-55 $GtCO_2$-eq yr^{-1} by 2030 and 14-26 $GtCO_2$
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) $GtCO_2$ in pathways likely limiting warming to 2.0°C. change to 880 (640-1130) $GtCO_2$ in pathways likely limiting warming to 2.0°C.
Chapter 3	5	37	4-11 $GtCO_2$-eq yr^{-1} change to 8 (4-12)

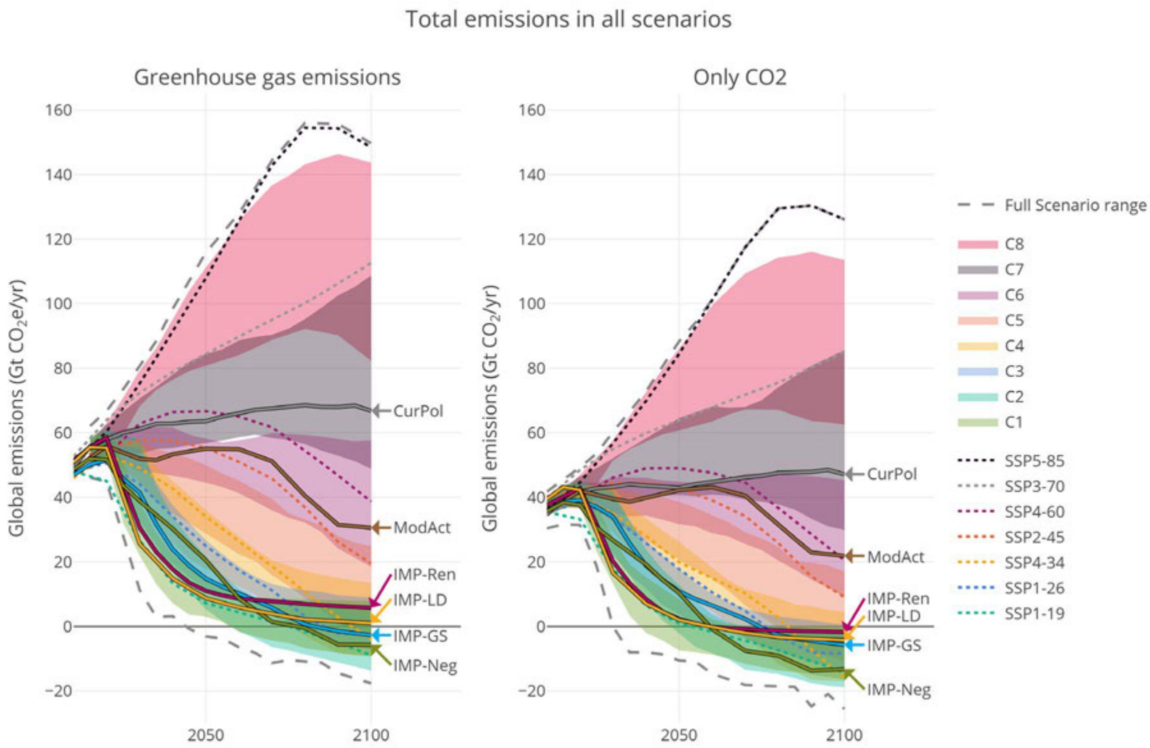
Chapter 3	5	6	Replace: to an average of 1.3-2.1 GtCO2-eq per year With to an average of 1.4-2.0 GtCO2-eq per year
Chapter 3	43	9	and 84 (74–98) % in 2050 change to and 84 (73–98) % in 2050
Chapter 3	37	21	net zero around 2060-2100 change to net zero around 2055-2095
Chapter 3	37	24	4-11 GtCO2-eq yr-1 change to 4-12 GtCO2-eq yr-1
Chapter 3	26	36	to 52-60 GtCO2-eq yr-1 by 2030 and to 46-67 change to to 54-60 GtCO2-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	Replace: Pathways accelerating actions compared to current NDCs that reduce annual GHG emissions to 47 (38-51) GtCO2-eq by 2030, or 3-9 GtCO2-eq below projected emissions from fully implementing current NDCs reduce the mitigation challenge for likely limiting warming to 2°C after 2030. WIth: Pathways accelerating actions compared to NDCs announced prior to COP26 that reduce annual GHG emissions to 48 (38-52) GtCO2-eq by 2030, or 2-9 GtCO2-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.
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 GtCO2-eq.
Chapter 3	40	4-6	Replace: As they need to reach net zero CO2 only a few years later, with 2030 CO2 emission levels being around twice as high, they imply post-2030 CO2 emissions reduction rates that are almost double that of pathways limiting warming to 1.5°C with no or limited overshoot With: As they need to reach net zero CO2 only a few years later, from 2030 CO2 emission levels that are about as high as 2020 levels, they imply post-2030 CO2 emissions reduction rates that are substantially higher (by around 30%) than in pathways limiting warming to 1.5°C with no or limited overshoot
Chapter 3	40	Footnote 6	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 CO2 emissions during 2065 - 2070 (2060 - ...) 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 CO2 emissions during 2065 - 2070 (2060 - 2100)
Chapter 3	41	11-13	Replace: the time lag between reaching net zero CO2 and net zero GHG is 11-14 (6-40) years and the amount of net negative CO2 emissions deployed to balance non-CO2 emissions at the time of net zero is -6 to -7 (-10 to -4) GtCO2 With: the time lag between reaching net zero CO2 and net zero GHG is 12-14 (7-39) years and the amount of net negative CO2 emissions deployed to balance non-CO2 emissions at the time of net zero GHG is around -7 (-10 to -4) GtCO2
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.

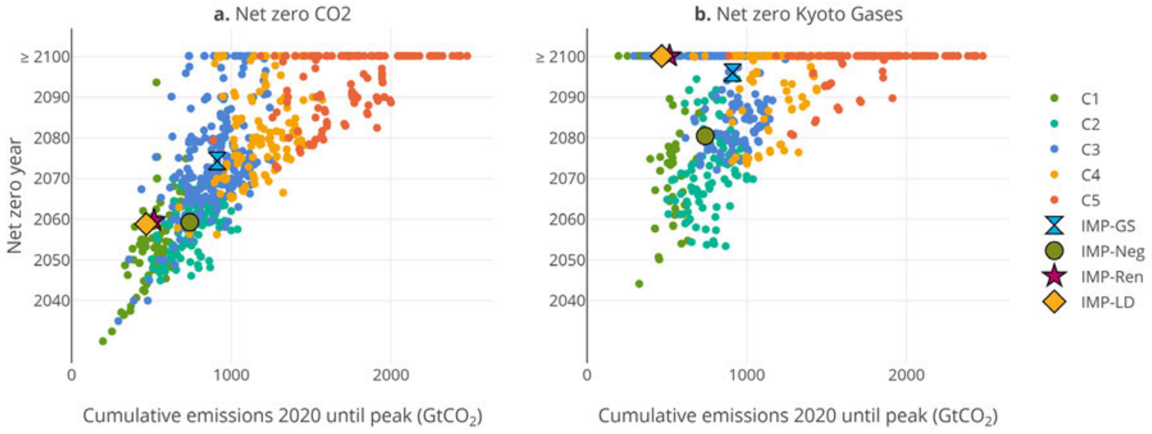
Corrected Fig 3.7



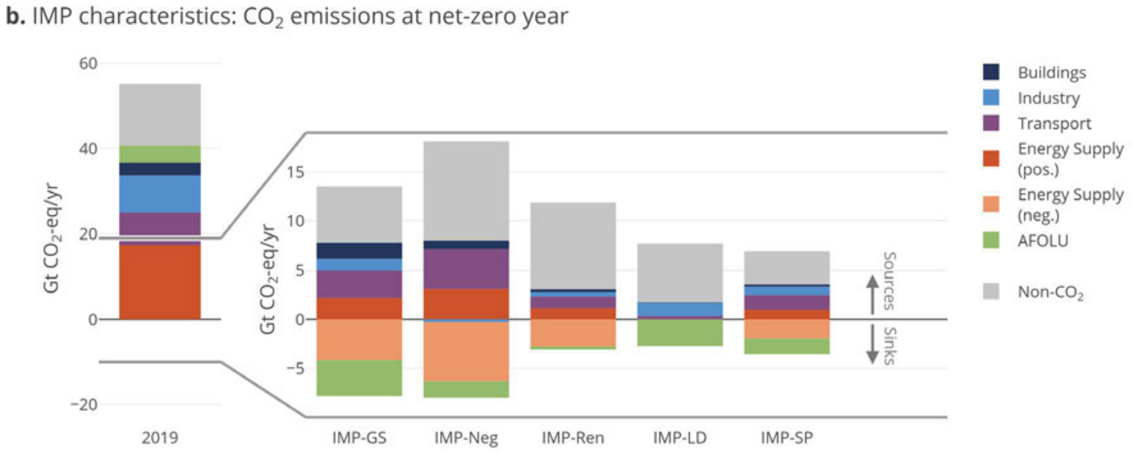
Corrected Fig 3.10



Corrected Fig 3.14



Corrected Fig 3.16b



Chapter 3: Mitigation Pathways Compatible with Long-Term Goals

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Executive summary

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

Pathways consistent with the implementation and extrapolation of countries' current policies see GHG emissions reaching 52-60 $GtCO_2$-eq yr^{-1} by 2030 and to 46-67 $GtCO_2$-eq yr^{-1} by 2050, leading to a median global warming of 2.4°C to 3.5°C by 2100 (*medium confidence*). These pathways consider policies at the time that they were developed. The Shared Socioeconomic Pathways (SSPs) permit a more systematic assessment of future GHG emissions and their uncertainties than was possible in AR5. The main emissions drivers include growth in population, reaching 8.5-9.7 billion by 2050, and an increase in global GDP of 2.7-4.1% per year between 2015 and 2050. Final energy demand in the absence of any new climate policies is projected to grow to around 480 to 750 EJ yr^{-1} in 2050 (compared to around 390 EJ in 2015). *(medium confidence)* The highest emissions scenarios in the literature result in global warming of >5°C by 2100, based on assumptions of rapid economic growth and pervasive climate policy failures. (*high confidence*). {3.3}

Many pathways in the literature show how to likely limit global warming compared to preindustrial times to 2°C with no overshoot or to 1.5°C with limited overshoot. The likelihood of limiting warming to 1.5C with no or limited overshoot has dropped in AR6 compared to SR1.5 because global GHG emissions have risen since the time SR1.5 was published, leading to higher near-term emissions (2030) and higher cumulative CO_2 emissions until the time of net zero *(medium confidence)*. Only a small number of published pathways limit global warming to 1.5°C without overshoot over the course of the 21st century. {3.3, Annex III.II.3}

Cost-effective mitigation pathways assuming immediate actions to likely limit warming to 2°C are associated with net global GHG emissions of 30-49 $GtCO_2$-eq yr^{-1} by 2030 and 13-27 $GtCO_2$-eq yr^{-1} by 2050 *(medium confidence)*. This corresponds to reductions, relative to 2019 levels, of 12-46% by 2030 and 52-77% by 2050. Pathways that limit global warming to below 1.5°C with no or limited overshoot require a further acceleration in the pace of the transformation, with net GHG emissions typically around 21-36 $GtCO_2$-eq yr^{-1} by 2030 and 1-15 $GtCO_2$-eq yr^{-1} by 2050; thus reductions of 38–63% by 2030 and 75-98% by 2050 relative to 2019 levels. {3.3}

Pathways following current NDCs[1] until 2030 reach annual emissions of 47-57 $GtCO_2$-eq by 2030, thereby making it impossible to limit warming to 1.5°C with no or limited overshoot and strongly increasing the challenge to likely limit warming to 2°C *(high confidence)*. A high

FOOTNOTE [1] 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.

overshoot of 1.5°C increases the risks from climate impacts and increases the dependence on large scale carbon dioxide removal from the atmosphere. A future consistent with current NDCs implies higher fossil fuel deployment and lower reliance on low carbon alternatives until 2030, compared to mitigation pathways with immediate action to likely limit warming to 2°C and below. To likely limit warming to 2°C after following the NDCs to 2030, the pace of global GHG emission reductions would need to accelerate quite rapidly from 2030 onward: to an average of 1.3-2.1 $GtCO_2$-eq per year between 2030 and 2050, which is similar to global CO_2 emission reductions in 2020 due to the COVID-19 pandemic, and around 70% faster than in immediate action pathways likely limiting warming to 2°C. Accelerating emission reductions after following an NDC pathway to 2030 would be particularly challenging because of the continued build-up of fossil fuel infrastructure that would be expected to take place between now and 2030. {3.5, 4.2}

Pathways accelerating actions compared to current NDCs that reduce annual GHG emissions to 47 (38-51) GtCO2-eq by 2030, or 3-9 GtCO2-eq below projected emissions from fully implementing current NDCs reduce the mitigation challenge for likely limiting warming to 2°C after 2030. *(medium confidence)*. The accelerated action pathways are characterized by a global, but regionally differentiated, roll-out of regulatory and pricing policies. Compared to NDCs, they see less fossil fuels and more low-carbon fuels until 2030, and narrow, but do not close the gap to pathways assuming immediate global action using all available least-cost abatement options. All delayed or accelerated action pathways likely limiting warming to below 2°C converge to a global mitigation regime at some point after 2030 by putting a significant value on reducing carbon and other GHG emissions in all sectors and regions. {3.5}

Mitigation pathways limiting warming to 1.5°C with no or limited overshoot reach 50% reductions of CO_2 in the 2030s, relative to 2019, then reduce emissions further to reach net zero CO_2 emissions in the 2050s. Pathways likely limiting warming to 2°C reach 50% reductions in the 2040s and net zero CO_2 by 2070s (*medium confidence*). {3.3, Cross-Chapter Box 3 in Chapter 3}

Peak warming in mitigation pathways is determined by the cumulative net CO_2 emissions until the time of net zero CO_2 and the warming contribution of other GHGs and climate forcers at that time *(high confidence)*. Cumulative net CO_2 emissions from 2020 to the time of net zero CO_2 are 510 (330-710) $GtCO_2$ in pathways that limit warming to 1.5°C with no or limited overshoot and 890 (640-1160) $GtCO_2$ in pathways likely limiting warming to 2.0°C. These estimates are consistent with the assessment of remaining carbon budgets by WGI after adjusting for differences in peak warming levels. {3.3, Box 3.4}

Rapid reductions in non-CO_2 GHGs, particularly methane, would lower the level of peak warming *(high confidence)*. Residual non-CO_2 emissions at the time of reaching net zero CO_2 range between 4-11 $GtCO_2$-eq yr-1 in pathways likely limiting warming to 2.0°C or below. Methane (CH_4) is reduced by around 20% (1-46%) in 2030 and almost 50% (26-64%) in 2050, relative to 2019. Methane emission reductions in pathways limiting warming to 1.5°C with no or limited overshoot are substantially higher by 2030, 33% (19-57%), but only moderately so by 2050, 50% (33-69%). Methane emissions reductions are thus attainable at relatively lower GHG prices but are at the same time limited in scope in most 1.5-2°C pathways. Deeper methane emissions reductions by 2050 could further constrain the peak warming. N_2O emissions are reduced too, but similar to CH_4, emission reductions saturate for more stringent climate goals. In the mitigation pathways, the emissions of cooling aerosols are reduced due to reduced use of fossil fuels. The overall impact on non-CO_2-related warming combines these factors. {3.3}

Net zero GHG emissions imply net negative CO_2 emissions at a level compensating residual non-CO_2 emissions. Only 30% of the pathways likely limiting warming to 2°C or below reach net zero GHG emissions in the 21st century. (*high confidence*). In those pathways reaching net zero GHGs, it is achieved around 10-20 years later than for net zero CO_2. (*medium confidence*). The reported quantity of residual non-CO_2 emissions depends on accounting: the choice of GHG metric. Reaching and sustaining global net zero GHG emissions, measured in terms of GWP-100, results in a gradual decline of temperature. (*high confidence*) {3.3, Cross-Chapter Box 3 in Chapter 3, Cross-Chapter Box 2 in Chapter 2}

Pathways likely limiting warming to 2°C and below exhibit substantial reductions in emissions from all sectors (*high confidence*). Projected CO_2 emissions reductions between 2019 and 2050 in 1.5°C pathways with no or limited overshoot are around 77% (31-96%) for energy demand, 115% for energy supply (90 to 167%), and 148% for AFOLU (94 to 387%). In pathways likely limiting warming to 2°C, projected CO_2 emissions are reduced between 2019 and 2050 by around 49% for energy demand, 97% for energy supply, and 136% for AFOLU. *(medium confidence)*{3.4}

Delaying or sacrificing emissions reductions in one sector or region involves compensating reductions in other sectors or regions if warming is to be limited (*high confidence*). Mitigation pathways show differences in the timing of decarbonization and when net zero CO_2 emissions are achieved across sectors and regions. At the time of global net zero CO_2 emissions, emissions in some sectors and regions are positive while others are negative; the ordering depends on the mitigation options available, the cost of those options, and the policies implemented. In cost-effective mitigation pathways, the energy supply sector typically reaches net zero CO2 before the economy as a whole, while the demand sectors reach net zero CO_2 later, if ever (*high confidence*). {3.4}

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

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

The measures required to likely limit warming to 2°C or below can result in large scale transformation of the land surface (*high confidence*). Pathways likely limiting warming to 2°C or below are projected to reach net zero CO_2 emissions in the AFOLU sector between 2020s and 2070, with an increase of forest cover of about 322 million ha (-67 to 890 million ha) in 2050 in pathways limiting warming to 1.5°C with no or limited overshoot. Cropland area to supply biomass for bioenergy (including BECCS) is around 199 (56-482) million ha in 2100 in pathways limiting warming to 1.5°C with no or limited overshoot. The use of bioenergy can lead to either increased or reduced emissions, depending on the scale of deployment, conversion technology, fuel displaced, and how/where the biomass is produced *(high confidence)*. {3.4}

Anthropogenic land CO_2 emissions and removals in IAM pathways cannot be directly compared with those reported in national GHG inventories (*high confidence*). Methodologies enabling a more like-for-like comparison between models' and countries' approaches would support more accurate assessment of the collective progress achieved under the Paris Agreement. {3.4, 7.2.2.5}

Pathways that likely limiting warming to 2°C or below involve some amount of CDR to compensate for residual GHG emissions remaining after substantial direct emissions reductions in all sectors and regions (*high confidence*). CDR deployment in pathways serves multiple purposes: accelerating the pace of emissions reductions, offsetting residual emissions, and creating the option for net negative CO_2 emissions in case temperature reductions need to be achieved in the long term (*high confidence*). CDR options in the pathways are mostly limited to BECCS, afforestation and DACCS. CDR through some measures in AFOLU can be maintained for decades but not in the very long term because these sinks will ultimately saturate (high confidence). {3.4}

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

Limiting warming requires shifting energy investments away from fossil-fuels and towards low-carbon technologies (*high confidence*). The bulk of investments are needed in medium- and low-income regions. Investment needs in the electricity sector are on average 2.3 trillion USD2015 yr^{-1} over 2023-2052 for pathways limiting temperature to 1.5°C with no or limited overshoot, and 1.7 trillion USD2015 yr^{-1} for pathways likely limiting warming to 2°C. {3.6.1}

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

Mitigation pathways likely limiting warming to 2°C entail losses in global GDP with respect to reference scenarios of between 1.3% and 2.7% in 2050; and in pathways limiting warming to 1.5°C with no or limited overshoot, losses are between 2.6% and 4.2%. Yet, these estimates do not account for the economic benefits of avoided climate change impacts *(medium confidence)*. In mitigation pathways likely limiting warming to 2°C, marginal abatement costs of carbon are about 90 (60-120) USD2015/tCO_2 in 2030 and about 210 (140-340) USD2015/tCO_2 in 2050; in pathways that limit warming to 1.5°C with no or limited overshoot, they are about 220 (170-290) USD2015/tCO_2 in 2030 and about 630 (430-990) USD2015/tCO_2 in 2050[2]. {3.6.1}

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

FOOTNOTE[2] Numbers in parenthesis represent he interquartile range of the scenario samples.

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

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

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

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

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

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

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

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

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

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

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_2 emissions to net zero. Thus, a central cross-cutting topic within the Chapter is the timing of reaching net zero CO_2 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_2 emissions pathways that avoid temperature overshoot and hence do not rely on net negative CO_2 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.

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.

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

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

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

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

3.1.3 Complementary use of large scenario ensembles and a limited set of Illustrative Mitigation Pathways (IMPs)

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

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

In parallel, based on the overall AR6 assessment seven illustrative pathways (IP) were defined representing critical mitigation strategies discussed in the assessment. The seven pathways are composed of two sets: (i) one set of five Illustrative Mitigation Pathways (IMPs) and (ii) one set of two reference pathways illustrative for high emissions. The IMPs are on the one hand representative of the scenario space but help in addition to communicate archetypes of distinctly different systems transformations and related policy choices. Subsequently, seven scenarios were selected from the full database that fitted these storylines of each IP best. For these scenarios are more strict vetting criteria were applied. The selection was done by first applying specific filters based on the storyline followed 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; Sognnaes et al. 2021).

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

3.2.1.2 Mitigation scenarios

Mitigation scenarios explore different strategies to meet climate goals and are typically derived from reference scenarios by adding climate or other policies. Mitigation pathways are often developed to meet a predefined level of climate change, often referred to as a backcast. There are relatively few IAMs that include an endogenous climate model or emulator due to the added computational complexity, though exceptions do exist. In practice, models implement climate constraints by either iterating carbon price assumptions (Strefler et al. 2021b) or by adopting an associated carbon budget (Riahi et al. 2021). In both cases, other GHGs are typically controlled by CO2-equivalent pricing. A large part of the AR5 literature has focused on forcing pathways towards a target at the end of the century (van Vuuren et al. 2007, 2011; Clarke et al. 2009; Blanford et al. 2014; Riahi et al. 2017), featuring a temporary overshoot of the warming and forcing levels (Geden and Löschel 2017). In comparison, many recent studies explore mitigation strategies that limit overshoot (Johansson et al. 2020; Riahi et al. 2021). An increasing number of IAM studies also explore climate pathways that limit adverse side-effects with respect to other societal objectives, such as food security (van Vuuren et al. 2019; Riahi et al. 2021) or larger sets of sustainability objectives (Soergel et al. 2021a).

3.2.2 The utility of Integrated Assessment Models

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

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

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

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

The climate constraint implementation can have a meaningful impact on model results. The literature so far included many temperature overshoot scenarios with heavy reliance on long-term CDR and net negative CO_2 emissions to bring back temperatures after the peak (Johansson et al. 2020; Rogelj et al. 2019b). New approaches have been developed to avoid temperature overshoot. The new generation of scenarios show that CDR is important beyond its ability to reduce temperature, but is essential also for offsetting residual emissions to reach a net zero CO_2 emissions (Rogelj et al. 2019b; Johansson et al. 2020; Riahi et al. 2021; Strefler et al. 2021b).

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

3.2.3 The scenario literature and scenario databases

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

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

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

3.2.4 The AR6 scenario database

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

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

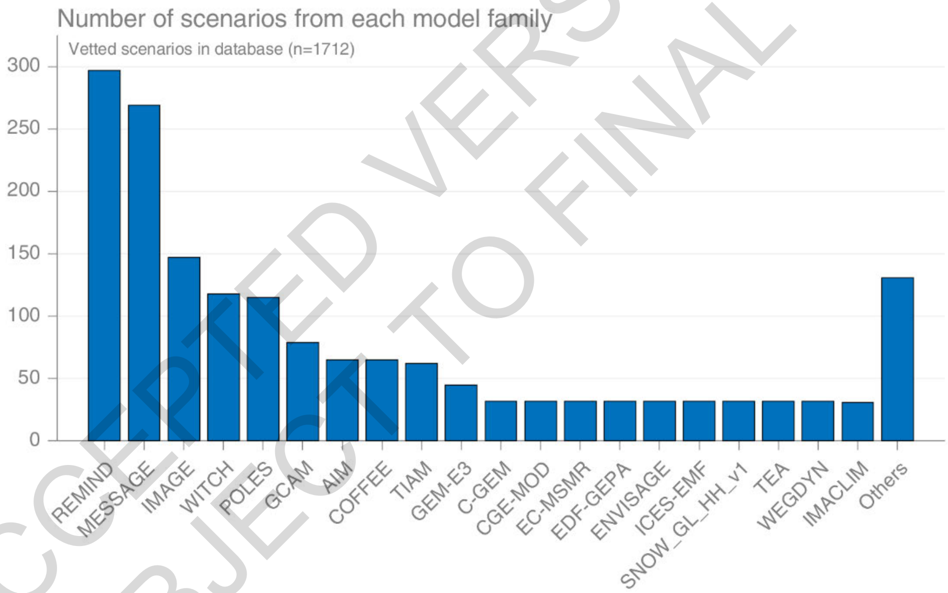


Figure 3.1 Scenario counts from each model family defined as all versions under the same model's name.

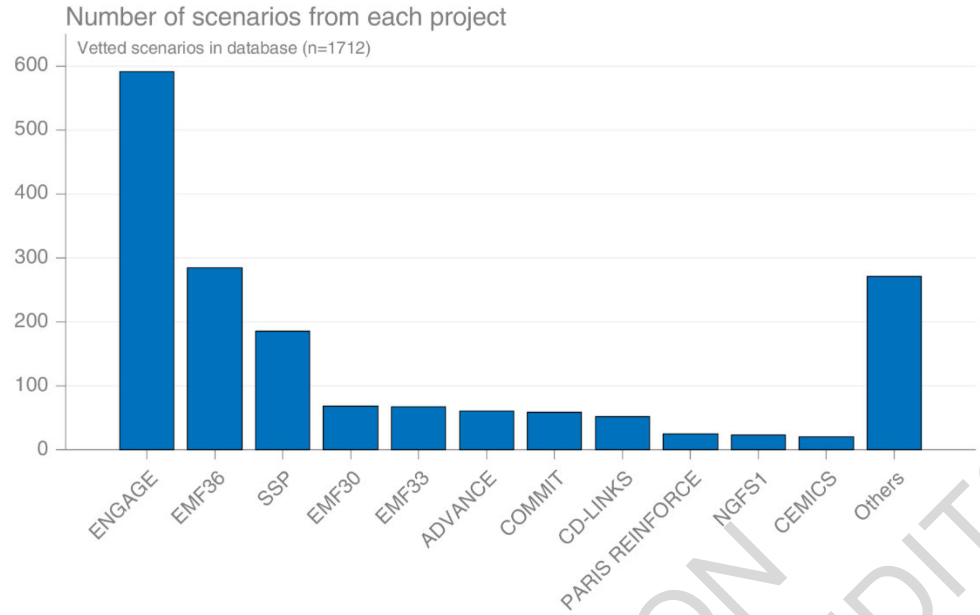


Figure 3.2 Scenario counts from each named project.

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
C1: Below 1.5°C with no or limited overshoot	<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	**97**
C2: Below 1.5°C with high overshoot	<1.5°C peak warming with <33% chance and < 1.5°C end of century warming with >50% chance			**133**
C3: Likely below 2°C	<2°C peak warming with >67% chance	SSP2-2.6	GS, Neg	**311**
C4: Below 2ºC	<2°C peak warming with >50% chance			**159**
C5: Below 2.5°C	<2.5°C peak warming with >50% chance			**212**

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

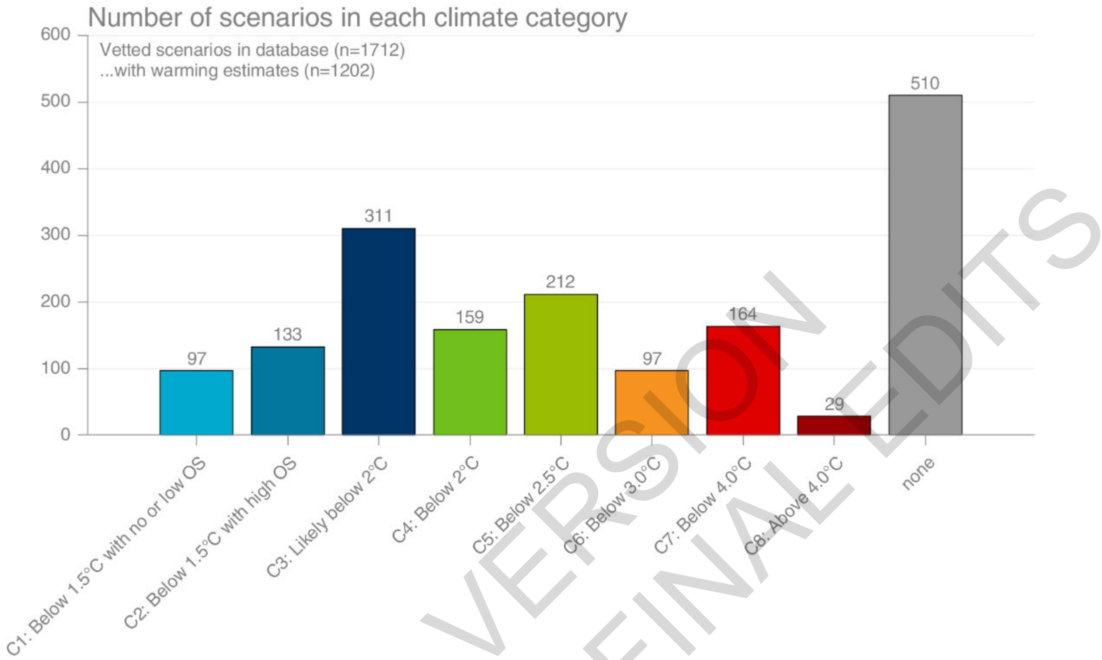


Figure 3.3 Of the 1686 scenarios that passed vetting, 1202 had sufficient data available to be classified according to temperature, with an uneven distribution across warming levels.

In addition to the temperature classification, each scenario is assigned to one of the following policy categories: (P0) diagnostic scenarios – 100 of 1686 vetted scenarios; (P1) scenarios with no globally coordinated policy and either (P1a) no climate mitigation efforts – 119, (P1b) current national mitigation efforts – 59, (P1c) Nationally Determined Contributions (NDCs) – 110, or (P1d) other non-standard assumptions – 104; (P2) globally coordinated climate policies with immediate (i.e. before 2030) action – 73, (P2a) without any transfer of emission permits – 435, (P2b) with transfers – 70; or (P2c) with additional policy assumptions – 55; (P3) globally coordinated climate policies with delayed (i.e. from 2030 onwards or after 2030) action, preceded by (P3a) no mitigation commitment or current national policies – 7, (P3b) NDCs – 376, (P3c) NDCs and additional policies – 18 and (P3d) other non-standard regional assumptions – 0; (P4) Cost-Benefit Analysis (CBA) – 2. The policy categories were identified using text pattern matching on the scenario metadata and calibrated on the best-known scenarios from model intercomparisons, with further validation against the related literature, reported emission and carbon price trajectories, and exchanges with modellers. If the information available is enough to qualify a policy category number but not sufficient for a subcategory, then only the number is retained (e.g., P2 instead of P2a/b/c). A suffix added after P0 further qualifies a diagnostic scenario as one of the other policy categories.To demonstrate the diversity of the scenarios, the vetted scenarios were classified into different categories along the dimensions of population, GDP, energy, and cumulative emissions (Figure 3.4). The number of scenarios in each category provides some insight into the current literature, but this does not indicate a higher probability of that category occurring in reality. For population, the majority of scenarios are consistent with the SSP2 'middle of the road' category, with very few scenarios exploring the outer extremes. GDP has a slightly larger variation, but overall, most scenarios are around the SSP2 socioeconomic assumptions. The level of CCS and CDR is expected to change depending on the extent of mitigation, but there remains extensive use of both CDR and CCS in scenarios. CDR is dominated by bioenergy with CCS (BECCS) and sequestration on land, with relatively few scenarios using Direct Air Capture with Carbon Storage (DACCS) and even less with Enhanced Weathering and other technologies (not shown). In terms of energy consumption, final energy has a much smaller range than primary energy as conversion losses are not included in final energy. Both mitigation and reference scenarios are shown, so there is a broad spread in different energy carriers represented in the database. Bioenergy has a number of scenarios at around 100EJ, representing a constraint used in many model intercomparisons.

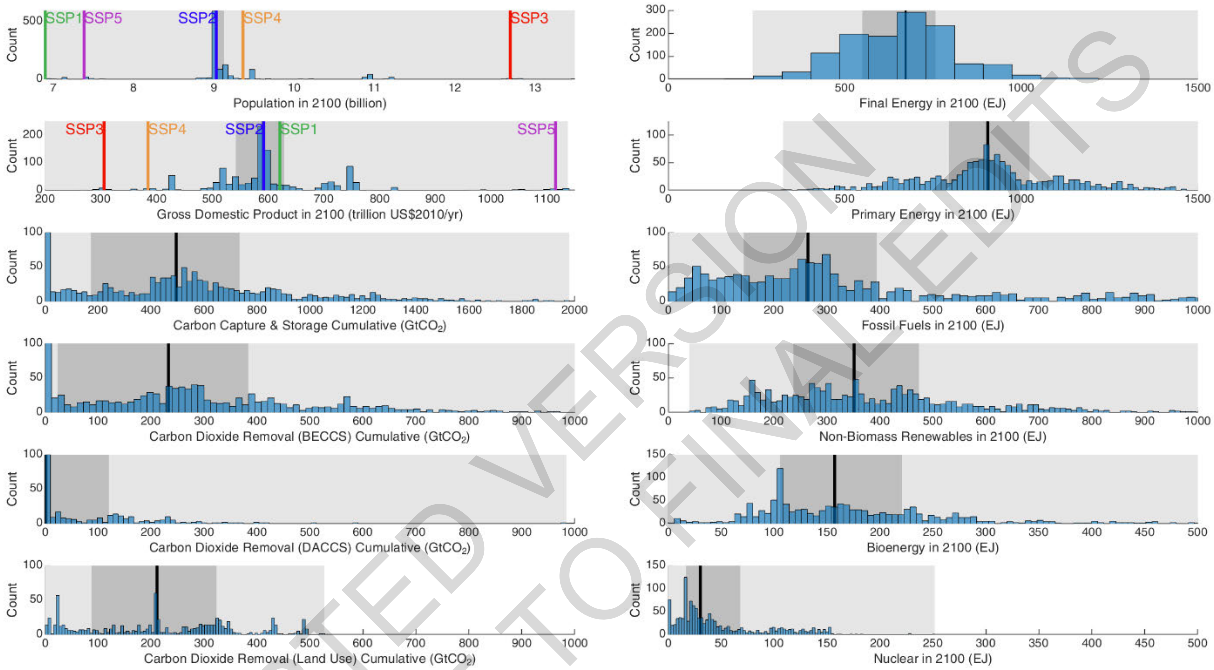


Figure 3.4 Histograms for key categories in the AR6 scenario database. Only scenarios that passed vetting are shown. For population and GDP, the SSP input data are also shown. The grey shading represents the 0-100% range (light grey), 25-75% range (dark grey), and the median is a black line. The figures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

Source: AR6 scenarios database.

3.2.5 Illustrative Mitigation Pathways

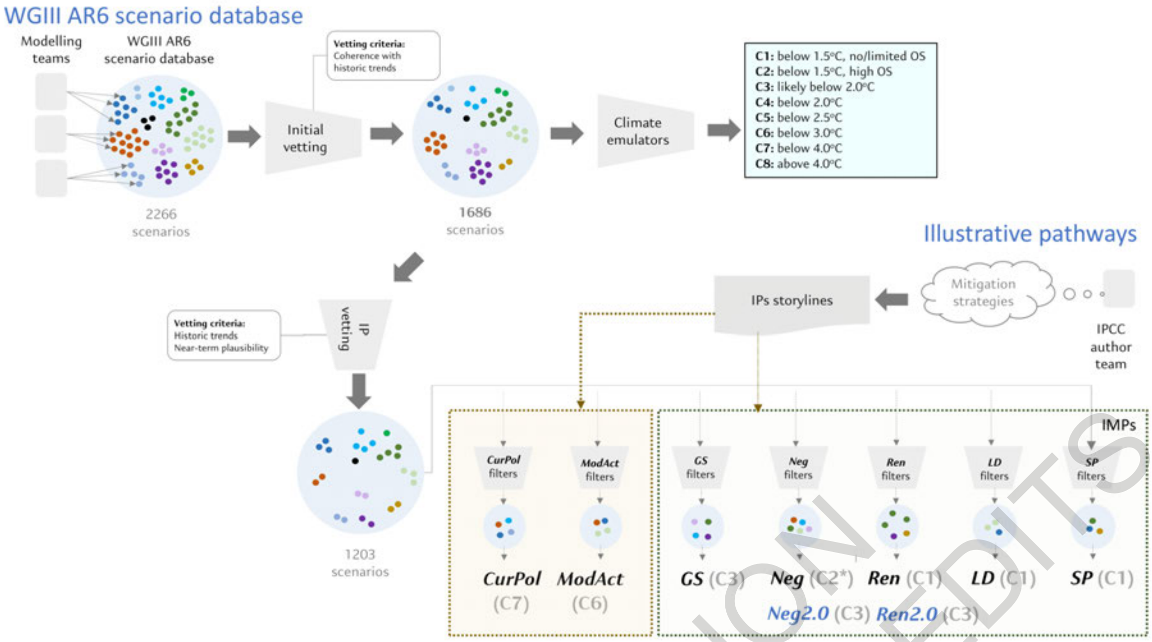
Successive IPCC Ars have used scenarios to illustrate key characteristics of possible climate (policy) futures. In IPCC AR5 four RCPs made the basis of climate modelling in WGI and WGII, with WGIII assessing over 1,000 scenarios spanning those RCPs (Clarke et al. 2014). Of the over 400 hundred scenarios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

In WGIII, IMPs were selected to denote the implications of different societal choices for the development of future emissions and associated transformations of main GHG emitting sectors (see Box 3.1 and Figure 3.5a). The most important function of the IMPs is to illustrate key themes that form a common thread in the report, both with a storyline and a quantitative illustration. The storyline describes the key characteristics that define an IMP. The quantitative versions of the IMPs provide numerical values that are internally consistent and comparable across chapters of the report. The quantitative IMPs have been selected from the AR6 scenario database. No assessment of the likelihood of each IMP has been made.

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

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

Panel A



Panel B

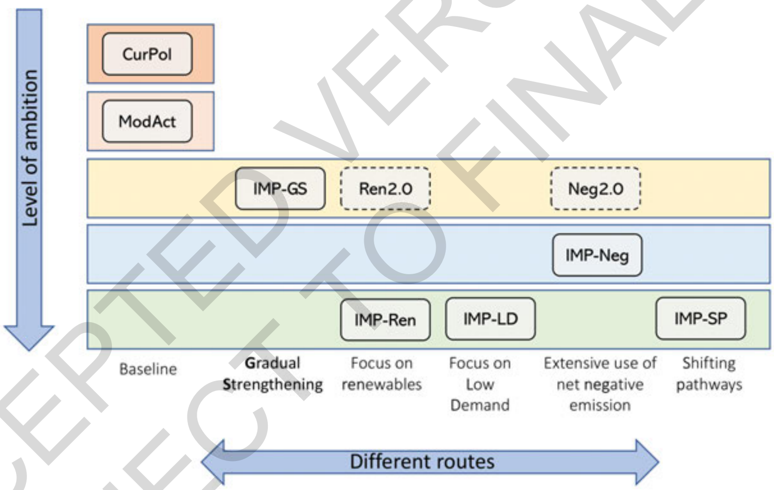


Figure 3.5 Panel A: Process for creating the AR6 scenario database and selecting the illustrative (mitigation) pathways. The compiled scenarios in the AR6 scenarios database were vetted for consistency with historical statistics and subsequently a temperature classification was added using climate model 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*).

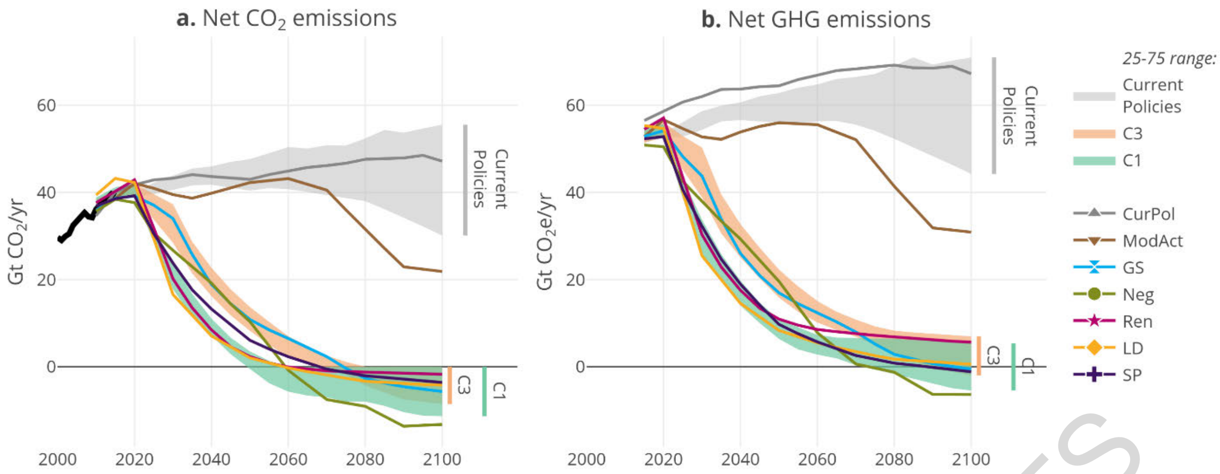


Figure 3.6 Overview of the net CO_2 emissions and Kyoto GHG emissions for each IMP

The IMPs are selected to have different mitigation strategies, which can be illustrated looking at the energy system and emission pathways (Figure 3.7 and Figure 3.8). The mitigation strategies show the different options in emission reduction (Figure 3.7). Each panel shows the key characteristics leading to total GHG emissions, consisting of residual (gross) emissions (fossil CO_2 emissions, CO_2 emissions from industrial processes, and non-CO_2 emissions) and removals (net land-use change, bioenergy with carbon capture and storage, and direct air carbon capture and storage), in addition to avoided emissions through the use of carbon capture and storage on fossil fuels. The ***Neg*** and ***GS*** scenarios were shown to illustrate scenarios with a significant role of CDR. The energy supply (Figure 3.8) shows the phase-out of fossil fuels in the ***LD***, ***Ren*** and ***SP*** cases, but a less substantial decrease in the ***Neg*** case. The ***GS*** case needs to make up its slow start by 1) rapid reductions mid-century and 2) massive reliance on net negative emissions by the end of the century. The ***CurPol*** and ***ModAct*** cases both result in relatively high emissions, showing a slight increase and stabilization compared to current emissions, respectively.

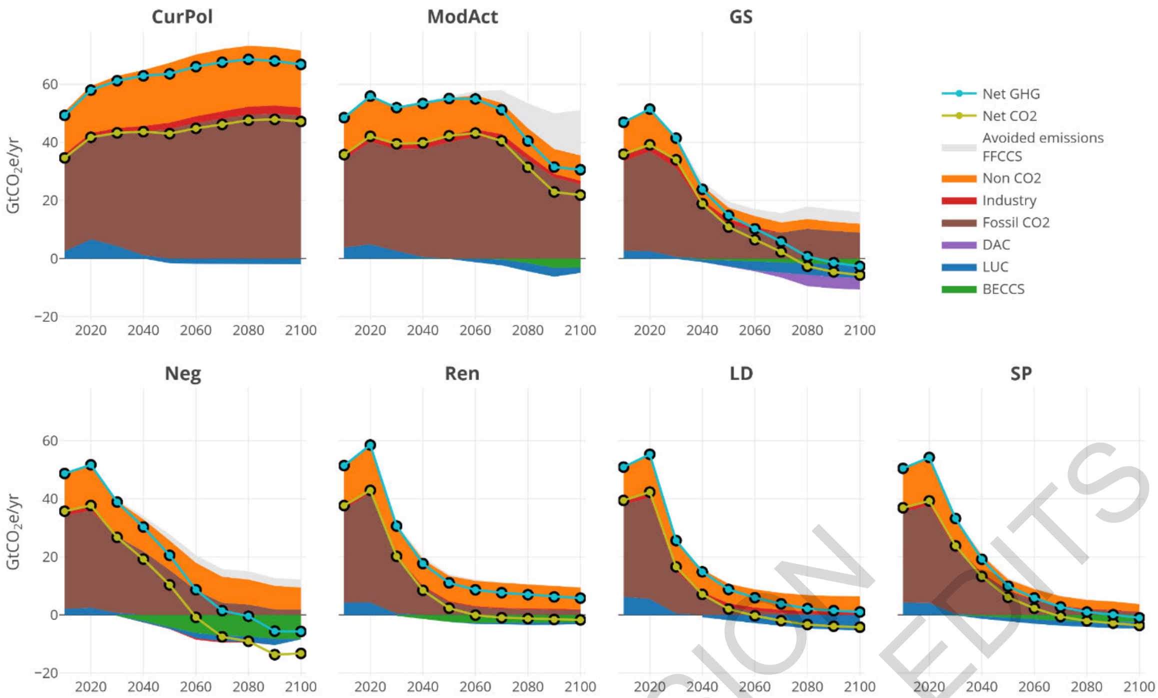


Figure 3.7 The residual fossil fuel and industry emissions, net land-use change, CDR, and non-CO_2 emissions (using AR6 GWP100) for each of the seven illustrative pathways. Fossil CCS is also shown, though this does not lead to emissions to the atmosphere.

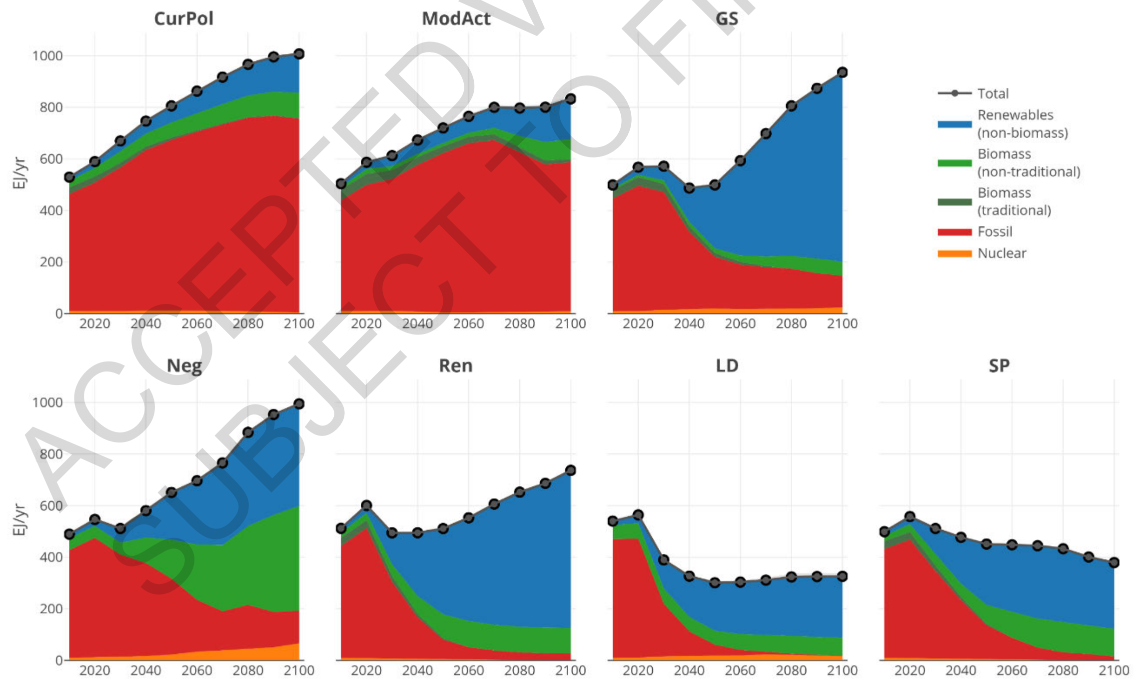


Figure 3.8 The energy system in each of the illustrative pathways.

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_2 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 (Sognnaes 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 represents an example of the opposite – while SSP2 and SSP4 are placed more in the middle. Nearly all scenarios assessed here do not account for climate impacts on growth (mostly for methodological reasons). As discussed in Section 3.5 these impacts can be considerable. An emerging area of literature emphasises the possibility of stabilisation (or even decline) of income levels in developed countries, arguing that such a trend would be preferred or even needed for environmental reasons (Anderson and Larkin 2013; Kallis et al. 2020; Hickel and Kallis 2020; Keyßer and Lenzen 2021; Hickel et al. 2021) (see also Chapter 5). Such scenarios are not common among IAM outcomes, that are more commonly based on the idea that decarbonisation can be combined with economic growth by a combination of technology, lifestyle and structural economic changes. Still, such scenarios could result in a dramatic reduction of energy and resource consumption (see further).

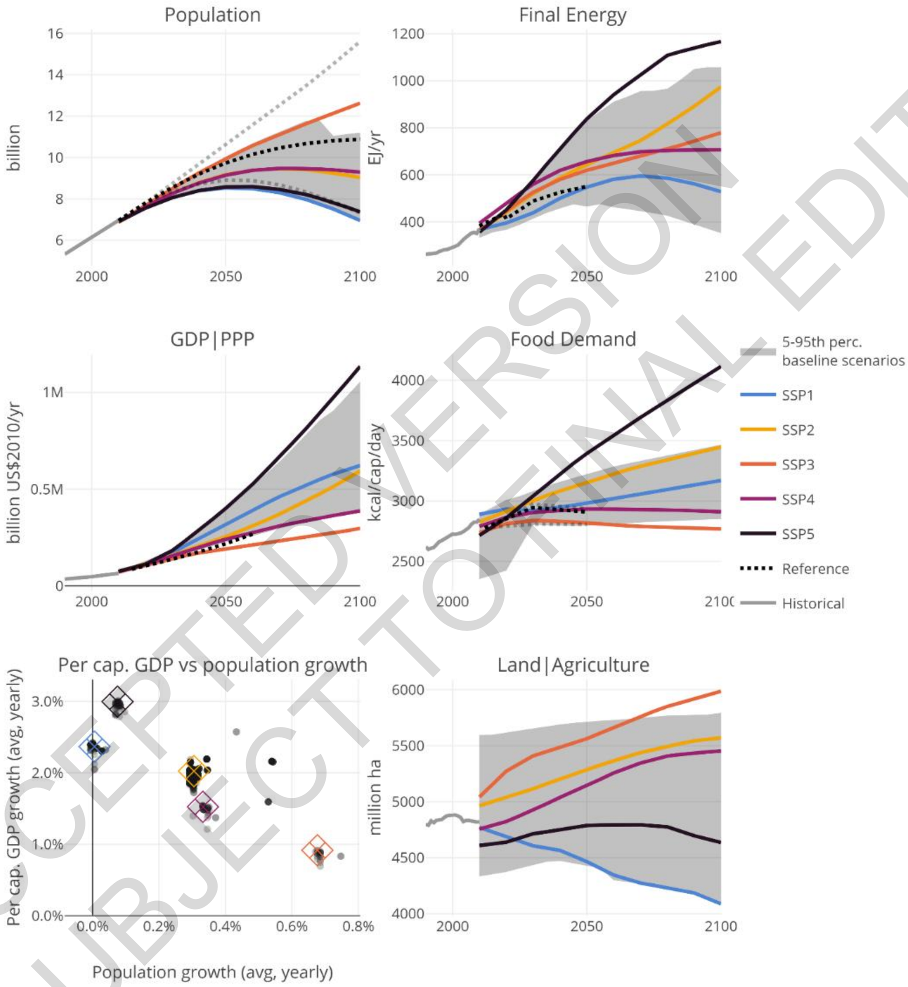


Figure 3.9 Trends in key scenarios characteristics and driving forces as included in the SSP scenarios (showing 5-95th percentiles of the reference scenarios as included in the database in grey shading). Reference (dotted lines) refers to UN low, medium and high population scenario (UN 2019), OECD Long-term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

Scenarios show a range of possible energy projections. In the absence of climate policy, most scenarios project the final energy demand to continue to grow to around 650-800 EJ yr^{-1} in 2100 (based on the scenario database). Some projections show a very high energy demand up to 1000 EJ yr^{-1} (comparable to SSP5). The scenario of the IEA lies within the SSP range but near the SSP1 projection. However, it should be noted that the IEA scenario includes current policies (most reference scenarios do not) and many scenarios published before 2021 did not account for the Covid-19 crisis. Several researchers discuss the possibility of decoupling material and energy demand from economic growth in the literature, mainly in developed countries (Kemp-Benedict 2018) (decoupling here refers to either a much slower increase in demand or even a decrease). In the scenario literature, this is reflected by scenarios with very low demand for final energy based on increased energy efficiency and less energy-intensive lifestyles (e.g., SSP1 and the LED scenario) (Grubler et al. 2018; van Vuuren et al. 2018). While these studies show the feasibility of such pathways, their energy efficiency improvement rates are considerably above the historic range of around 2% (Haberl et al. 2020).

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

3.3.2 Emission pathways and temperature outcomes

3.3.2.1 Overall mitigation profiles and temperature consequences

Figure 3.10 shows the GHG and CO_2 emission trajectories for different temperature categories as defined in Section 3.2 (the temperature levels are calculated using simple climate models, consistent with the outcomes of the recent WGI assessment, Cross-Chapter Box 7.1). It should be noted that most scenarios currently in the literature do not account for an impact of Covid-19 (see Box 3.2). The higher categories (C6 and C7) mostly included scenarios with no or modest climate policy. Because of the progression of climate policy, it is becoming more common that reference scenarios incorporate implemented climate policies. Modelling studies typically implement current or pledged policies up until 2030 (Vrontisi et al. 2018; Roelfsema et al. 2020; Sognnaes et al. 2021) with some studies focusing also on the policy development in the long term (IEA 2021a; Höhne et al. 2021). (Jeffery et al. 2018; Gütschow et al. 2018)Based on the assessment by Chapter 4, reference pathways consistent with the implementation and extrapolation of current policies are associated with increased GHG emissions from 59 (53-65) $GtCO_2$-eq yr^{-1} in 2019 to 52-60 $GtCO_2$-eq yr^{-1} by 2030 and to 46-67 $GtCO_2$-eq yr^{-1} by 2050 (see Figure 3.6). Pathways with these near-term emissions characteristics, lead to a median global warming of 2.4°C to 3.5°C by 2100 (see also further in this section). These pathways consider policies at the time that they were developed. A recent model comparison that harmonised socioeconomic, technological, and policy assumptions (Giarola et al. 2021) found a 2.2-2.9°C median temperature rise in 2100 for current and stated policies, with the results sensitive to the model used and the method of implementing policies (Sognnaes et al. 2021). Scenario inference and construction methods using similar policy assumptions leads to a median range of 2.9-3.2°C in 2100 for current policies and 2.4-2.9°C in 2100 for 2030 pledges (Höhne et al. 2021). The median spread of 1°C across these studies (2.2-3.2°C) indicates the deep uncertainties involved with modelling temperature outcomes of 2030 policies through to 2100. (Höhne et al. 2021)

The lower categories include increasingly stringent assumed climate policies. For all scenario categories, except the highest category, emissions peak in the 21st century. For the lowest categories, the emissions peak is mostly before 2030. In fact, for scenarios in the category that avoids temperature overshoot for the 1.5ºC scenario (C1 category), GHG emissions are reduced already to almost zero around the middle of the century. Typically, CO_2 emissions reach net zero about 10-20 years before total GHG emissions reach net zero. The main reason is that scenarios reduce non-CO_2 greenhouse gas emissions less than CO2 due to a limited mitigation potential (see 3.3.2.2). The figure also shows that many scenarios in the literature with a temperature outcome below 2 ˚C show net negative emissions. There are, however, also exceptions in which more immediate emission reductions limits the need for CDR. The IMPs illustrate alternative pathways to reach the C1-C3 temperature levels.

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Box 3.2 Impact of Covid-19 on long-term emissions

The reduction in CO_2 emissions of the Covid-19 pandemic in 2020 was estimated to be about 6% (see section 4.2.2.4 and Table S4.2) lower than 2019 levels (BP 2021, Crippa et al. 2021, IEA 2021, Le Quéré et al. 2021; Friedlingstein et al. 2020; Forster et al. 2020; Liu et al. 2020c). Near-real-time monitoring estimates show a rebound in emissions levels, meaning 2021 emissions levels are expected to be higher than 2020 (Le Quéré et al. 2021). The longer-term effects are uncertain but so far do not indicate a clear structural change for climate policy related to the pandemic. The increase in renewable shares in 2020 could stimulate a further transition, but slow economic growth can also slow down (renewable) energy investments. Also, lifestyle changes during the crisis can still develop in different directions (working from home, but maybe also living further away from work). Without a major intervention, most long-term scenarios project that emission will start to follow a similar pathway as earlier projections (although at a reduced level) (IEA 2020b; Kikstra et al. 2021a; Rochedo et al. 2021). If emissions reductions are limited to only a short time, the adjustment of pathways will lead to negligible outcomes in the order of 0.01K (Forster et al. 2020; Jones et al. 2021). At the same time, however, the large amount of investments pledged in the recovery packages could provide a unique opportunity to determine the long-term development of infrastructure, energy systems and land use (Hepburn et al. 2020; Pianta et al. 2021; Andrijevic et al. 2020b). Near-term alternative recovery pathways have been shown to have the potential to influence carbon price pathways, and energy investments and electrification requirements under stringent mitigation targets (Kikstra et al. 2021a; Rochedo et al. 2021; Bertram et al. 2021; Pollitt et al. 2021; Shan et al. 2021). Most studies suggest a noticeable reduction in 2030 emissions. However, much further reductions would be needed to reach the emission levels consistent with mitigation scenarios that would likely stay below 2ºC or lower (see Chapter 4). At the moment, the share of investments in greenhouse gas reduction is relatively small in most recovery packages, and no structural shifts for climate policies are observed linked to the pandemic. Finally, most of the scenarios analysed in this Chapter do not include the 2020 emissions reduction related to the Covid-19 pandemic. The effect of the pandemic on the pathways will likely be very small. The assessment of climate mitigation pathways in this chapter should be interpreted as being almost exclusively based on the assumption of a fast recovery with limited persistent effects on emissions or structural changes.

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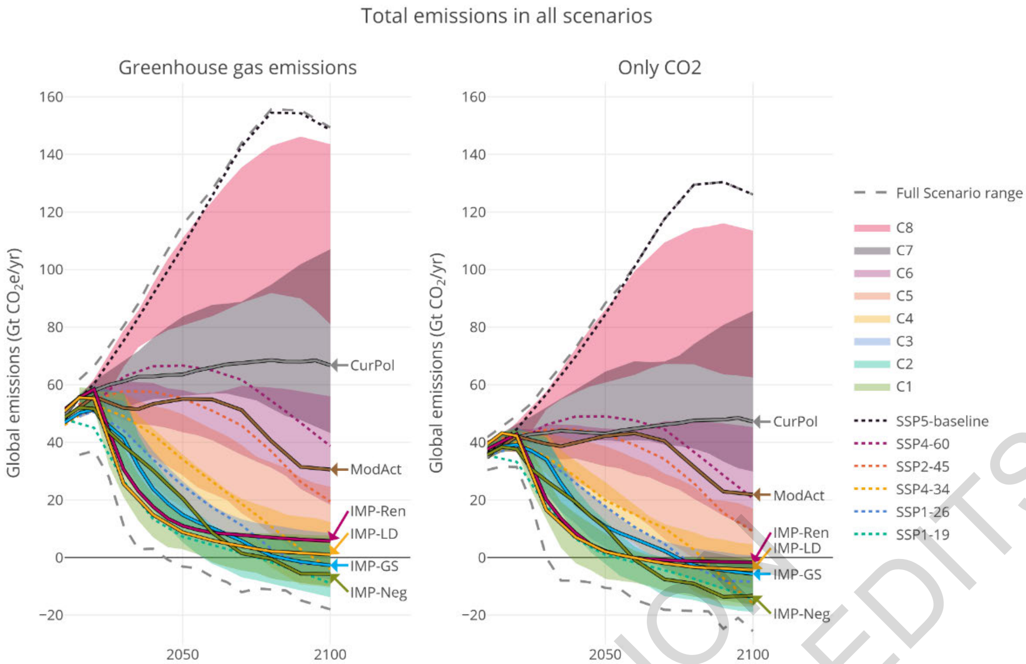

Figure 3.10 Total emission profiles in the scenarios based on climate category for GHGs (AR6 GWP-100) and CO_2. The IMPs are also indicated

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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/m2). 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.

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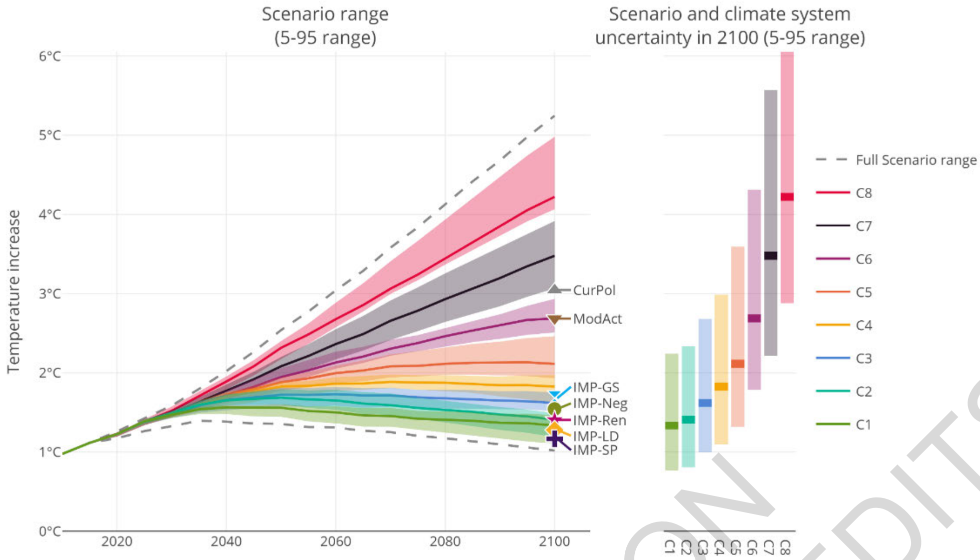

Figure 3.11: Global mean temperature outcome of the ensemble of scenarios included in the climate categories C1-C7 (based on RCM calibrated to the WGI assessment, both in terms of future and historic warming). The left panel shows the ranges of scenario uncertainty (shaded area) with the P50 RCM probability (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).

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

3.3.2.2 The role of carbon dioxide and other greenhouse gases

The trajectory of future CO_2 emissions plays a critical role in mitigation, given CO_2 long-term impact and dominance in total greenhouse gas forcing. As shown in Figure 3.12, CO_2 dominates total greenhouse gas emissions in the high emissions scenarios but is also reduced most, going from scenarios in the highest to lower categories. In C4 and below, most scenarios exhibit net negative CO_2 emissions in the second half of the century compensating for some of the residual emissions of non-CO_2 gases as well as reducing overall warming from an intermediate peak. Still, early emission reductions and further reductions in non-CO_2 emissions can also lead to scenarios without net negative emissions in 2100, even in C1 and C3 (shown for the 85-95th percentile). In C1, avoidance of significant overshoot implies that immediate gross reductions are more relevant than long-term net negative emissions (explaining the lower number than in C2) but carbon dioxide removal is still playing a role in compensating for remaining positive emissions in hard-to-abate sectors.

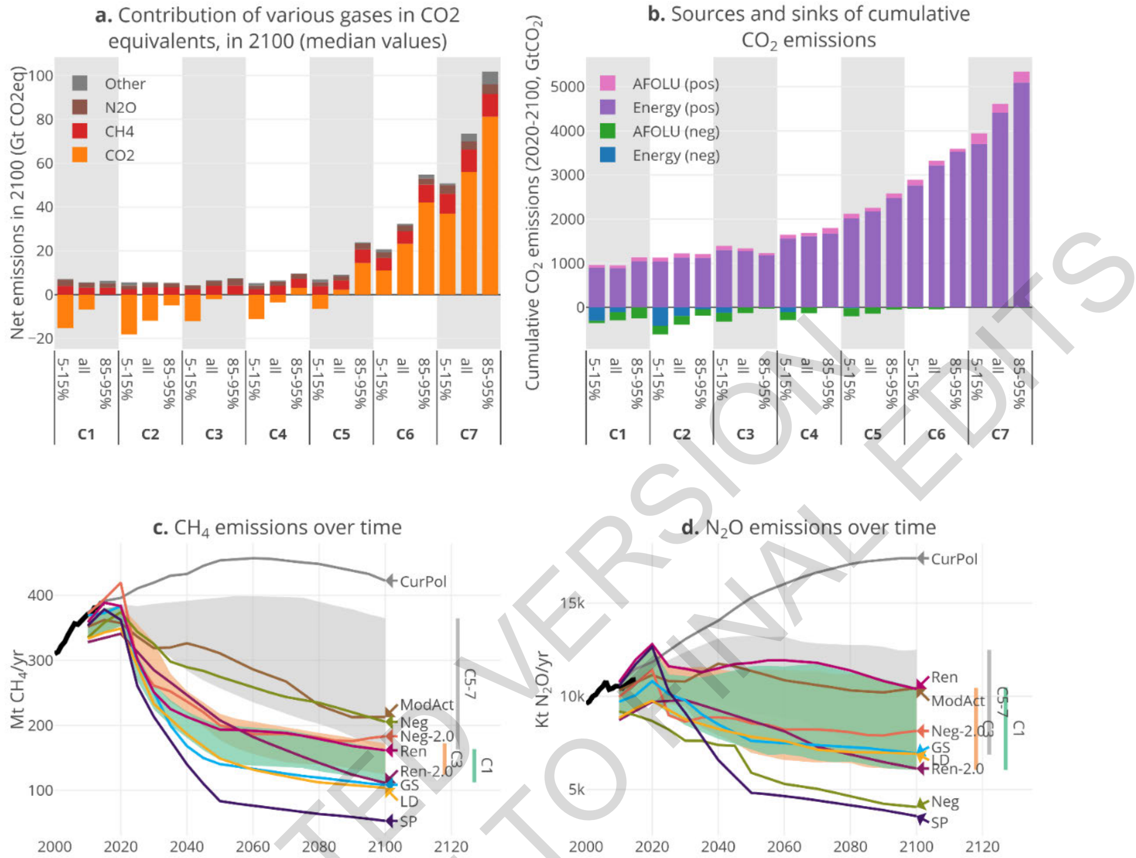

Figure 3.12 Upper left: The role of CO_2 and other greenhouse gases. Emission in CO_2-eq in 2100 (using AR6 GWP-100) (other = halogenated gases) and upper right: Cumulative CO_2 emissions in the 2020-2100 period. The lower left and right panel show the development of CH4 and N2O emissions over time. Energy emissions include the contribution of BECCS. For both energy and AFOLU sectors, the positive and negative values represent the cumulated annual balances. In both panels, the three bars per scenario category represent the lowest 5-15th percentile, the average value and the highest 5-15th percentile. These illustrate the range of scenarios in each category. The definition of C1-C7 can be found in Table 3.1

CH_4 and N_2O emissions are also reduced from C7 to C1, but this mostly occurs between C7 and C5. The main reason is the characteristics of abatement potential: technical measures can significantly reduce CH_4 and N_2O emissions at relatively low costs to about 50% of the current levels (e.g., by reducing CH_4 leaks from fossil fuel production and transport, reducing landfill emissions gazing, land management and introducing measure related to manure management, see also Chapter 7 and 11). However, technical potential estimates becomes exhausted even if the stringency of mitigation is increased (Harmsen et al. 2019a,b; Höglund-Isaksson et al. 2020). Therefore, further reduction may come from changes in activity levels, such as switching to a less meat-intensive diet reducing livestock (Stehfest et al. 2009; Willett et al. 2019; Ivanova et al. 2020) (see also Chapter 7). Other non-CO_2 GHG emissions (halogenated gases) are reduced to low levels for scenarios below 2.5°C.

Short-lived climate forcers (SLCFs) also play an important role in climate change, certainly for short-term changes (see Figure SPM.2, WGI) (Shindell et al. 2012). These forcers consist of 1) substances contributing to warming, such as methane, black carbon and tropospheric ozone and 2) substances contributing to cooling (other aerosols, such as related to sulphur emissions). Most SLCFs are also air pollutants, and reducing their emissions provides additional co-benefits (Shindell et al. 2017a,b; Hanaoka and Masui 2020). In the case of the first group, emission reduction thus leads to both air pollution and climate benefits. For the second, group there is a possible trade-off (Shindell and Smith 2019; Lund et al. 2020). As aerosol emissions are mostly associated with fossil fuel combustion, the benefits of reducing CO_2 could, in the short term, be reduced as a result of lower aerosol cooling. There has been an active discussion on the exact climate contribution of SLCF focused policies in the literature. This discussion partly emerged from different assumptions on possible reductions in the absence of ambitious climate policy and the uncertain global climate benefit from aerosol (black carbon) (Rogelj et al. 2014). The latter is now assessed to be smaller than originally thought (Smith et al. 2020b; Takemura and Suzuki 2019) (see also WGI Chapter 6, Section 6.4). Reducing SLCF emissions is critical to meet long-term climate goals and might help reduce the rate of climate change in the short term. Deep SLCF emission reductions also increase the remaining carbon budget for a specific temperature goal (Rogelj et al. 2015a; Reisinger et al. 2021) (see Box 3.4). A more detailed discussion can be found in WGI Chapter 5 and 6.

For accounting of emissions and the substitution of different gases as part of a mitigation strategy, typically, emission metrics are used to compare the climate impact of different gases. Most policies currently use Global Warming Potentials with a 100-year time horizon as this is also mandated for emissions reporting in the Paris Rulebook (for a wider discussion of GHG metrics, see Box 2.2 in Chapter 2 and WGI, Chapter 7, Section 7.6). Alternative metrics have also been proposed, such as those using a shorter or longer time horizon or those that focus directly on the consequences of reaching a certain temperature target (Global Temperature Change Potential, GTP), allowing a more direct comparison with cumulative CO_2 emissions (Allen et al. 2016; Lynch et al. 2020) or focusing on damages (Global Damage Potential) (an overview is given in Chapter 2, and Cross-Chapter Box 3). Depending on the metric, the value attributed to reducing short-lived forcers like methane can be lower in the near term (e.g., in the case of GTP) or higher (GWP with short reference period). For most metrics, however, the impact on mitigation strategies is relatively small, among others, due to the marginal abatement cost curve of methane (low costs for low to medium mitigation levels; expensive for high levels). The timing of reductions across different gases impacts warming and the co-benefits (Harmsen et al. 2016; Cain et al. 2019). Nearly all scenarios in the literature use GWP-100 in cost-optimisation, reflecting the existing policy approach; the use of GWP-100 deviates from cost-optimal mitigation pathways by at most a few percent for temperature goals of likely below 2°C and lower (see Box 2.2 in Chapter 2).

Cumulative CO_2 emissions and temperature goals

The dominating role of CO_2 and its long lifetime in the atmosphere and some critical characteristics of the earth system implies that there is a strong relationship between cumulative CO_2 emissions and temperature outcomes (MacDougall and Friedlingstein 2015; Meinshausen et al. 2009; Allen et al. 2009; Matthews et al. 2009). This is illustrated in Figure 3.13 that plots the cumulative CO_2 emissions against the projected outcome for global mean temperature, both until a temperature peak and full century. The deviations from in linear relationship in Figure 3.13 are mostly caused by different non-CO_2 emission and forcing levels (see also Rogelj et al. (2015b)). This means that reducing non-CO_2 emissions can play an important role in limiting peak warming: the smaller the residual non-CO2 warming, the larger the carbon budget. This impact on carbon budgets can be substantial for stringent warming limits. For 1.5°C pathways, variations in non-CO_2 warming across different emission scenarios have been found to vary the remaining carbon budget by approximately 220 $GtCO_2$ (see WGI Chapter 5, Subsection 5.5.2.2). In addition to reaching net zero CO_2 emissions, a strong reduction in methane emissions is the most critical component in non-CO_2 mitigation to keep the Paris climate goals in reach (van Vuuren et al. 2018; Collins et al. 2018) (see also WGI, Chapter 5, 6 and 7). It should be noted that the temperature categories (C1-C7) generally aligned with the horizontal axis, except for the end-of-century values for C1 and C2 that coincide.

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Box 3.4 Consistency of remaining carbon budgets in the WGI assessment and cumulative CO_2 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_2 emissions (Chapter 5, Section 5.5, Box 5.3). Consistently, WGI has confirmed that net zero CO_2 emissions are required to halt CO_2-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_2 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_2 emissions until the time of net zero CO_2 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_2 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

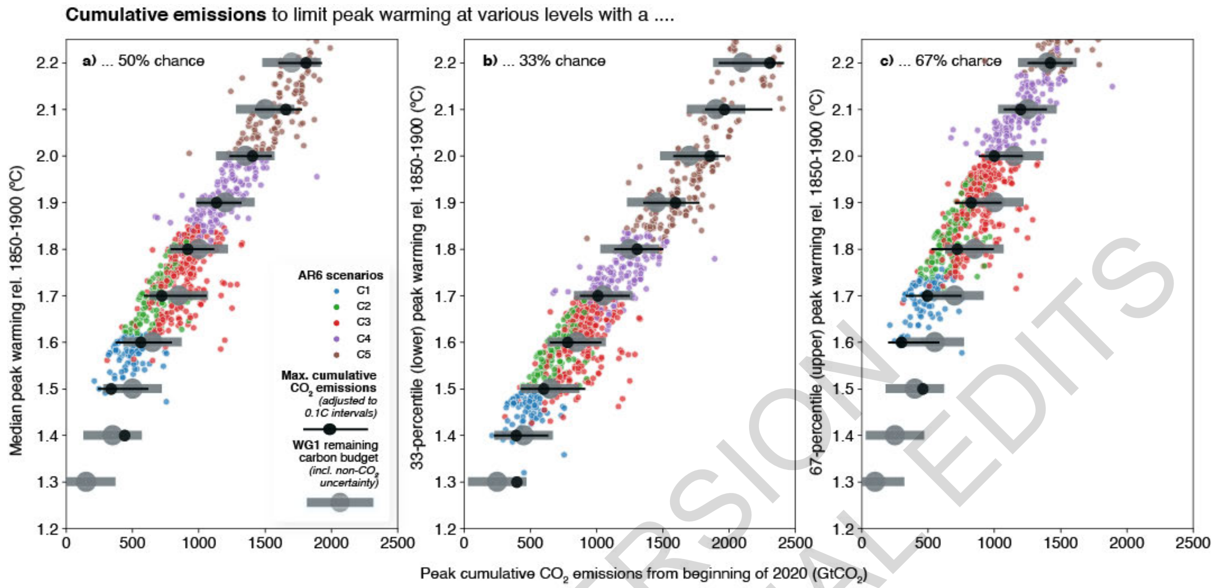
WGI estimated the remaining carbon budgets from their assessment of (i) the transient climate response to cumulative emissions of carbon dioxide (TCRE), and estimates of (ii) the historical human-induced warming, (iii) the temperature change after reaching net zero CO_2 emissions, (iv) the contribution of future non-CO_2 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 $GtCO_2$ for limiting warming to 1.5°C with 33% / 50% / 67% chance and 1350 / 1150 $GtCO_2$ for limiting warming to 2°C with 50% / 67% chance. The estimates are subject to considerable uncertainty related to historical warming, future non-CO_2 forcing, and poorly quantified climate feedbacks. For instance, variation in non-CO_2 emissions across scenarios are estimated to either increase or decrease the remaining carbon budget estimates by 220 $GtCO_2$. The estimates of the remaining carbon budget assume that non-CO_2 emissions are reduced consistently with the tight temperature targets for which the budgets are estimated.

Cumulative CO_2 emissions until net zero estimated by WGIII

WGIII provides estimates of cumulative net CO_2 emissions (from 2020 inclusive) until the time of reaching net zero CO_2 emissions (henceforth called "peak cumulative CO_2 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 $GtCO_2$ for C1; 540-930 for C2 and 640-1160 for C3).

Comparing the WGI remaining carbon budgets and remaining cumulative CO_2 emissions of the WGIII scenarios

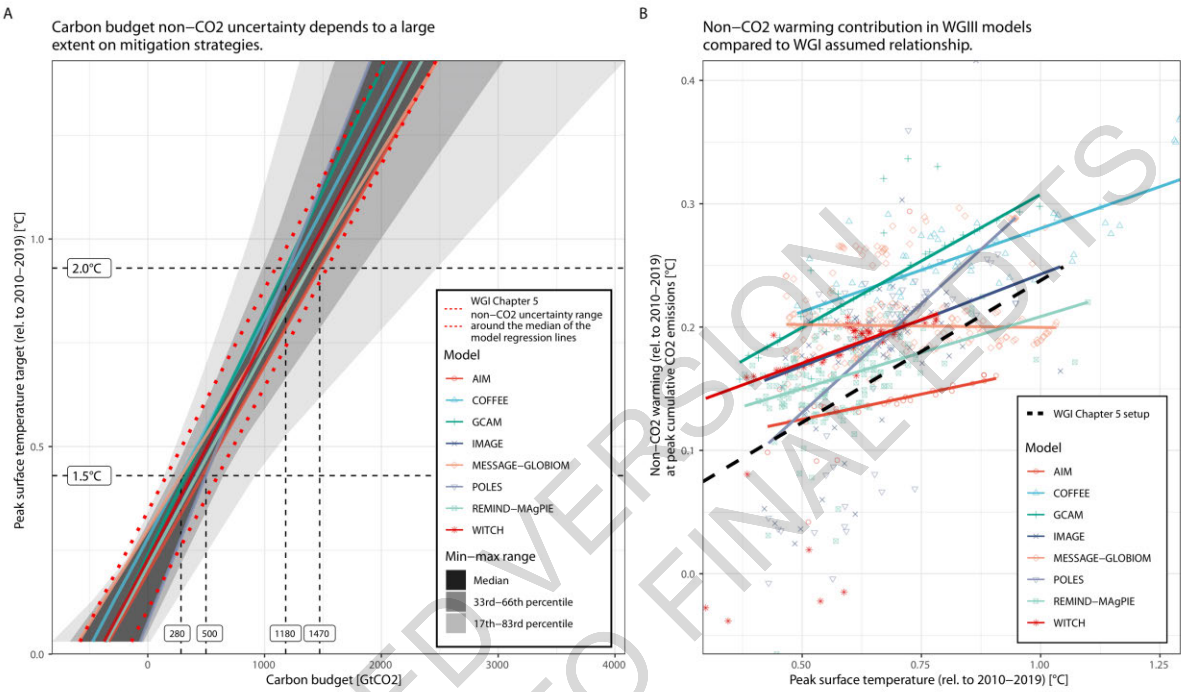
A comparison between WGI and WGIII findings requires recognising that, unlike in WGI, cumulative emissions in WGIII are not provided for a specific peak warming threshold or level but are instead provided for a set of scenarios in a category, representing a specific range of peak temperature outcomes (for instance the C4 category contains scenarios with a median peak warming anywhere between approximately 1.8°C and up to 2°C). When accounting for this difference, the WGI and WGIII findings are very consistent for temperature levels below 2ºC. Figure 1 compares the peak temperatures and associated cumulative CO_2 emissions (i.e., peak cumulative CO_2 emissions) for the WGIII scenarios to the remaining carbon budgets assessed by WGI. This shows only minor differences between the WGI and WGIII approaches.



Box 3.4 Figure 1: Cumulative CO_2 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 GtCO2 uncertainty due to non-CO_2 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_2 warming at the time of net zero CO_2 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_2 warming at peak cumulative CO_2 and peak surface temperature.

Estimates of the remaining carbon budgets thus vary with the assumed level of non-CO_2 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_2 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_2 warming for each single scenario is based on the individual scenario characteristics. This shown in the same figure by plotting the outcomes of scenario outcomes of a range models (dots). The lines show the fitted data for individual models, emphasizing the clear differences across models and the relationship with peak warming (policy level). In some scenarios stringent non-CO_2 emission reductions provide an option to reach more stringent climate goals with the same carbon budget. This is especially the case for scenarios with a very low non-CO_2 warming, for instance as a result of methane reductions through diet change. The left panel shows how these differences impact estimates of the remaining carbon budget. While the WGIII AR6 scenario database includes a broad range of non-CO_2 emission projections the overall range is still very consistent with the WGI relationship and the estimated uncertainty with a ±220 $GtCO_2$ range (see also panel B of Figure II.2 in Annex III.2.5).



Box 3.4 Figure 2: Panel A) Differences in regressions of the relationship between peak surface temperature and associated cumulative CO_2 emissions from 2020 derived from scenarios of eight integrated assessment model frameworks. The coloured lines show the regression at median for scenarios of the 8 modelling frameworks, each with more than 20 scenarios in the database and a detailed land-use representation. The red dotted lines indicate the non-CO_2 uncertainty range of WGI Chapter 5 (± 220 GtCO2), here visualised around the median of the 8 model framework lines. Carbon budgets from 2020 until 1.5C (0.43K above 2010-2019 levels) and 2.0C (0.93K above 2010-2019 levels) are shown for minimum and maximum model estimates at the median, rounded to the nearest 10$GtCO_2$. Panel B) Shows the relationship between the estimated non-CO2 warming in mitigation scenarios that reach net zero and the associated peak surface temperature outcomes. The coloured lines show the regression at median for scenarios of the 8 modelling frameworks with more than 20 scenarios in the database and a detailed land-use representation. The black dashed line indicates the non-CO2 relationship based on the scenarios and climate emulator setup as was assessed in WGI Chapter 5.

Overall, the slight differences between the cumulative emissions in WGIII and the carbon budget in WGI are because the non-CO_2 warming in the WGIII AR6 scenarios is slightly lower than in the SR1.5 scenarios that are used for the budget estimates in WGI (Annex III.2.5.1). In addition, improved consistency with Cross-Chapter Box 7.1 in WGI results in a non-CO2 induced temperature difference of about ~0.05K between the assessments. Re-calculating the remaining carbon budget using the WGI methodology combined with the full WGIII AR6 scenario database results in a reduction of the estimated remaining 1.5C carbon budget by about 100 $GtCO_2$ (-20%), and a reduction of ~40 $GtCO_2$ (-3%) for 2C. Accounting also for the categorisation effect, the difference between the WGI and WGIII estimates is found to be small and well within the uncertainty range (Figure 1). This means that the cumulative CO_2 emissions presented in WGIII and the WGI carbon budgets are highly consistent.

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

Policy implications

The concept of a finite carbon budget means that the world needs to get to net zero CO_2, no matter whether global warming is limited to 1.5°C or well below 2°C (or any other level). Moreover, exceeding the remaining carbon budget will have consequences by overshooting temperature levels. Still, the relationship between the timing of net zero and temperature targets is a flexible one, as discussed further in Cross-Chapter Box 3. It should be noted that national level inventory as used by UNFCCC for the land use, land-use change and forestry sector are different from the overall concept of anthropogenic emissions employed by IPCC WG1. For emissions estimates based on these inventories, the remaining carbon budgets must be correspondingly reduced by approximately 15%, depending on the scenarios (Grassi et al., 2021) (see also Chapter 7).

One of the uncertainties of the remaining carbon budget is the level of non-CO_2 emissions which is a function of policies and technology development. This represents a point of leverage for policies rather than an inherent geophysical uncertainty. Stringent non-CO_2 emission reductions hence can provide – to some degree – an option to reach more stringent climate goals with the same carbon budget.

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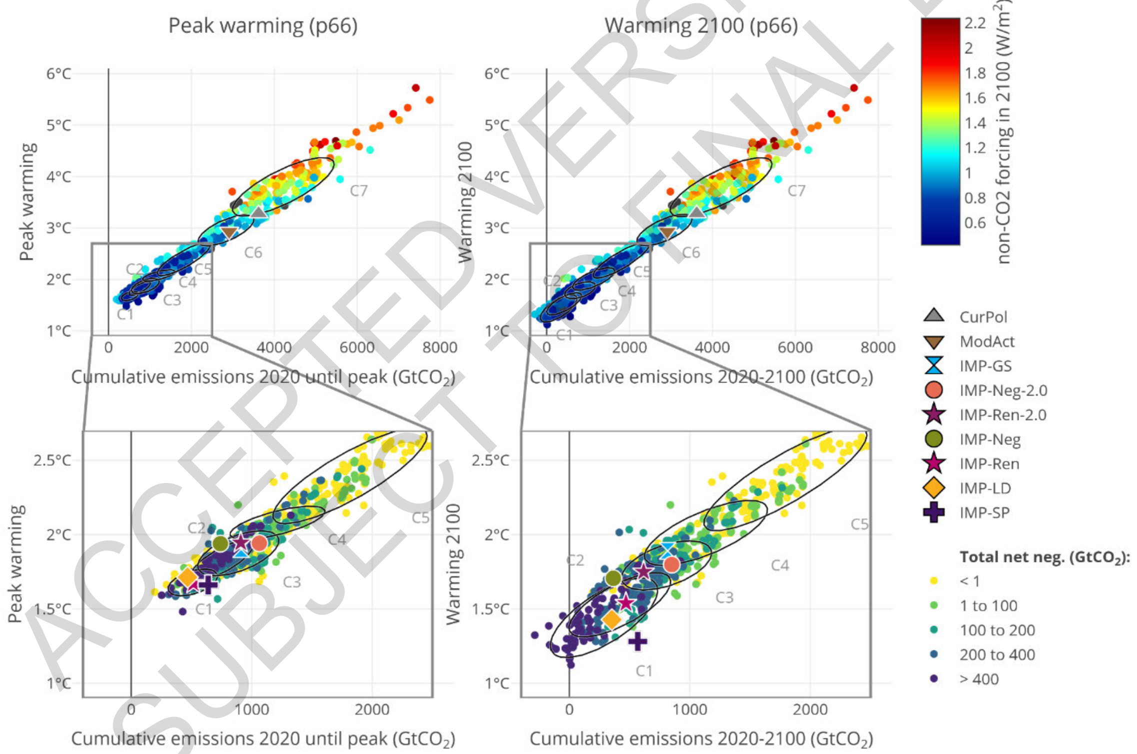

Figure 3.13: The near-linear relationship between cumulative CO_2 emissions and temperature. The left panel shows cumulative emissions until net zero emission is reached. The right panel shows cumulative emissions until the end of the century, plotted against peak and end-of-century temperature, respectively. Both are shown as a function of non-CO_2 forcing and cumulative net negative CO_2 emissions. Position temperature categories (circles) and IPs are also indicated, including two 2°C sensitivity cases for *Neg* (Neg-2.0) and *Ren* (Ren-2.0).

The near-linear relationship implies that cumulative CO_2 emissions are critically important for climate outcomes (Collins et al. 2013). The maximum temperature increase is a direct function of the cumulative emissions until net zero CO_2 emissions is reached (the emission budget) (Figure 3.13, left side). The end-of-century temperature correlates well with cumulative emissions across the century (right panel). For long-term climate goals, positive emissions in the first half of the century can be offset by net removal of CO_2 from the atmosphere (net negative emissions) at the cost of a temporary overshoot of the target (Tokarska et al. 2019). The bottom panels of Figure 3.13 show the contribution of net negative CO_2 emissions.

Focusing on cumulative emissions, the right-hand panel of Figure 3.12 shows that for high-end scenarios (C6-C7), most emissions originate from fossil fuels, with a smaller contribution from net deforestation. For C5 and lower, there is also a negative contribution to emissions from both AFOLU emissions and energy systems. For the energy systems, these negative emissions originate from bio-energy-and-carbon-capture-and-storage (BECCS), while for AFOLU, they originate from re- and afforestation. For C3-C5, reforestation has a larger CDR contribution than BECCS, mostly due to considerably lower costs (Rochedo et al. 2018). For C1 and C2, the tight carbon budgets imply in many scenarios more CDR use (Riahi et al. 2021). Please note that net negative emissions are not so relevant for peak temperature targets, and thus the C1 category, but CDR can still be used to offset the remaining positive emissions (Riahi et al. 2021). While positive CO_2 emissions from fossil fuels are significantly reduced, inertia and hard-to-abate sectors imply that in many C1-C3 scenarios, around 800-1000 $GtCO_2$ of net positive cumulative CO_2 emissions remain. This is consistent with literature estimates that current infrastructure is associated with 650 $GtCO_2$ (best estimate) if operated until the end of its lifetime (Tong et al. 2019). These numbers are considerably above the estimated carbon budgets for 1.5 °C estimated in WGI, hence explaining CDR reliance (either to offset emissions immediately or later in time).

Creating net negative emissions can thus be an important part of a mitigation strategy to offset remaining emissions or compensate for emissions earlier in time. As indicated above, there are different ways to potentially achieve this, including re- and afforestation and BECCS (as often covered in IAMs) but also soil carbon enhancement, direct air carbon capture and storage (DACCS) and ocean alkalinization (see Chapter 12). Except for reforestation, these options have not been tested at large scale and often require more R&D. Moreover, the reliance on CDR in scenarios has been discussed given possible consequences of land use related to biodiversity loss and food security (BECCS and afforestation), the reliance on uncertain storage potentials (BECCS and DACCS), water use (BECCS), energy use (DACCS), the risks of possible temperature overshoot and the consequences for meeting sustainable development goals (Venton 2016; Peters and Geden 2017; Smith et al. 2016; van Vuuren et al. 2017; Anderson and Peters 2016; Honegger et al. 2021). In the case of BECCS, it should be noted that bio-energy typically is associated with early-on positive CO_2 emissions and net-negative effects are only achieved in time (carbon debt), and its potential is limited (Cherubini et al. 2013; Hanssen et al. 2020) (most IAMs have only a very limited representation of these time dynamics). Several scenarios have therefore explored how reliance on net negative CO_2 emissions can be reduced or even avoided by alternative emission strategies (Grubler et al. 2018; van Vuuren et al. 2018) or early reductions by more stringent emission reduction in the short-term (Rogelj et al. 2019b; Riahi et al. 2021). A more in-depth discussion of land-based mitigation options can be found in Chapter 7. It needs to be emphasized that even in strategies with net negative CO_2 emissions, the emission reduction via more conventional mitigation measures (efficiency improvement, decarbonisation of energy supply) is much larger than the CDR contribution (Tsutsui et al. 2020).

3.3.2.3 The timing of net zero emissions

In addition to the constraints on change in global mean temperature, the Paris Agreement also calls for reaching a balance of sources and sinks of GHG emissions (Art. 4). Different interpretations of the concept related to balance have been published (Rogelj et al. 2015c; Fuglestvedt et al. 2018). Key concepts include that of net zero CO_2 emissions (anthropogenic CO_2 sources and sinks equal zero) and net zero greenhouse gas emission (see also Annex I Glossary and Box 3.3). The same notion can be used for all GHG emissions, but here ranges also depend on the use of equivalence metrics (Chapter 2, Box 2.2). Moreover, it should be noted that while reaching net zero CO_2 emissions typically coincides with the peak in temperature increase; net zero GHG emissions (based on GWP-100) implies a decrease in global temperature (Riahi et al. 2021) and net zero GHG emission typically requires negative CO_2 emissions to compensate for the remaining emissions from other GHGs. Many countries have started to formulate climate policy in the year that net zero emissions (either CO_2 or all greenhouse gases) are reached – although, at the moment, formulations are often still vague (Rogelj et al. 2021). There has been increased attention on the timing of net zero emissions in the scientific literature and ways to achieve it.

Figure 3.14 shows that there is a relationship between the temperature target, the cumulative CO_2 emissions budget, and the net zero year for CO_2 emissions (left) and the sum of greenhouse gases (right) for the scenarios published in the literature. In other words, the temperature targets from the Paris Agreement can, to some degree, be translated into a net zero emission year (Tanaka and O'Neill 2018). There is, however, a considerable spread. In addition to the factors influencing the emission budget (see WGI and section 3.3.2.2), this is influenced by the emission trajectory until net zero is reached, decisions related to temperature overshoot and non-CO_2 emissions (especially for the moment CO_2 reaches net zero emissions). Scenarios with limited or no net negative emissions and rapid near-term emission reductions can allow small positive emissions (e.g., in hard-to-abate-sectors). They may therefore have a later year that net zero CO_2 emissions are achieved. High emissions in the short-term, in contrast, require an early net zero year.

For the scenarios in the C1 category (warming below 1.5°C (50% probability) with limited overshoot), the net zero year for CO_2 emissions is typically around 2035-2070 For scenarios in C3 (likely limiting warming to below 2°C), CO_2 emissions reach net zero around 2060-2100. Similarly, also the years for net zero GHG emissions can be calculated (see right graph). The GHG net zero emissions year is typically around 10-20 years later than the carbon neutrality. Residual non-CO_2 emissions at the time of reaching net zero CO_2 range between 4-11 $GtCO_2$-eq in pathways that *likely* limit warming to 2.0°C or below. In pathways likely limiting warming to 2°C, methane is reduced by around 20% (1-46%) in 2030 and almost 50% (26-64%) in 2050, and in pathways limiting warming to 1.5°C with no or limited overshoot by around 33% (19-57) in 2030 and a similar 50% (33-69%) in 2050. Emissions reduction potentials assumed in the pathways become largely exhausted when limiting warming to below 2°C. N_2O emissions are reduced too, but similar to CH4, emission reductions saturate for stringent climate goals. In the mitigation pathways, the emissions of cooling aerosols are reduced due to reduced use of fossil fuels. The overall impact on non-CO_2-related warming combines these factors.
In cost-optimal scenarios, regions will mostly achieve net zero emissions as a function of options for emission reduction, CDR, and expected baseline emission growth (van Soest et al. 2021b). This typically implies relatively early net zero emission years in scenarios for the Latin America region and relatively late net zero years for Asia and Africa (and average values for OECD countries). However, an allocation based on equity principles (such as responsibility, capability and equality) might result in different carbon neutrality years, based on the principles applied – with often earlier net zero years for the OECD (Fyson et al. 2020; van Soest et al. 2021b). Therefore, the emission trajectory until net zero emissions is a critical determinant of future warming (see Section 3.5). The more CO_2 is emitted until 2030, the less CO_2 can be emitted after that to stay below a warming limit (Riahi et al. 2015). As discussed before, also non-CO_2 forcing plays a key role in the short term.

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Cross-Chapter Box 3: Understanding net zero CO_2 and net zero GHG emissions

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This cross-chapter box surveys scientific, technical and policy aspects of net zero carbon dioxide (CO_2) and net zero greenhouse gas (GHG) emissions, with a focus on timing, the relationship with warming levels, and sectoral and regional characteristics of net zero emissions. Assessment of net zero GHG emissions additionally requires consideration of non-CO_2 gases and choice of GHG emission metrics used to aggregate emissions and removals of different GHGs (Cross-Chapter Box 2 in Chapter 2; Cross-Chapter Box 7 in Chapter 10). The following considers net zero CO_2 and GHG emissions globally, followed by regional and sectoral dimensions.

Net zero CO_2

Reaching net zero CO_2 emissions globally is necessary for limiting global warming to any level. At the point of net zero CO_2, the amount of CO_2 human activity is putting into the atmosphere equals the amount of CO_2 human activity is removing from the atmosphere (see Glossary). Reaching and sustaining net zero CO_2 emissions globally stabilizes CO_2-induced warming. Reaching net zero CO_2 emissions and then moving to net negative CO_2 emissions globally leads to a peak and decline in CO_2-induced warming (WGI AR6 Chapter 5.5, 5.6).

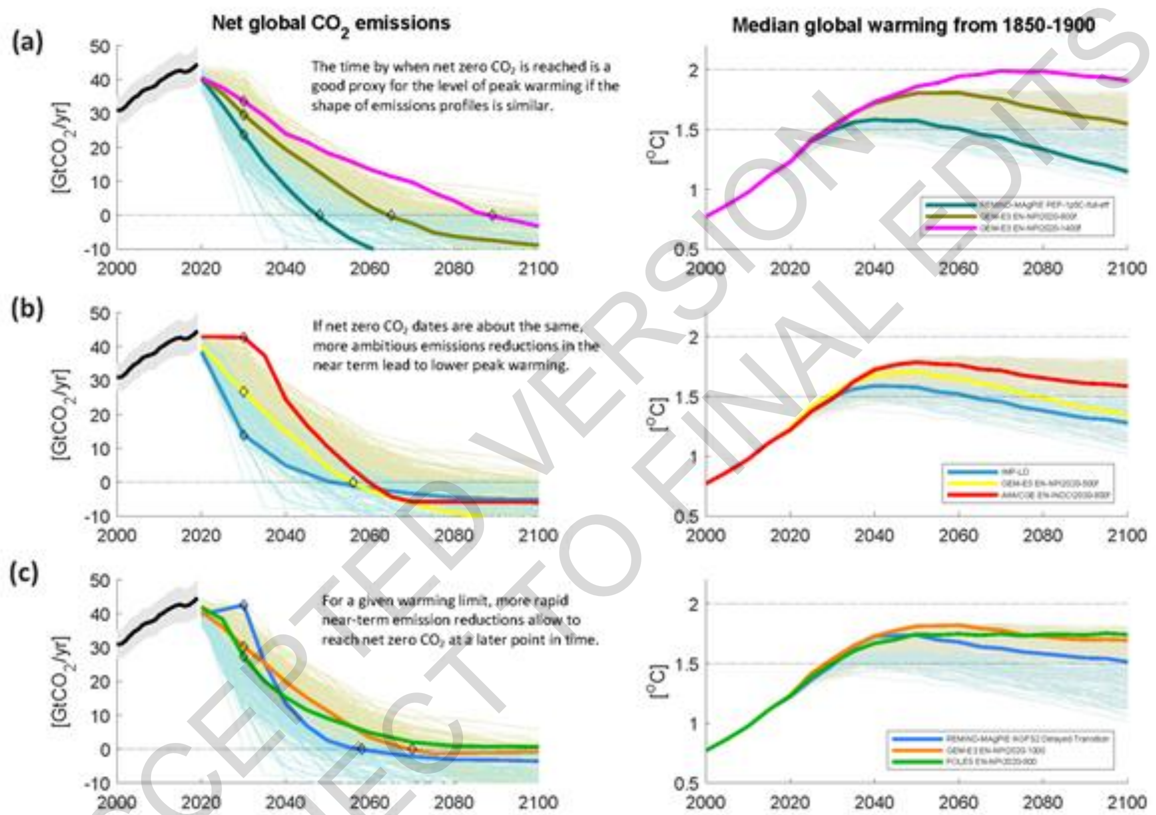
Limiting warming to 1.5°C or *likely* to 2°C requires deep, rapid, and sustained reductions of other greenhouse gases including methane alongside rapid reductions of CO_2 emissions to net zero. This ensures that the warming contributions from non-CO_2 forcing agents as well as from CO_2 emissions are both limited at low levels. WGI estimated remaining carbon budgets until the time of reaching net zero CO_2 emissions for a range of warming limits, taking into account historical CO_2 emissions and projections of the warming from non-CO_2 forcing agents (WGI AR6 Chapter 5.5, Cross-chapter box 3).

The earlier global net zero CO_2 emissions are reached, the lower the cumulative net amount of CO_2 emissions and human-induced global warming, all else being equal (Figure 1a in this Box)**.** For a given net zero date, a variation in the shape of the CO_2 emissions profile can lead to a variation in the cumulative net amount of CO_2 emissions until the time of net zero CO_2 and as a result to different peak warming levels. For example, cumulative net CO_2 emissions until the time of reaching net zero CO_2 will be smaller, and peak warming lower, if emissions are reduced steeply and then more slowly compared to reducing emissions slowly and then more steeply (Figure 1b in this Box).

Net zero CO_2 emissions are reached between 2050-2055 (2035-2070) in global emissions pathways limiting warming to 1.5°C with no or limited overshoot, and between 2070-2075 (2060-…) in pathways *likely* limiting warming to 2°C as reported in the AR6 scenario database (median five-year interval and 5th-95th percentile ranges)[3]. The variation of non-CO_2 emissions in 1.5-2°C pathways varies the available remaining carbon budget which can move the time of reaching net zero CO_2 in these pathways forward or backward[4]. The shape of the CO_2 emissions reduction profile

FOOTNOTE [3] 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_2 emissions during the 21st century. This is not inconsistent with the fundamental scientific requirement to reach net-zero CO_2 emissions for a stable climate, but reflects that in some pathways, concurrent reductions in non-CO_2 emissions temporarily compensate for on-going warming from CO_2 emissions. These would have to reach net-zero CO_2 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 CO2 by 2100.

FOOTNOTE [4] WGI Chapter 5.5 estimates a variation of the remaining carbon budget by ± 220 $GtCO_2$ due to variations of the non-CO_2 warming contribution in 1.5-2°C pathways. This translates to a shift of the timing of also affects the time of reaching net zero CO_2 (Figure 1c in this Box). Global emission pathways that more than halve CO_2 emissions from 2020 to 2030 can follow this rapid reduction by a more gradual decline towards net zero CO_2 and still limit warming to 1.5°C with no or limited overshoot, reaching the point of net zero after 2050. The literature since SR1.5 included a larger fraction of such pathways than were available at the time of SR1.5. This is the primary reason for the small backward shift in the median estimate of reaching global net zero CO_2 emissions in 1.5°C pathways collected in the AR6 scenario database compared to SR1.5. This does not mean that the world is assessed to have more time to rapidly reduce current emissions levels compared to SR1.5. The assessment of emissions reductions by 2030 and 2040 in pathways limiting warming to 1.5°C with no or limited overshoot has not changed substantially. It only means that the exact timing of reaching net zero CO_2 after a steep decline of CO_2 emissions until 2030 and 2040 can show some variation, and the SR1.5 median value of 2050 is still close to the middle of the current range (Figure 1c in this Box).



Cross-Chapter Box 3 Figure 1: Selected global CO_2 emissions trajectories with similar shape and different net zero CO_2 date (Panel a), different shape and similar net zero CO_2 date (Panel b), and similar peak warming, but varying shapes and net zero CO_2 dates (Panel c). Funnels show pathways limiting warming to 1.5°C with no or limited overshoot (light blue) and likely limiting warming to 2°C (beige). Historic CO_2 emissions from Chapter 2.2 (EDGAR v6).

Pathways coinciding with emissions levels projected from the implementation of current NDCs would result in substantially (>0.1°C) exceeding 1.5°C. They would have to reach net zero CO_2

net zero CO_2 by about ±10 years, assuming global CO_2 emissions decrease linearly from current levels of around 40 $GtCO_2$ to net zero.

around 5-10 years later[5] than in pathways with no or limited overshoot in order to reach the net negative emissions that would then be required to return warming to 1.5°C by 2100. Those high overshoot pathways have higher transient warming and higher reliance on net-negative CO_2 emissions towards the end of the 21st century. As they need to reach net zero CO_2 only a few years later, with 2030 CO_2 emission levels being around twice as high, they imply post-2030 CO_2 emissions reduction rates that are almost double that of pathways limiting warming to 1.5°C with no or limited overshoot (Section 3.5).

Pathways following emissions levels projected from the implementation of current NDCs until 2030 would have to reach net zero CO_2 around 10 years earlier[6] than cost-effective pathways to likely limit warming to 2°C. While cost-effective pathways take around 50-55 years to reach net zero CO_2 emissions, those pathways would only have 35-40 years left for transitioning to net zero CO_2 from 2030 onwards, close to the transition times that 1.5°C pathways are faced with today. Current CO_2 emissions and 2030 emission levels projected under the current NDCs are in a similar range**.** (3.5, 4.2)

Net zero GHG emissions

The amount of CO_2-equivalent emissions and the point when net zero GHG emissions are reached in multi-GHG emissions pathways depends on the choice of GHG emissions metric. Various GHG emission metrics are available for this purpose[7]. GWP100 is the most commonly used metric for reporting CO_2-equivalent emissions and is required for emissions reporting under the Rulebook of the Paris Agreement. (Cross-Chapter Box 2 in Chapter 2, Annex II section 9, Annex I)

For most choices of GHG emissions metric, reaching net zero GHG emissions requires net negative CO_2 emissions in order to balance residual CH_4, N_2O and F-gas emissions. Under foreseen technology developments, some CH_4, N_2O and F-gas emissions from, e.g., agriculture and industry will remain over the course of this century. Net negative CO_2 emissions will therefore be needed to balance these remaining non-CO_2 GHG emissions to obtain net zero GHG emissions at a point in time after net zero CO_2 has been reached in emissions pathways. Both the amount of net negative CO_2 emissions and the time lag to reaching net zero GHG depend on the choice of GHG emission metric.

Reaching net zero GHG emissions globally in terms of GWP100 leads to a reduction in global warming from an earlier peak. This is due to net negative CO_2 emissions balancing the GWP100-equivalent emissions of short lived GHG emissions, which by themselves do not contribute to further warming if sufficiently declining (Fuglestvedt et al. 2018; Rogelj et al. 2021). Hence, 1.5-2°C

FOOTNOTE [5] 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 [6] 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 CO2 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 95th percentile. (Chapter 3.3 Table 3.1.)

FOOTNOTE [7] Defining net zero GHG emissions for a basket of greenhouse gases (GHGs) relies on a metric to convert GHG emissions including methane (CH_4), nitrous oxide (N_2O), fluorinated gases (F-gases), and potentially other gases, to CO_2-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).

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

Global net zero GHG emissions measured in terms of GWP100 are reached between 2095-2100 (2055 - ...)[8] in emission pathways limiting warming to 1.5°C with no or limited overshoot (median and 5th-95th percentile)**.** Around 50% of pathways limiting warming to 1.5°C with no or limited overshoot and 70% of pathways limiting likely warming to 2°C do not reach net zero GHG emissions in terms of GWP100 before 2100. These pathways tend to show less reduction in warming after the peak than pathways that reach net zero GHG emissions. For the subset of pathways that reach net zero GHG emissions before 2100, including 90% of pathways that return warming to 1.5°C by 2100 after a high (>0.1°C) overshoot, the time lag between reaching net zero CO2 and net zero GHG is 11-14 (6-40) years and the amount of net negative CO2 emissions deployed to balance non-CO2 emissions at the time of net zero is -6 to -7 (-10 to -4) GtCO2 (range of medians and lowest 5th to highest 95 percentile across the four scenario classes that limit median warming to 2°C or lower). (section 3.3, Table 3.1)

Sectoral and regional aspects of net zero

The timing of net zero CO_2 or GHG emissions may differ across regions and sectors. Achieving net zero emissions globally implies that some sectors and regions must reach net zero CO_2 or GHG ahead of the time of global net zero CO_2 or GHG if others reach it later. Similarly, some sectors and regions would need to achieve net negative CO_2 or GHG emissions to compensate for continued emissions by other sectors and regions after the global net zero year. Differences in the timing to reach net zero emissions between sectors and regions depend on multiple factors, including the potential of countries and sectors to reduce GHG emissions and undertake carbon dioxide removal, the associated costs, and the availability of policy mechanisms to balance emissions and removals between sectors and countries (Fyson et al. 2020; Strefler et al. 2021a; van Soest et al. 2021b). A lack of such mechanisms could lead to higher global costs to reach net zero emissions globally, but less interdependencies and institutional needs (Fajardy and Mac Dowell 2020). Sectors will reach net zero CO_2 and GHG emissions at different times if they are aiming for such targets with sector-specific policies or as part of an economy-wide net zero emissions strategy integrating emissions reductions and removals across sectors. In the latter case, sectors with large potential for achieving net-negative emissions would go beyond net zero to balance residual emissions from sectors with low potential which in turn would take more time compared to the case of sector-specific action. Global pathways project global AFOLU emissions to reach global net zero CO_2 the earliest, around 2030-2035 in pathways likely to limit warming to 2°C and below, by rapid reduction of deforestation and enhancing carbon sinks on land, although net zero GHG emissions from global AFOLU are typically reached 30 years later, if at all. The ability of global AFOLU CO_2 emissions to reach net zero as early as in the 2030s in modelled pathways hinges on optimistic assumptions about the ability to establish global cost-effective mechanisms to balance emissions reductions and removals across regions and sectors. These assumptions have been challenged in the literature and the Special Report on Climate Change and Land (IPCC SRCCL).

The adoption and implementation of net zero CO_2 or GHG emission targets by countries and regions also depends on equity and capacity criteria. The Paris Agreement recognizes that peaking of emissions will occur later in developing countries (Article 4.1). Just transitions to net zero CO_2 or GHG could be expected to follow multiple pathways, in different contexts. Regions may decide about net zero pathways based on their consideration of potential for rapid transition to low-carbon development pathways, the capacity to design and implement those changes, and perceptions of equity within and across countries. Cost-effective pathways from global models have been shown to

FOOTNOTE [8] 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 -…

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

The accounting of anthropogenic carbon dioxide removal on land matters for the evaluation of net zero CO_2 and net zero GHG strategies. Due to the use of different approaches between national inventories and global models, the current net CO_2 emissions are lower by 5.5 $GtCO_2$, and cumulative net CO_2 emissions in modelled 1.5-2°C pathways would be lower by 104-170 GtCO2, if carbon dioxide removals on land are accounted based on national GHG inventories. National GHG inventories typically consider a much larger area of managed forest than global models, and on this area additionally consider the fluxes due to human-induced global environmental change (indirect effects) to be anthropogenic, while global models consider these fluxes to be natural. Both approaches capture the same land fluxes, only the accounting of anthropogenic vs. natural emission is different. Methods to convert estimates from global models to the accounting scheme of national GHG inventories will improve the use of emission pathways from global models as benchmarks against which collective progress is assessed. (7.2.2.5, Cross-Chapter Box 3 in this chapter)

Net zero CO_2 and carbon neutrality have different meanings in this assessment, as is the case for net zero GHG and GHG neutrality. They apply to different boundaries in the emissions and removals being considered. Net zero (GHG or CO_2) refers to emissions and removals under the direct control or territorial responsibility of the reporting entity. In contrast, (GHG or carbon) neutrality includes anthropogenic emissions and anthropogenic removals within and also those beyond the direct control or territorial responsibility of the reporting entity. At the global scale, net zero CO_2 and carbon neutrality are equivalent, as is the case for net zero GHG and GHG neutrality. The term "climate neutrality" is not used in this assessment because the concept of climate neutrality is diffuse, used differently by different communities, and not readily quantified.

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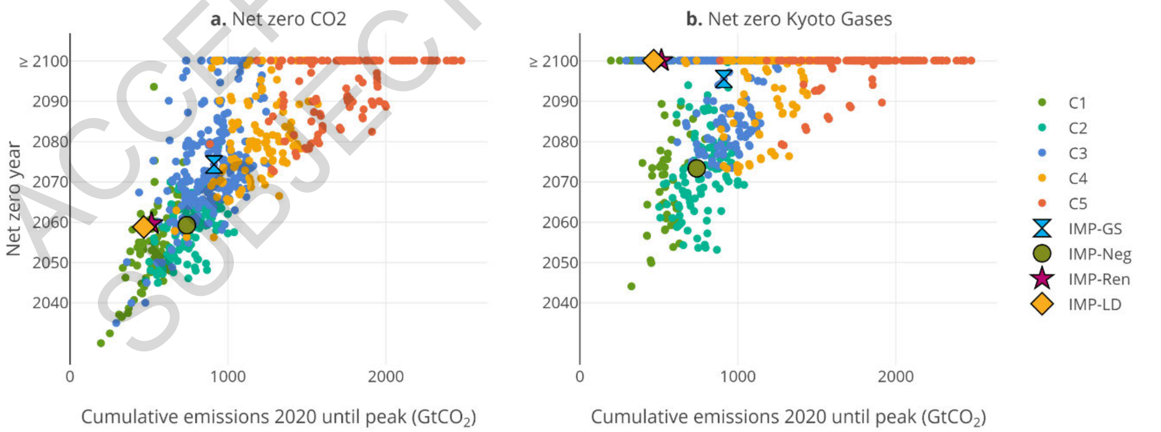

Figure 3.14: Net zero year for CO_2 and all GHGs (based on AR6 GWP-100) as a function of remaining carbon budget and temperature outcomes (not that stabilize (near) zero are also included in determining the net zero year)

Table 3.2 summarizes the key characteristics for all temperature categories in terms of cumulative CO_2 emissions, near-term emission reductions, and the years of peak emission and net zero CO_2 and GHG emissions. The table shows again that many pathways in the literature likely limit global warming to 2°C or limit warming to 1.5°C with limited overshoot compared to preindustrial levels.

Cumulative net CO_2 emissions from the year 2020 until the time of net zero CO_2 in pathways that limit warming to 1.5°C with no or limited overshoot are 510 (330-710) $GtCO_2$ and in pathways *likely* to limit warming to below 2.0°C 890 (640-1160) $GtCO_2$ (see also Cross-Chapter Box 3 in this chapter). Mitigation pathways *likely* to limit global warming to 2°C compared to pre-industrial levels are associated with net global GHG emissions of 40 (32–55) $GtCO_2$-eq yr^{-1} by 2030 and 20 (13-26) $GtCO_2$-eq yr^{-1} in 2050. These correspond to GHG emissions reductions of 21 (1-42) % by 2030, and 64 (53-77) % by 2050 relative to 2019 emission levels. Pathways that limit global warming to below 1.5°C with no or limited overshoot require a further acceleration in the pace of the transformation, with GHG emissions reductions of 43 (34–60) % by 2030 and 84 (74–98) % in 2050 relative to modelled 2019 emission levels. The likelihood of limiting warming to below 1.5°C with no or limited overshoot of the most stringent mitigation pathways in the literature (C1) has declined since SR1.5. This is because emissions have risen since 2010 by about 9 $GtCO_2$ yr^{-1}, resulting in relatively higher near-term emissions of the AR6 pathways by 2030 and slightly later dates for reaching net zero CO_2 emissions compared to SR1.5

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

Table 3.2 GHG, CO_2 emissions and warming characteristics of different mitigation pathways submitted to the AR6 scenarios database and as categorized in the climate assessment.

p50 (p5-p95) [0]	Global Mean Surface Air Temperature change		GHG emissions Gt CO_2-eq/yr			GHG emissions reductions from 2019 % [5]			Emissions milestones [6,7]				Cumulative CO_2 emissions Gt CO_2 [9]		Cumulative net-negative CO_2 emissions Gt CO_2	Temperature change 50% probability [10] °C		Likelihood of staying below (%) [11]			Time when specific temeprature levels are reached (with a 50% probability)		
Category [1, 2, 3, 4] [# pathways]	Category description	WG1 SSP & IPs alignment	2030	2040	2050	2030	2040	2050	Peak CO_2 emissions	Peak GHG emissions	net-zero CO_2 [% net-zero pathways]	net-zero GHGs [8] [% net-zero pathways]	2020 to netzero CO_2	2020-2100	year of net-zero CO_2 to 2100	at peak warming	2100	<1.5°C	<2.0°C	<3.0°C	1.5°C	2.0°C	3.0°C
C1 [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%] (...-...)
C2 [133]	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%] (...-...)
C3 [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%] (...-...)
C3a [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%] (...-...)
C3b [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%] (...-...)
C4 [159]	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%] (...-...)
C5 [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%] (...-...)
C6 [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%] (...-...)
C7 [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)
C8 [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)

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 areC3 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 CO2) 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_2 & 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 CO2-equivalent factors. For each scenario, a minimum of native reporting of CO2, CH4, and N2O 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 CO2 emissions of the pathways are harmonized to the 2015 CO_2 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.

3.3.2.4 Mitigation strategies

Detailed sectoral implications are discussed in Section 3.4 and Chapters 5-11 (see also Table 3.3). The stringency of climate policy has clear implications for mitigation action (Figure 3.15). There are a number of important commonalities of pathways likely limiting warming to 2C and below: for instance, they all rely on significant improvement of energy efficiency, rapid decarbonisation of supply and, many of them, CDR (in energy supply or AFOLU), either in terms of net negative emissions or to compensate residual emissions. Still, there are also important differences and the (IMPs) show how different choices can steer the system into alternative directions with different combinations of response options. For decarbonisation of energy supply many options exist, including CCS, nuclear power, and renewables (see Chapter 6). In the majority of the scenarios reaching low greenhouse targets, a considerable amount of CCS is applied (panel d). The share of renewables is around 30-70% in the scenarios reaching a global average temperature change of likely below 2ºC and clearly above 40% for scenarios reaching 1.5ºC (panel c). Scenarios have been published with 100% renewable energy systems even at a global scale, partly reflecting the rapid progress made for these technologies in the last decade (Breyer and Jefferson 2020; Creutzig et al. 2017; Jacobson et al. 2018). These scenarios do not show in the graph due to a lack of information from non-energy sources. There is a debate in the literature on whether it is possible to achieve a 100% renewable energy system by 2050 (Brook et al. 2018). This critically depends on assumptions made on future system integration, system flexibility, storage options, consequences for material demand and the ability to supply high-temperature functions and specific mobility functions with renewable energy. The range of studies published showing 100% renewable energy systems show that it is possible to design such systems in the context of energy system models (Lehtveer and Hedenus 2015a,b; Hong et al. 2014a,b; Zappa et al. 2019; Pfenninger and Keirstead 2015; Sepulveda et al. 2018; IEA 2021b) (see also Box 6.6 in Chapter 6 on 100% renewables in net zero CO_2 systems). Panel e and f, finally, show the contribution of CDR – both in terms of net negative emissions and gross CDR. The contribution of total CDR obviously exceeds the net negative emissions. It should be noted that while a majority of scenarios relies on net negative emissions to reach stringent mitigation goals – this is not the case for all of them.

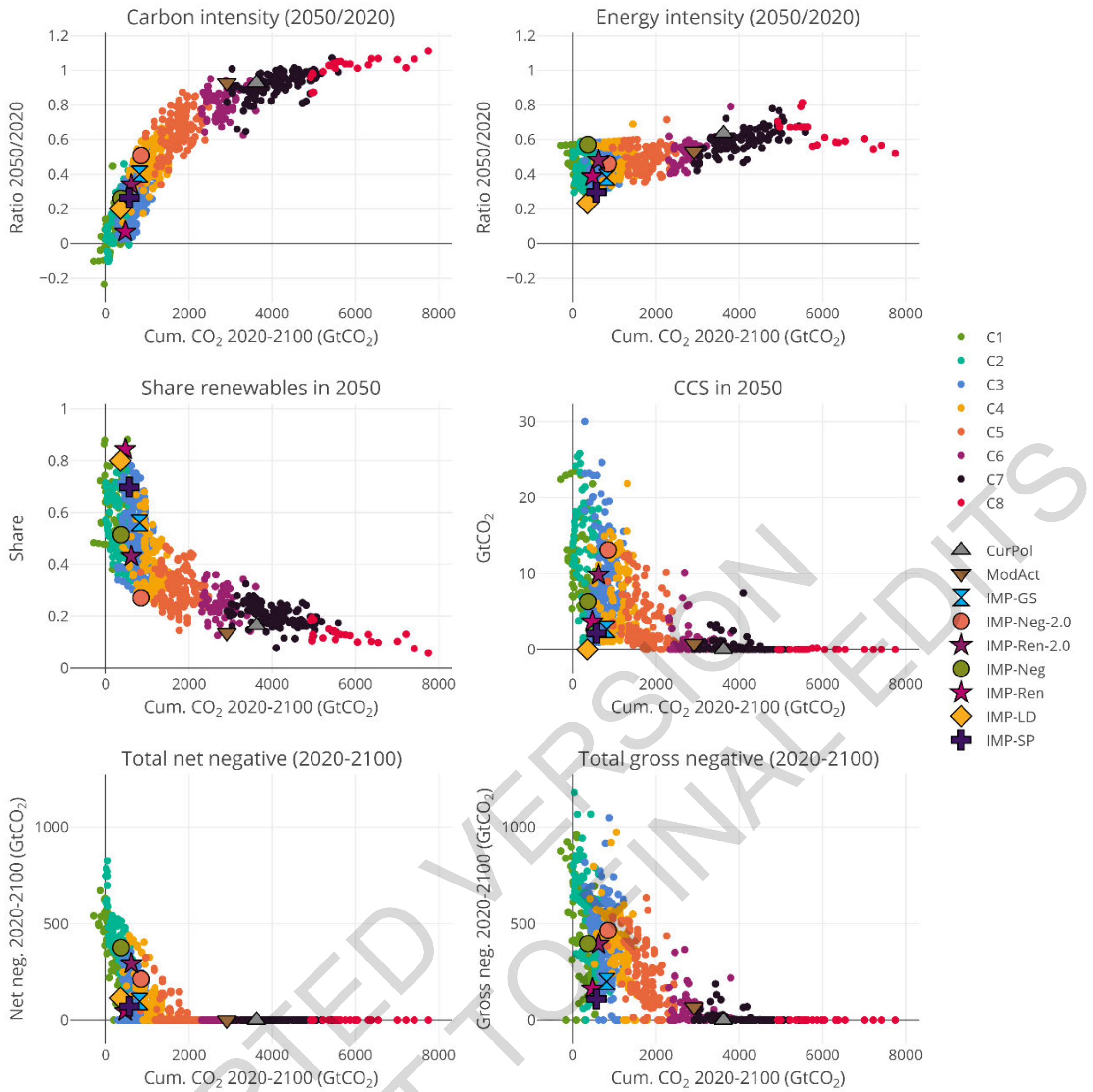

Figure 3.15: Characteristics of scenarios as a function of the remaining carbon budget (mean decarbonisation rate is shown as the average reduction in the period 2010-2050 divided by 2010 emissions). The categories C1-C7 are explained in Table 3.1

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

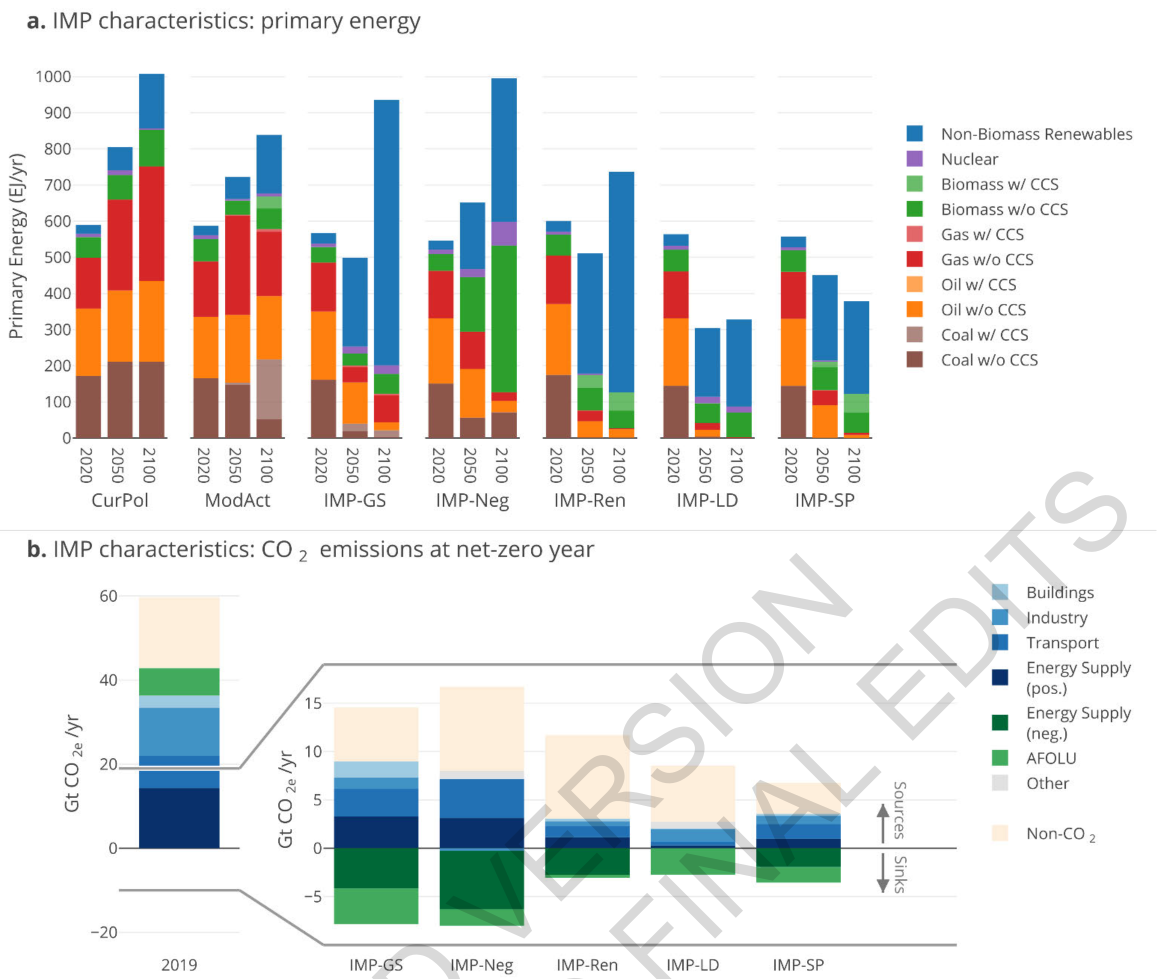

Figure 3.16: Primary energy use and net emissions at net zero year for the different IMPS

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

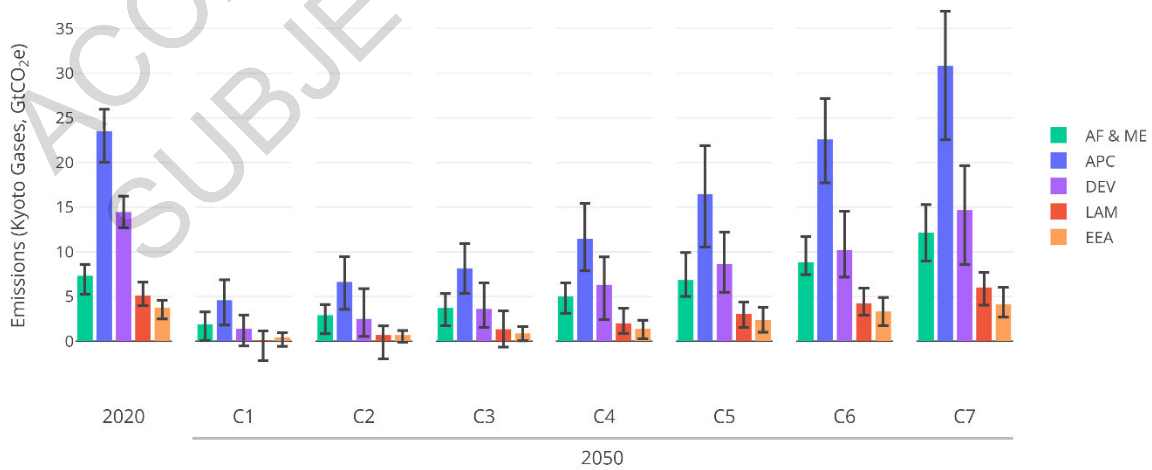

Figure 3.17, the share of the latter regions will further increase to about 70% by 2050. In the scenarios in the literature, emissions are typically almost equally reduced across the regions.

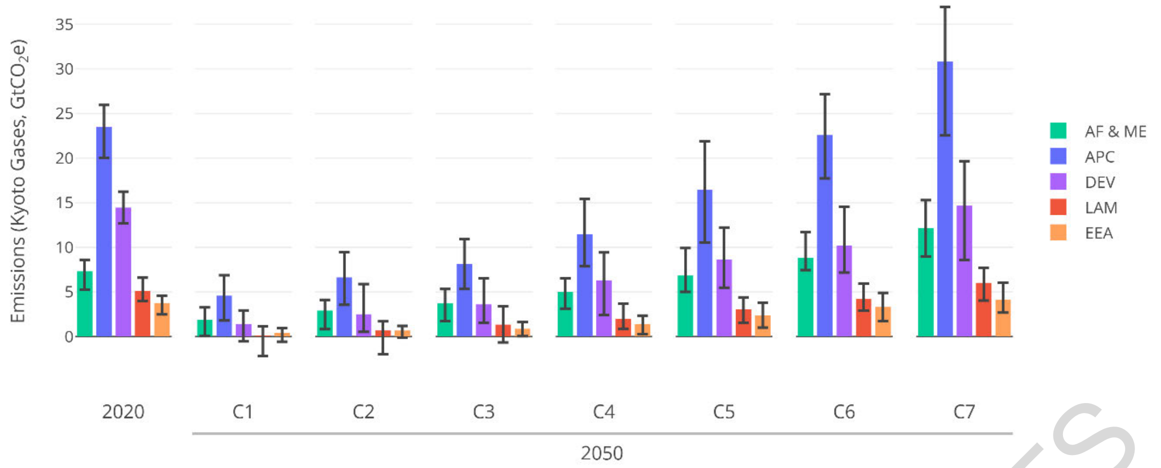

Figure 3.17[9]: Emissions by region (including 5-95th percentile range)

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 $GtCO_2$ for 17th-83rd 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_2 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_2 fertilization. On the one hand, elevated CO_2 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[9] 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.

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

In summary, a limited number of studies quantify the impact of climate on emissions pathways. The most important impact in energy systems might be through the impact on demand, although climate change could also impact renewable mitigation potential -certainly at the local and regional scale. Climate change might be more important for land-use related mitigation measures, including afforestation, bioenergy and nature-based solutions. The net effect of changes in climate and CO_2 fertilization are uncertain but could be substantial (see also Chapter 7).

3.4 Integrating sectoral analysis into systems transformations

This section describes the role of sectors in long-term emissions pathways (see Table 3.3). We discuss both sectoral aspects of IAM pathways and some insights from sectoral studies. Sectoral studies typically include more detail and additional mitigation options compared to IAMs. However, sectoral studies miss potential feedbacks and cross-sectoral linkages that are captured by IAMs. Additionally, since IAMs include all emissions sources, these models can be used to identify pathways to a particular climate goals. In such pathways, emissions are balanced across sectors typically based on relative marginal abatement costs; as a result, some sectors are sources and some are sinks at the time of net zero CO_2 emissions. For these reasons, the mitigation observed in each sector in an IAM may differ from the potential in sectoral studies. Given the strengths and limitations of each type of model, IAMs and sectoral models are complementary, providing different perspectives.

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_2, 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[1]	Residential and commercial buildings, other non-specified[2]	Chapter 9
3.4.4	Transportation[1]	Road, rail, aviation, and shipping	Chapter 10
3.4.5	Industry[1]	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

[1] Direct energy use and direct emissions only; emissions do not include those associated with energy production

[2] Other non-specified fuel use, including military. Some models report this category in the buildings sector, while others report it in the "Other" sector

3.4.1 Cross-sector linkages

3.4.1.1 Demand and supply strategies

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

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

Figure 3.18: Indicators of demand and supply-side mitigation in the Illustrative Pathways (lines) and the 5-95% range of Reference, 1.5°C and 2°C scenarios (shaded areas). shows indicators of supply- and demand-side mitigation in the IMPs, as well as the range across the database. Two of these IMPs (***SP***, ***LD***) show strong reductions in energy demand, resulting in less reliance on bioenergy and limited CDR from energy supply. In contrast, ***Neg*** has higher energy demand, depending more on bioenergy and net negative CO_2 emissions from energy supply.

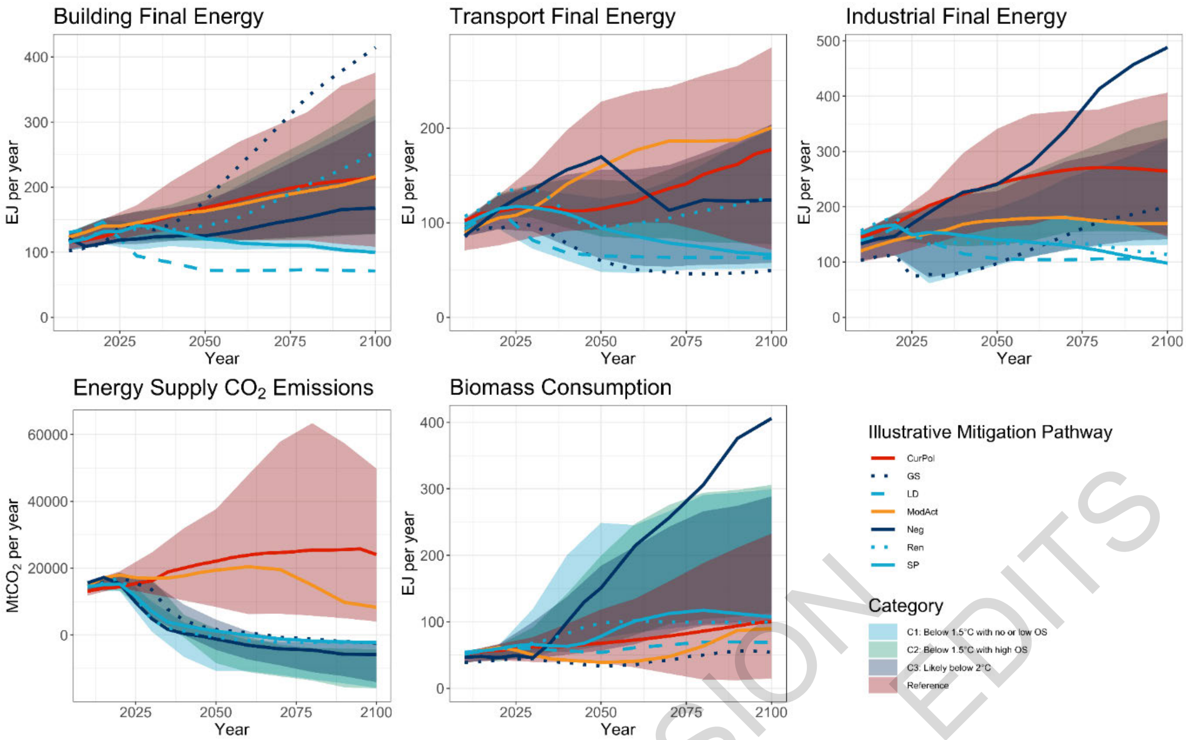

Figure 3.18: Indicators of demand and supply-side mitigation in the Illustrative Pathways (lines) and the 5-95% range of Reference, 1.5°C and 2°C scenarios (shaded areas).

3.4.1.2 Sectoral emissions strategies and the timing of net zero

Mitigation pathways show differences in the timing of decarbonization (Figure 3.20) and the timing of net zero (Figure 3.19) across sectors and regions (*high confidence*); the timing in a given sector depends on the cost of abatement in it, the availability of CDR options, the scenario design, near-term emissions levels, and the amount of non-CO_2 abatement (Yeh et al. 2017; Emmerling et al. 2019; Rogelj et al. 2019a,b; Johansson et al. 2020; van Soest et al. 2021b; Ou et al. 2021; Azevedo et al. 2021) (Cross-Chapter Box 3 in this chapter). However, delaying emissions reductions, or more limited emissions reductions in one sector or region, involves compensating reductions in other sectors or regions if warming is to be limited *(high confidence)* (Rochedo et al. 2018; Price and Keppo 2017; Grubler et al. 2018; van Soest et al. 2021b).

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) [0]	Global Mean Surface Air Temperature change		Low-carbon share of Primary Energy [3,4] [%] 2020 = 16 (12-18)			CO_2 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)		
Category [1, 2] [# pathways]	Category description	WG1 SSP & IPs alignment	2030	2050	2100	2030	2050	2100	2030	2050	2100	2030	2050	2100	2030	2050	2100
C1 [97]	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)
C2 [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)
C3 [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)
C4 [159]	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 (450-796)	76 (71-87)	45 (39-65)	22 (19-41)	23 (19-28)	35 (23-44)	56 (44-69)
C5 [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)
C6 [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)
C7 [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)
C8 [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 (504-856)	941 (692-1136)	89 (88-92)	73 (64-79)	47 (25-51)	26 (22-30)	31 (28-35)	43 (35-50)

p50 (p5-p95) [0]	CO_2 intensity of electricity [Mt CO_2/ TWh] 2020 = 469 (419-538)			Non-energy GHG emissions [Gt CO_2-eq] 2020 = 18 (15-21)			Fossil CCS (2100) [Gt CO_2] 2020 = 0 (0-0)				CDR (2100) [Gt CO_2] 2020 = 0 (0-4)			
Category [1, 2] [# pathways]	2030	2050	2100	2030	2050	2100	2030	2050	2100	2020-2100	2030	2050	2100	2020-2100
C1 [97]	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)
C2 [133]	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)
C3 [311]	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)
C4 [159]	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)
C5 [212]	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)
C6 [97]	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)
C7 [164]	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)
C8 [29]	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)

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.

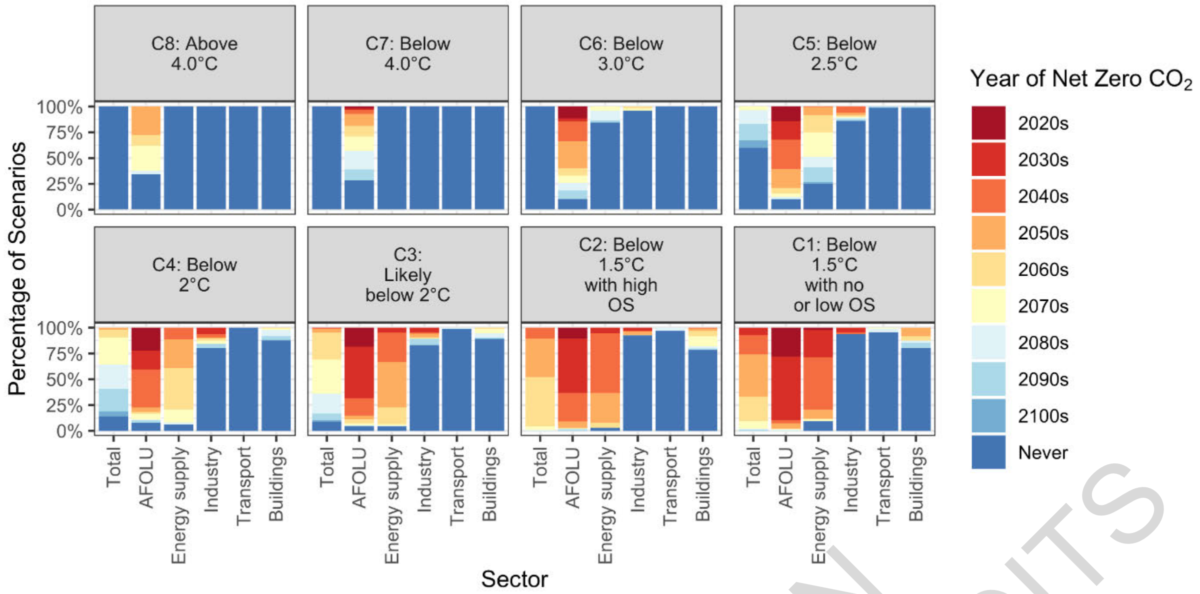

Figure 3.19: Decade in which sectoral CO_2 emissions first reach net negative values. Each panel is a different temperature level. The colours indicate the decade in which CO_2 emissions go negative; the y-axis indicates the share of scenarios achieving net zero in that decade. Only scenarios that pass 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_2 emissions, emissions in some sectors are positive and some negative. In cost-effective mitigation pathways, the energy supply sector typically reaches net zero CO_2 before the economy as a whole, while the demand sectors reach net zero CO_2 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_2 emissions from transport, industry, and buildings are positive, and non-CO_2 GHG emissions are also positive at the time of global net zero CO_2 emissions (Figure 3.20).

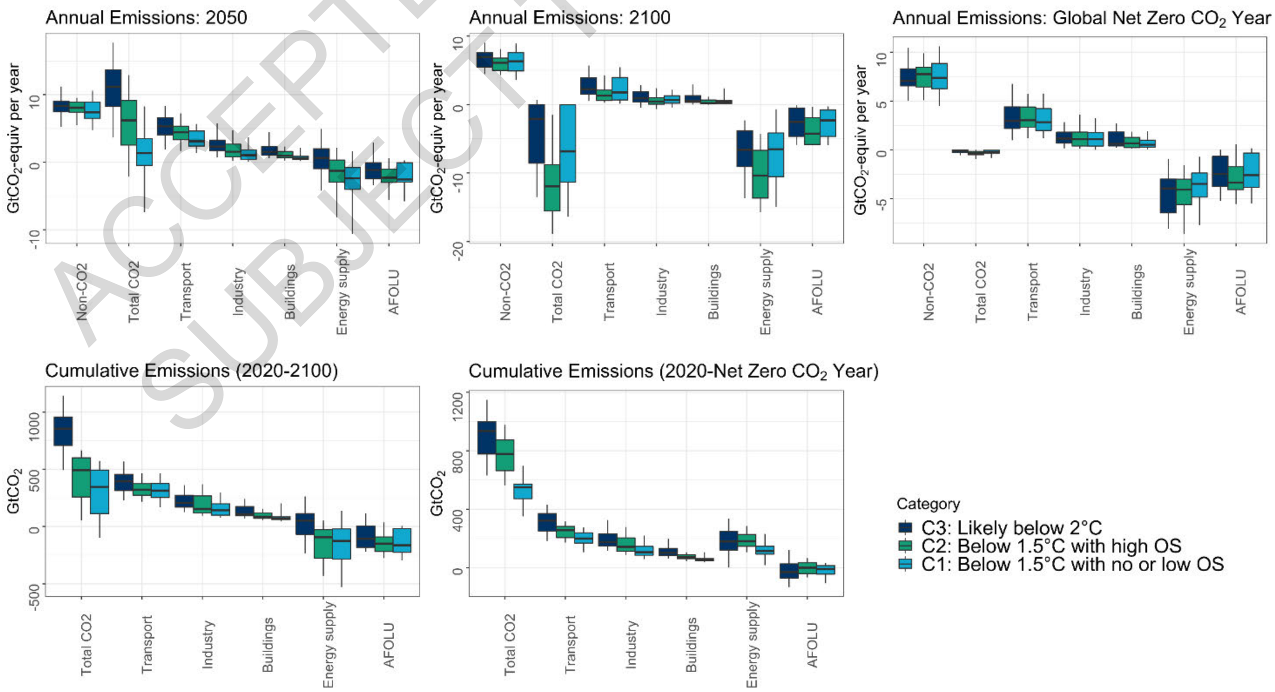

Figure 3.20: Greenhouse gas emissions, including CO_2 emissions by sector and total non-CO_2 GHGs in 2050 (top left), 2100 (top middle), year of global net zero CO_2 (top right), cumulative CO_2 emissions from

2020-2100 (bottom left), and cumulative CO_2 emissions from 2020 until the year of net zero CO_2 for scenarios that limit warming to below 2°C. Scenarios are grouped by their temperature category. "Industry" includes CO_2 emissions associated with industrial energy use only; sectors shown in this figure do not necessarily sum to total CO_2. In this, and other figures in Section 3.4, unless stated otherwise, only scenarios that pass the vetting criteria are included (see Section 3.2). Boxes indicate the interquartile range, the median is shown with a horizontal black line, while vertical lines show the 5 to 95% interval.

So, while pathways indicate some flexibility in emissions reductions across sectors, all pathways involve substantial CO_2 emissions reductions in all sectors and regions (*high confidence*) (Rogelj et al. 2018a,b; Luderer et al. 2018; Méjean et al. 2019; Azevedo et al. 2021). Projected CO_2 emissions reductions between 2019 and 2050 in 1.5°C pathways with no or limited overshoot are around 77% for energy demand, with a 5-95% range of 31 to 96%,[10] 115% for energy supply (90 to 167%), and 148% for AFOLU (94 to 387%). In likely 2°C pathways, projected CO_2 emissions are reduced between 2019 and 2050 by around 49% for energy demand, 97% for energy supply, and 136% for AFOLU (see also 3.4.2-3.4.6). Almost 75% of GHG reductions at the time of net zero GHG are from the energy system, 13% are from AFOLU CO_2, and 13% from non-CO_2 (Figure 3.21). These reductions are achieved through a variety of sectoral strategies, illustrated in Figure 3.21 (right panel), and described in Sections 3.4.2 to 3.4.7; the primary strategies include declines in fossil energy, increases in low carbon energy use, and CDR to address residual emissions.

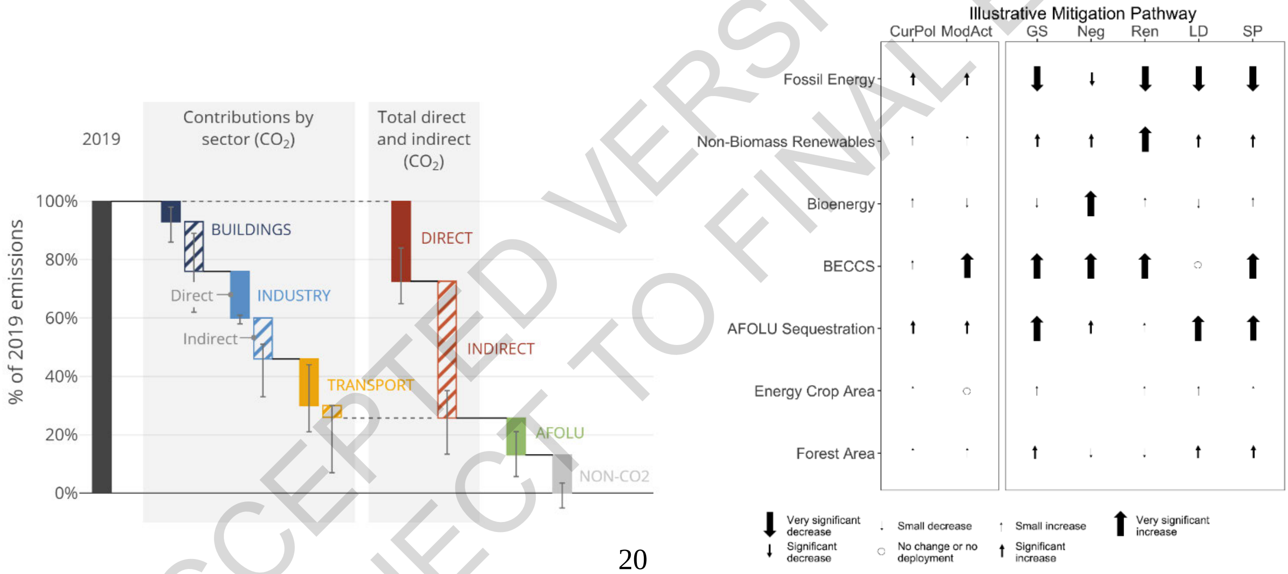

Figure 3.21: Left panel: Greenhouse gas emissions reductions from 2019 by sector at the year of net zero GHG for all scenarios that reach net zero GHG. Emissions reductions by sector for direct (demand) and indirect (upstream supply) are shown as the percent of total GHG reductions.
Right panel: key indicators in 2050 for the IMPs. Definitions of significant and very significant are defined relative to 2019 and vary between indicators, as follows: fossil energy (significant >10%, very significant >50%), renewables (>150 EJ yr^{-1}, >200 EJ yr^{-1}), bioenergy (>100%, >200%), BECCS (>2.0 $GtCO2\ yr^{-1}$, >3.5 $GtCO2\ yr^{-1}$), AFOLU (>100% decline, >130%), energy crops (>150 million ha, >400), forest (>5% increase, >15%).

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

FOOTNOTE [10] Unless otherwise specified, the values in parentheses in Section 3.4 from this point forward indicate the 5-95% range.

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

3.4.1.3 Linkages among sectors

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

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

Pathways with very high biomass production for energy use typically include very high carbon prices in the energy system (Popp et al. 2017; Rogelj et al. 2018b), little or no land policy (Calvin et al. 2014b), a high discount rate (Emmerling et al. 2019), and limited non-BECCS CDR options (e.g., afforestation, DACCS) (Fuhrman et al. 2020; Realmonte et al. 2019; Chen and Tavoni 2013; Marcucci et al. 2017; Calvin et al. 2014b). Higher levels of bioenergy consumption are likely to involve trade-offs with mitigation in other sectors, notably in construction (i.e., wood for material and structural products) and AFOLU (carbon stocks and future carbon sequestration), as well as trade-offs with sustainability (Section 3.7) and feasibility concerns (Section 3.8). Not all of these trade-offs are fully represented in all IAMs. Based on sectoral studies, the technical potential for bioenergy, when constraints for food security and environmental considerations are included, are 5-50 and 50-250 EJ yr^{-1} in 2050 for residues and dedicated biomass production systems, respectively (Chapter 7). Bioenergy deployment in IAMs is within the range of these potentials, with between 75 and 248 EJ yr^{-1} in 2050 in pathways that limit warming to 1.5°C with no or limited overshoot. Finally, IAMs do not include all potential feedstock and management practices, and have limited representation of institutions, governance, and local context (Butnar et al. 2020; Brown et al. 2019; Calvin et al. 2021).

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

3.4.2 Energy supply

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

In scenarios likely to limit warming to 2°C and below, transition of the energy supply sector to a low or no carbon system is rapid (Rogelj et al. 2016, 2018b; Luderer et al. 2018; Grubler et al. 2018; van Vuuren et al. 2018). CO_2 emissions from energy supply reach net zero around 2041 (2033 to 2057) in pathways limiting warming to below 1.5°C with no or limited overshoot and around 2053 (2040 to 2066) in pathways likely to limit warming to 2°C. Emissions reductions continue, with emissions reaching -7.1 $GtCO_2$ per year (-15 to -2.3 $GtCO_2$ per year) in 2100 in all pathways likely to limit warming to 2°C and below.

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

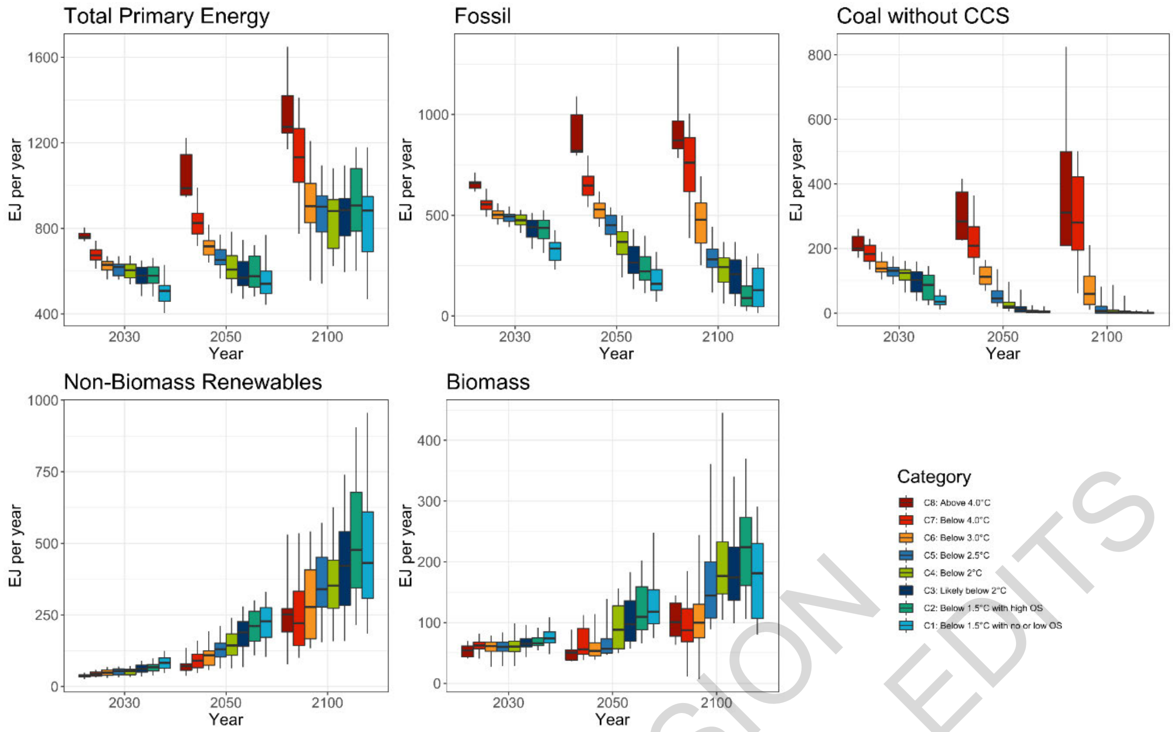

Figure 3.22 Primary energy consumption across scenarios: total primary energy (top left), fossil fuels (top middle), coal without CCS (top right), non-biomass renewables (bottom left), and biomass (bottom middle). Scenarios are grouped by their temperature category. Primary energy is reported in direct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

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

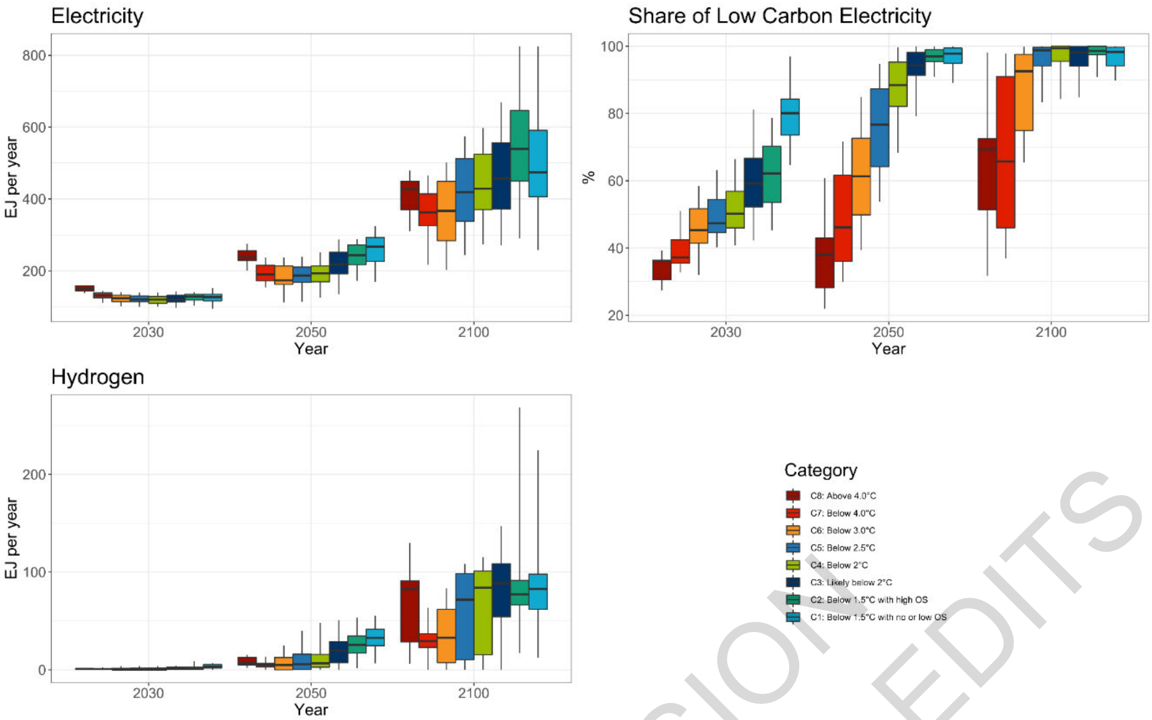

Figure 3.23: Electricity (top left), share of low carbon electricity (top right), and hydrogen (bottom left) production across all scenarios, grouped by the categories introduced in section 3.2. Low carbon includes non-biomass renewables, biomass, nuclear, and CCS.

3.4.3 Buildings

Global final energy use in the building sector increases in all pathways as a result of population growth and increasing affluence (Figure 3.24). There is very little difference in final energy intensity for the buildings sector across scenarios. Direct CO2 emissions from the buildings sector vary more widely across temperature stabilization levels than energy consumption. In 2100, scenarios above 3ºC [C7-C8] still show an increase of CO2 emissions from buildings around 29% above 2019, while all scenarios likely to limit warming to 2ºC 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.

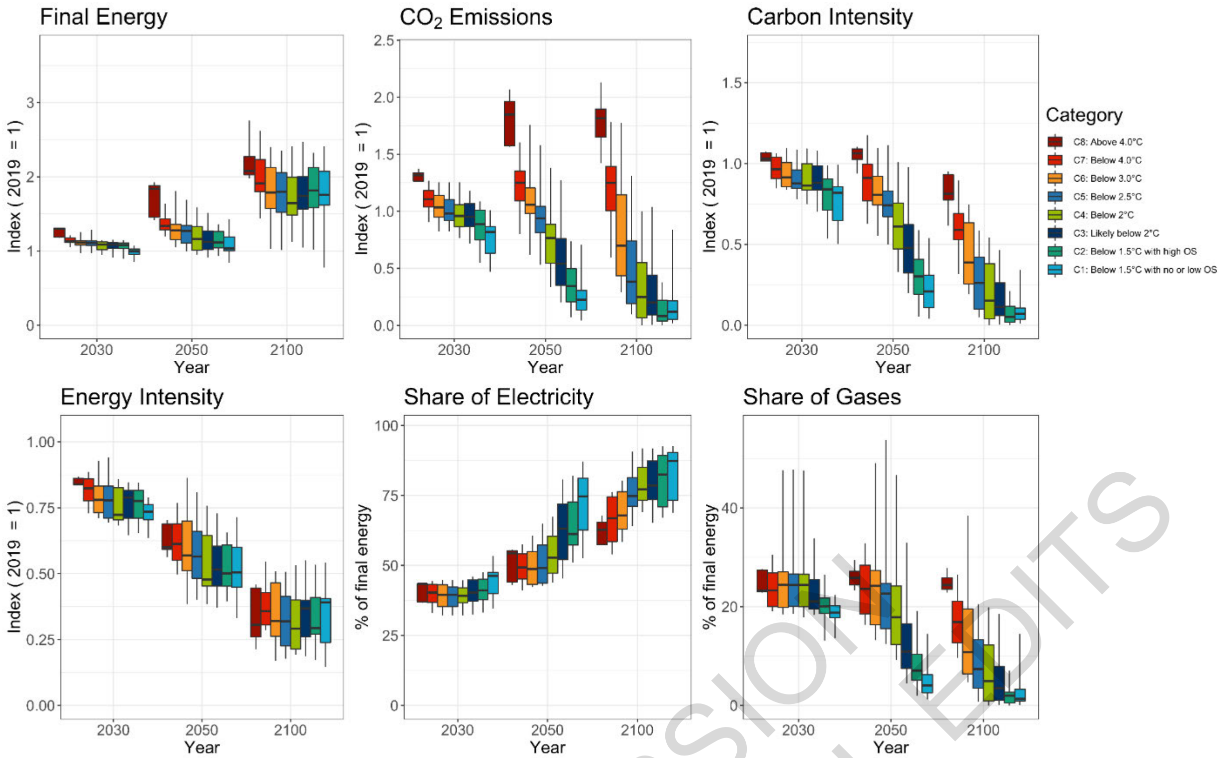

Figure 3.24: Buildings final energy (top left), CO_2 emissions (top middle), carbon intensity (top right), energy intensity (bottom left), share of final energy from electricity (bottom middle), and share of final energy from gases (bottom right). Energy intensity is final energy per unit of GDP. Carbon intensity is CO_2 emissions per EJ of final energy. The first four indicators are indexed to 2019[11], 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 2ºC 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 (Daioglou 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 (Daioglou 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 [11] 2019 values are from model results and interpolated from other years when not directly reported.

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

3.4.4 Transport

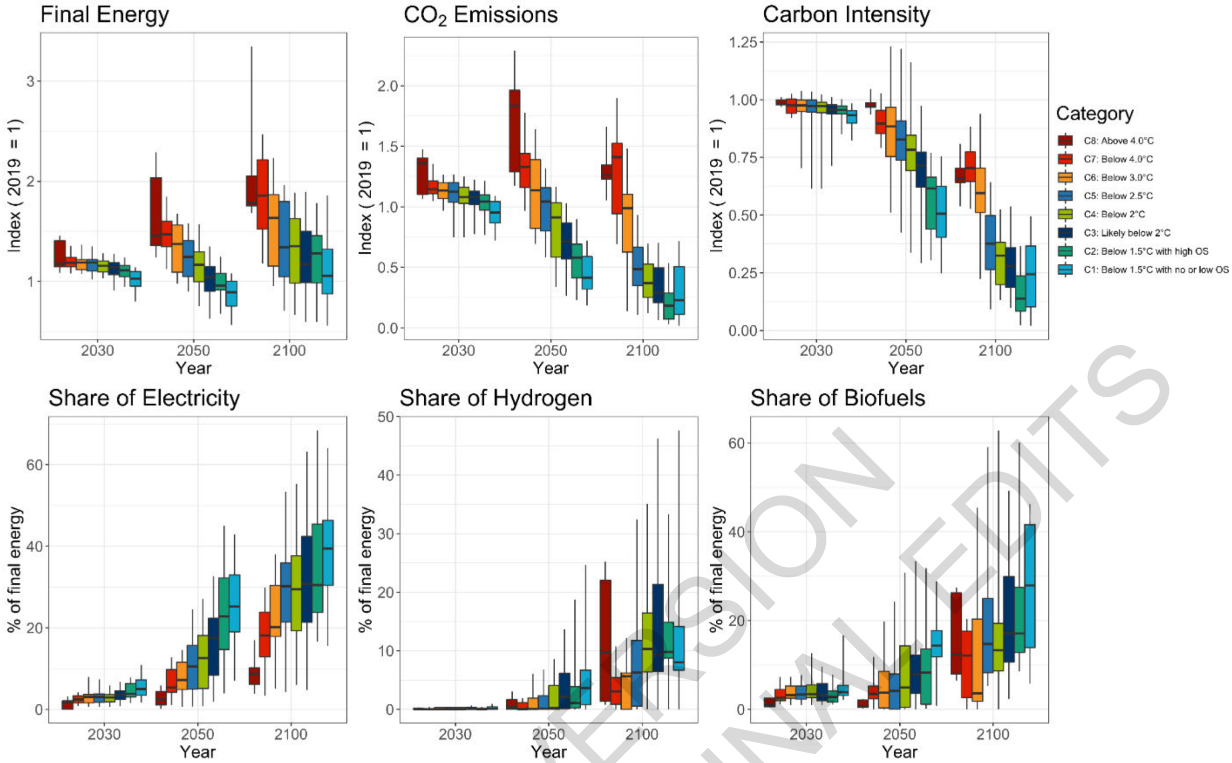

Figure 3.25: Transport final energy (top left), CO_2 emissions (top middle), carbon intensity (top right), and share of final energy from electricity (bottom left), hydrogen (bottom middle), and biofuels (bottom right). See Chapter 10 for a discussion of energy intensity. Carbon intensity is CO_2 emissions per EJ of final energy. The first three indicators are indexed to 2019[12], where values less than 1 indicate a reduction.

Reference scenarios show growth in transport demand, particularly in aviation and freight (Yeh et al. 2017; Sharmina et al. 2020; Müller-Casseres et al. 2021b). Energy consumption continues to be dominated by fossil fuels in reference scenarios, with some increases in electrification (Edelenbosch et al. 2020; Yeh et al. 2017). CO_2 emissions from transport increase for most models in reference scenarios (Yeh et al. 2017; Edelenbosch et al. 2020).

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

FOOTNOTE [12] 2019 values are from model results and interpolated from other years when not directly reported.

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

Across all IAM scenarios assessed, final energy demand for transport continues to grow, including in many stringent mitigation pathways (Figure 3.25). The carbon intensity of energy declines substantially by 2100 in likely 2°C and below scenarios, leading to substantial declines in transport sector CO2 emissions with increased electrification of the transport system (Figure 3.23).
The transport sector has more detail than other sectors in many IAMs (Edelenbosch et al. 2020); however, there is considerable variation across models. Some models (e.g., GCAM, IMAGE, MESSAGE-GLOBIOM) represent different transport modes with endogenous shifts across modes as a function of income, price, and modal speed (Edelenbosch et al. 2020).[13] However, IAMs, including those with detailed transport, exclude several supply-side (e.g., synthetic fuels) and demand-side (e.g., behaviour change, reduced shipping, telework and automation) mitigation options (Davis et al. 2018; Köhler et al. 2020; Mittal et al. 2017; Gota et al. 2019; Wilson et al. 2019; Creutzig et al. 2016; Sharmina et al. 2020; Pietzcker et al. 2014; Lefèvre et al. 2021; Müller-Casseres et al. 2021a,b).

As a result of these missing options and differences in how mitigation is implemented, IAMs tend to show less mitigation than the potential from national transport/energy models (Wachsmuth and Duscha 2019; Gota et al. 2019; Yeh et al. 2017; Edelenbosch et al. 2020). For the transport sector as a whole, studies suggest a mitigation potential of 4-5 $GtCO_2$ per year in 2030 (Edelenbosch et al. 2020) with complete decarbonization possible by 2050 (Gota et al. 2019; Wachsmuth and Duscha 2019). However, in the scenarios assessed in this chapter that limit warming to below 1.5°C with no or limited overshoot, transport sector CO_2 emissions are reduced by only 59% (28% to 81%) in 2050 compared to 2015. IAM pathways also show less electrification than the potential from other studies; pathways that limit warming to below 1.5°C with no or limited overshoot show a median of 25% (7 to 43%) of final energy from electricity in 2050, while the IEA NZE scenario includes 45% (IEA 2021a).

FOOTNOTE [13] Some of these models are treated as global transport energy sectoral models (GTEMs) in Chapter 10.

3.4.5 Industry

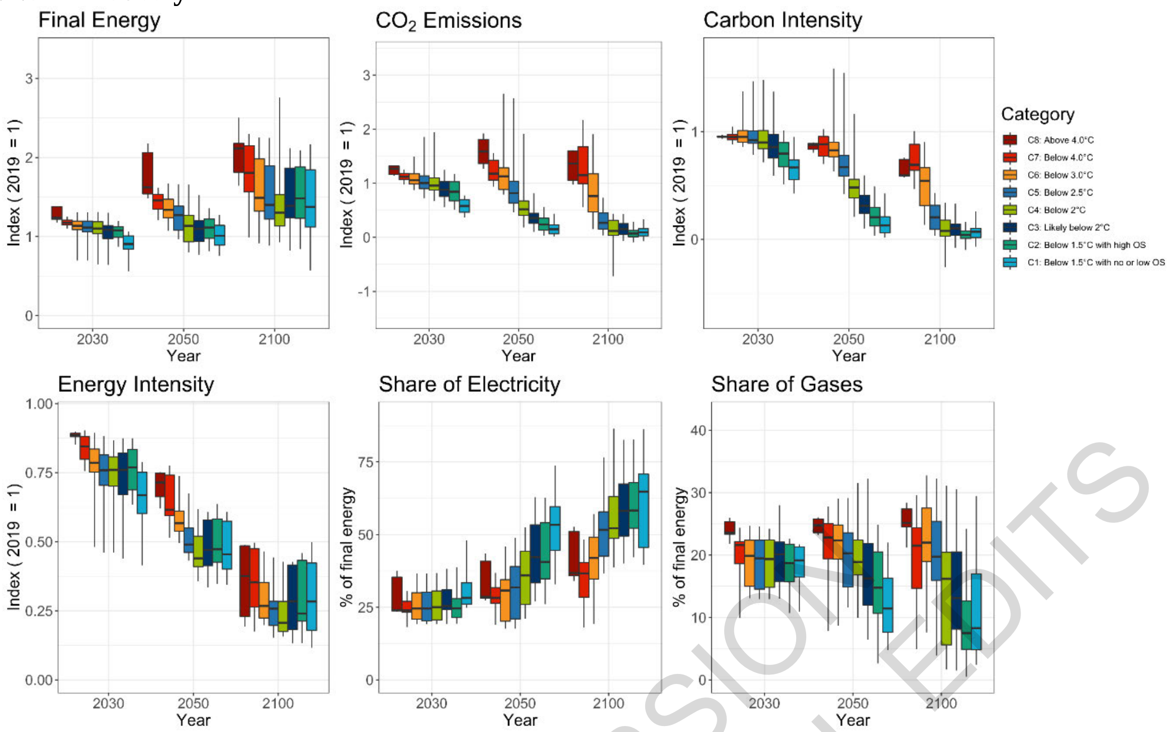

Figure 3.26: Industrial final energy, including feedstocks (top left), CO_2 emissions (top middle), carbon intensity (top right), energy intensity (bottom left), share of final energy from electricity (bottom middle), and share of final energy from gases (bottom right). Energy intensity is final energy per unit of GDP. Carbon intensity is CO_2 emissions per EJ of final energy. The first four indicators are indexed to 2019,[14] where values less than 1 indicate a reduction. Industrial sector CO_2 emissions include fuel combustion emissions only.

Reference scenarios show declines in energy intensity, but increases in final energy use in the industrial sector (Edelenbosch et al. 2017b). These scenarios show increases in CO_2 emissions both for the total industrial sector (Edelenbosch et al. 2020; Luderer et al. 2018; Edelenbosch et al. 2017b) and individual subsectors like cement and iron and steel (van Ruijven et al. 2016; van Sluisveld et al. 2021) or chemicals (Daioglou et al. 2014; van Sluisveld et al. 2021).

In mitigation pathways, CO_2 emissions reductions are achieved through a combination of energy savings (via energy efficiency improvements and energy conservation), structural change, fuel switching, and decarbonization of fuels (Grubler et al. 2018; Luderer et al. 2018; Edelenbosch et al. 2017b, 2020). Mitigation pathways show reductions in final energy for industry compared to the baseline (Edelenbosch et al. 2017b; Luderer et al. 2018; Edelenbosch et al. 2020) and reductions in the carbon intensity of the industrial sector through both fuel switching and the use of CCS (Paltsev et al. 2021; Luderer et al. 2018; Edelenbosch et al. 2017b, 2020; van Ruijven et al. 2016; van Sluisveld et al. 2021). The mitigation potential differs depending on the industrial subsector and the availability of CCS, with larger potential reductions in the steel sector (van Ruijven et al. 2016) and cement industry (Sanjuán et al. 2020) than in the chemicals sector (Daioglou et al. 2014). Many scenarios, including stringent mitigation scenarios, show continued growth in final energy; however, the carbon intensity of energy declines in all mitigation scenarios (Figure 3.26).

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

FOOTNOTE [14] 2019 values are from model results and interpolated from other years when not directly reported.

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

Sectoral studies indicate a large mitigation potential in the industrial sector by 2050, including the potential for net zero CO_2 emissions for steel, plastics, ammonia, and cement (Section 11.4.1). Detailed industry sector pathways show emissions reductions between 39 and 94% by mid-century compared to present day[15] (Section 11.4.2) and a substantial increase in direct electrification (IEA 2021a). IAMs show comparable mitigation potential to sectoral studies with median reductions in CO_2 emissions between 2019 and 2050 of 70% in scenarios likely to limit warming to 2°C and below and a maximum reduction of 96% (Figure 3.26). Some differences between IAMs and sectoral models can be attributed to differences in technology availability, with IAMs sometimes including more technologies (van Ruijven et al. 2016) and sometimes less (Sharmina et al. 2020). Figure 3.27: Reduction in AFOLU GHG emissions from 2019. The AFOLU CO_2 estimates in this figure are not necessarily comparable with country GHG inventories (see Chapter 7).

3.4.6 Agriculture, Forestry and Other Land Use (AFOLU)

Mitigation pathways show substantial reductions in CO_2 emissions, but more modest reductions in AFOLU CH_4 and N_2O emissions (*high confidence*) (Popp et al. 2017; Roe et al. 2019; Reisinger et al. 2021) (Figure 3.27). Pathways limiting warming to likely 2°C or below are projected to reach net zero CO_2 emissions in the AFOLU sector around 2033 (2024-2060); however AFOLU CH_4 and N_2O emissions remain positive in all pathways (Figure 3.27). While IAMs include many land-based mitigation options, these models exclude several options with large mitigation potential, such as biochar, agroforestry, restoration/avoided conversion of coastal wetlands, and restoration/avoided conversion of peatland (Smith et al. 2019; IPCC 2019a) (see also Chapter 7, Section 3.4). Sectoral studies show higher mitigation potential than IAM pathways, as these studies include more mitigation options than IAMs (*medium confidence*) (Chapter 7).

FOOTNOTE [15] Some studies calculate emissions reductions in 2050 compared to 2014, while others note emissions reductions in 2060 relative to 2018.

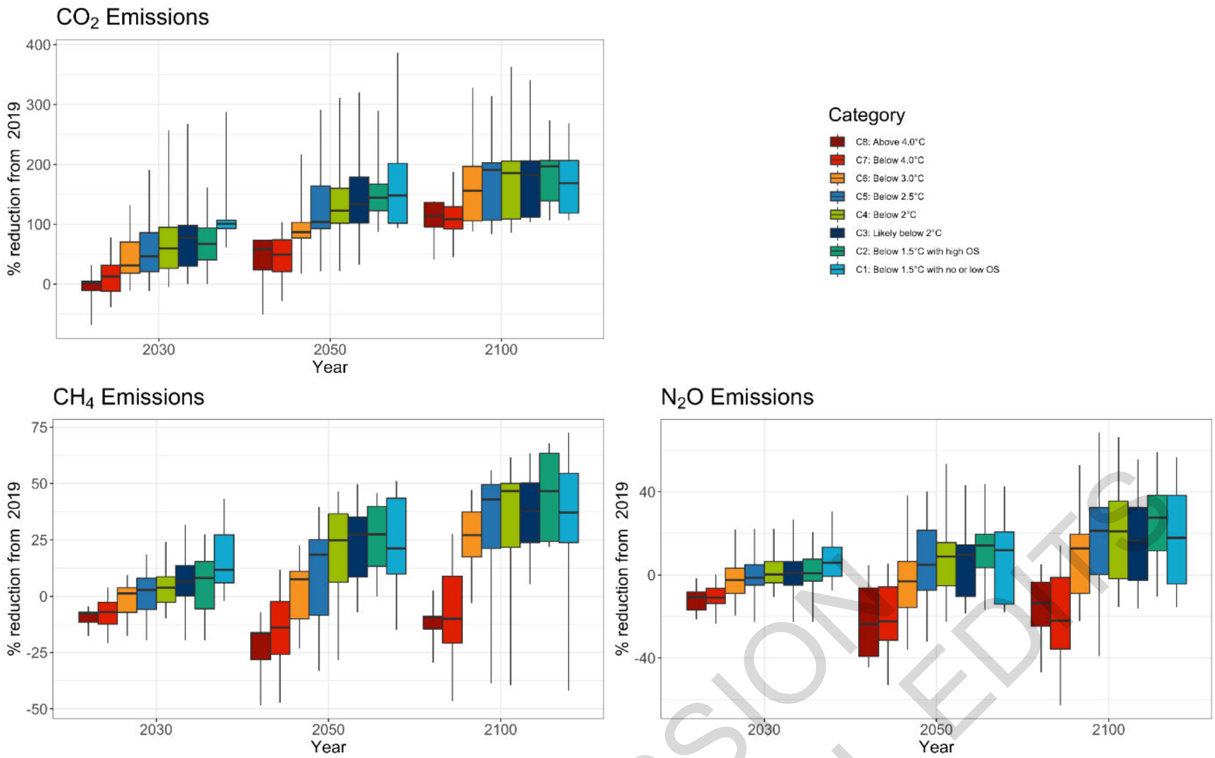

Figure 3.27: Reduction in AFOLU GHG emissions from 2019. The AFOLU CO_2 estimates in this figure are not necessarily comparable with country GHG inventories (see Chapter 7).

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

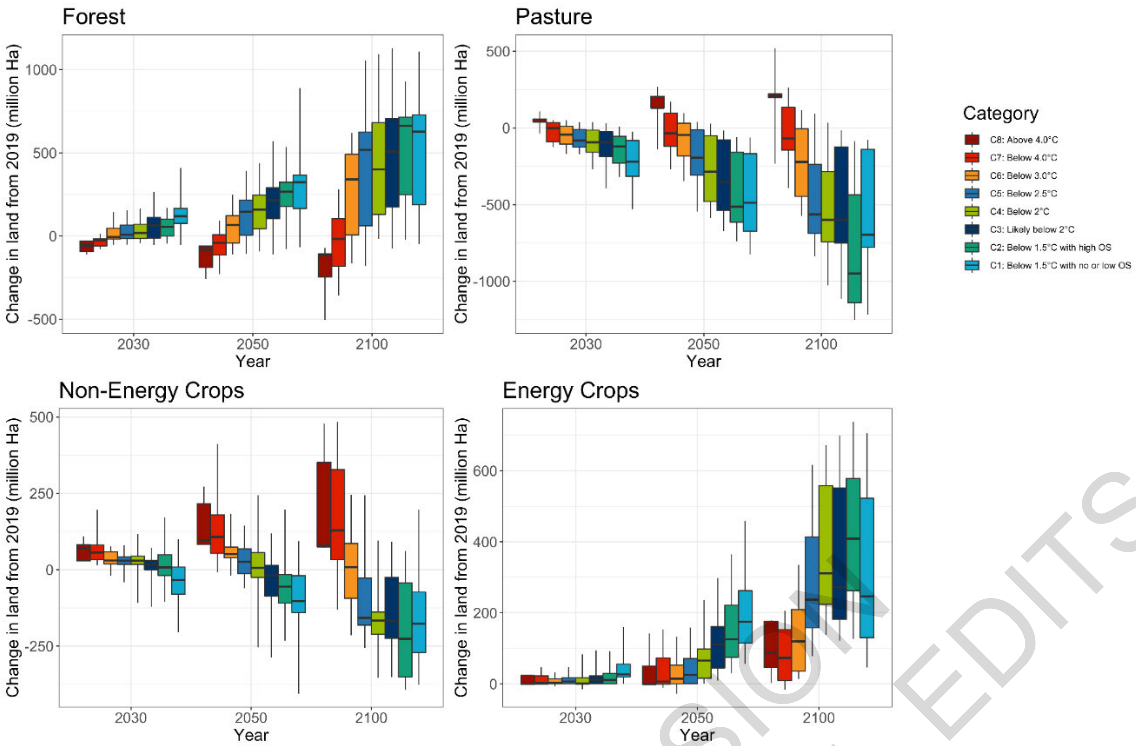

Figure 3.28: Change in Land Cover from 2019 in million hectares. Positive values indicate an increase in area.

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_2 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_2 emissions and removals differ by ~5.5 $GtCO_2\ yr^{-1}$ 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_2 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 $GtCO_2$. 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_2 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 detailed description of the individual technologies, including their costs, potentials, financing, risks, impacts, maturity and upscaling.

Very few studies and pathways include other CDR options (Table 3.5). Pathways with DACCS include potentially large removal from DACCS (up to 37 $GtCO_2$ yr^{-1} in 2100) in the second half of the century (Realmonte et al. 2019; Marcucci et al. 2017; Chen and Tavoni 2013; Fuhrman et al. 2020, 2021; Shayegh et al. 2021; Akimoto et al. 2021) and reduced cost of mitigation (Bistline and Blanford 2021; Strefler et al. 2021a). At large scales, the use of DACCS has substantial implications for energy use, emissions, land, and water; substituting DACCS for BECCS results in increased energy usage, but reduced land use change and water withdrawals (Fuhrman et al., 2020, 2021; Chapter 12.3.2; IPCC WGI Chapter 5). The level of deployment of DACCS is sensitive to the rate at which it can be scaled up, the climate goal or carbon budget, the underlying socioeconomic scenario, the availability of other decarbonization options, the cost of DACCS and other mitigation options, and the strength of carbon cycle feedbacks (Honegger and Reiner 2018; Fuss et al. 2013; Fuhrman et al. 2021; Bistline and Blanford 2021; Chen and Tavoni 2013; Strefler et al. 2021a; Fuhrman et al. 2020; Realmonte et al. 2019) (IPCC WGI Chapter 5). Since DACCS consumes energy, its effectiveness depends on the type of energy used; the use of fossil fuels would reduce its sequestration efficiency (Creutzig et al. 2019; Babacan et al. 2020; NASEM 2019). Studies with additional CDR options in addition to DACCS (e.g., enhanced weathering, BECCS, afforestation, biochar, and soil carbon sequestration) find that CO_2 removal is spread across available options (Holz et al. 2018; Strefler et al. 2021a). Similar to DACCS, the deployment of deep ocean storage depends on cost and the strength of carbon cycle feedbacks (Rickels et al. 2018).

3.5 Interaction between near-, medium- and long-term action in mitigation pathways

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

The assessment in this section shows that if mitigation ambitions in current NDCs[16] are followed until 2030, leading to estimated emissions of 47-57 $GtCO_2$-eq in 2030[17] (Chapter 4.2.2), it is no longer possible to stay below 1.5°C warming with no or limited overshoot (*high confidence*). Instead, it would entail high overshoot (typically >0.1ºC) and reliance on net negative CO_2 emissions with uncertain potential to return warming to 1.5°C by the end of the century. It would also strongly increase mitigation challenges to likely limit warming to 2°C *(high confidence)*. GHG emissions

FOOTNOTE [16] 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 [17] 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 $GtCO_2$-eq) and implementing both unconditional and conditional elements of current NDCs (47-53 $GtCO_2$-eq), if not specified otherwise.

reductions would need to abruptly increase after 2030 to an annual average rate of 1.3-2.1 GtCO2-eq during the period 2030-2050, around 70% higher than in mitigation pathways assuming immediate action[18] to likely limit warming to 2°C. The higher post-2030 reduction rates would have to be obtained in an environment of continued build-up of fossil fuel infrastructure and less development of low carbon alternatives until 2030. A lock-in into fossil-fuel intensive production systems (carbon lock-in) will increase the societal, economic and political strain of a rapid low-carbon transition after 2030 (*high confidence*).

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

3.5.1 Relationship between long-term climate goals and near- to medium-term emissions reductions

The close link between cumulative CO_2 emissions and warming has strong implications for the relationship between near-, medium-, and long-term climate action to limit global warming. The AR6 WGI Assessment has estimated a remaining carbon budget of 500 (400) $GtCO_2$ from the beginning of 2020 onwards for staying below 1.5°C with 50% (67%) likelihood, subject to additional uncertainties about historic warming and the climate response and variations in warming from non-CO_2 climate forcers (Canadell and Monteiro 2019) (see also WGI Chapter 5, Section 5.5). For comparison, if current CO_2 emissions of more than 40 GtCO2 are keeping up until 2030, more than 400 $GtCO_2$ will be emitted during 2021–2030, already exhausting the remaining carbon budget for 1.5°C by 2030.

The relationship between warming limits and near term action is illustrated in Figure 3.29, using a set of 1.5-2°C scenarios with different levels of near term action, overshoot and non-CO_2 warming contribution from a recent study (Riahi et al. 2021). In general, the more CO_2 is emitted until 2030, the less CO_2 can be emitted thereafter to stay within a remaining carbon budget and below a warming limit. Scenarios with immediate action to observe the warming limit give the longest time to exhaust the associated remaining carbon budget and reach net zero CO_2 emissions (light blue line in Figure 3.29, Cross-Chapter Box 3 in this chapter). In comparison, following projected NDC emissions until 2030 would imply a more pronounced drop in emissions from 2030 levels to net zero to make up for the additional near-term emissions (orange lines in Figure 3.29). If such a drop does not occur, the remaining carbon budget is exceeded and net negative CO_2 emissions are required to return global mean temperature below the warming limit (black lines in Figure 3.29) (Fuss et al. 2014; Clarke et al. 2014; Rogelj et al. 2018a).

FOOTNOTE [18] 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.

The relationship between warming limits and near-term action is also affected by the warming contribution of non-CO_2 greenhouse gases and other short lived climate forcers (3.3, Working Group I 6.7). The estimated budget values for limiting warming to 1.5-2°C already assume stringent reductions in non-CO_2 greenhouse gases and non-CO_2 climate forcing as found in 1.5-2°C pathways (3.3, Cross-Working Group Box 1; Working Group I 5.5, Box 5.2). Further variations in non-CO_2 warming observed across 1.5-2°C pathways can vary the median estimate for the remaining carbon budget by 220 $GtCO_2$ (Working Group I 5.5). In 1.5-2°C pathways, the non-CO_2 warming contribution differs strongly between the near-, medium and long term. Changes to the atmospheric composition of short-lived climate forcers dominate the warming response in the near term (Working Group I 6.7). CO_2 reductions are combined with strong reductions in air pollutant emissions due to rapid reduction in fossil fuel combustion and in some cases the assumption of stringent air quality policies (Rao et al. 2017b; Smith et al. 2020c). As air pollutants exert a net cooling effect, their reduction drives up non-CO_2 warming in the near term, which can be attenuated by the simultaneous reduction of methane and black carbon (Smith et al. 2020b; Shindell and Smith 2019) (Working Group I 6.7). After 2030, the reduction in methane concentrations and associated reductions in tropospheric ozone levels tend to dominate so that a peak and decline in non-CO_2 forcing and non-CO_2 induced warming can occur before net zero CO_2 is reached (Figure 3.29) (Rogelj et al. 2018a) The more stringent the reductions in methane and other short-lived warming agents like black carbon, the lower this peak and the earlier the decline of non-CO_2 warming, leading to a reduction of warming rates and overall warming in the near to medium term (Smith et al. 2020b; Harmsen et al. 2020). This is important for keeping warming below a tight warming limit that is already reached around mid-century as is the case in 1.5°C pathways (Xu and Ramanathan 2017). Early and deep reductions of methane emissions, and other short-lived warming agents like black carbon, provide space for residual CO_2-induced warming until the point of net zero CO2 emissions is reached (purple lines in Figure 3.29). Such emissions reductions have also been advocated due to co-benefits for, e.g., reducing air pollution (Rao et al. 2016; Shindell et al. 2017a, 2018; Shindell and Smith 2019; Rauner et al. 2020a; Vandyck et al. 2020).

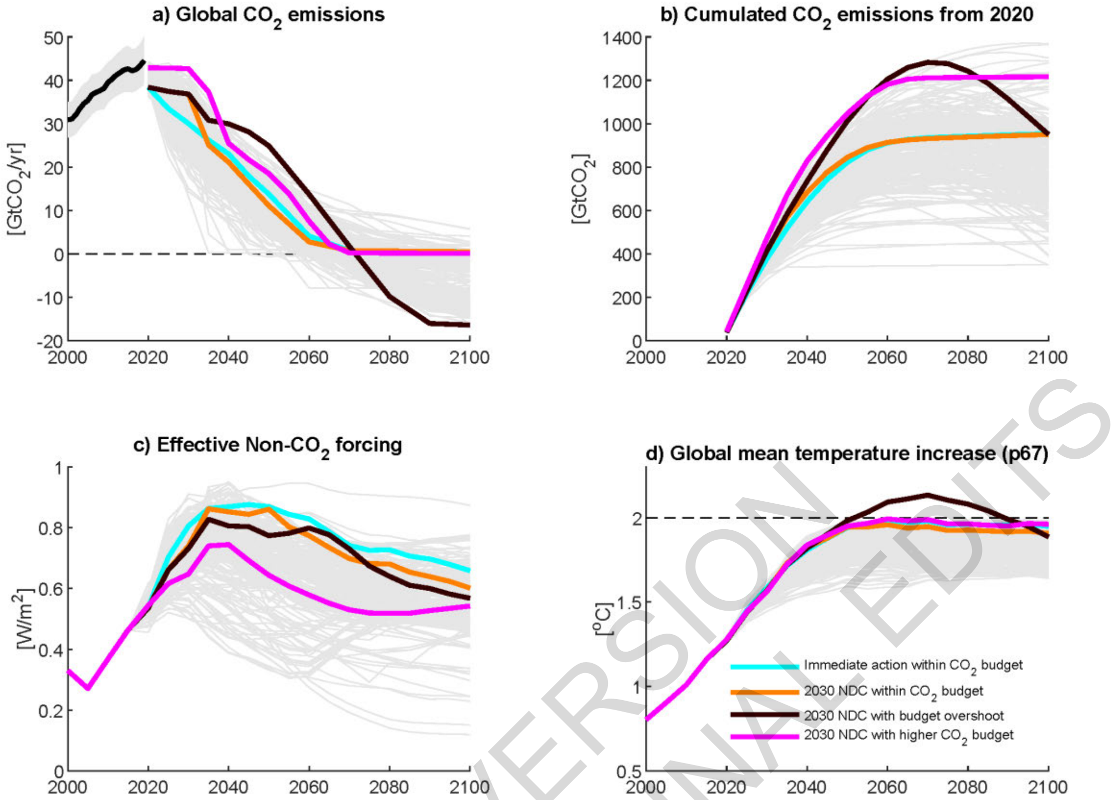

Figure 3.29: Illustration of emissions and climate response in four mitigation pathways with different assumptions about near term policy developments, global warming limit and non-CO_2 warming contribution drawn from Riahi et al. (2021). Shown are (a) CO_2 emissions trajectories, (b) cumulative CO_2 emissions, (c) effective non-CO_2 radiative forcing, and (d) the resulting estimate of the 67th percentile of global mean temperature response relative to 1850-1900. Light blue lines show a scenario that acts immediately on a remaining carbon budget of 900 $GtCO_2$ from 2020 without allowing net negative CO_2 emissions, i.e., temporary budget overshoot (COFFEE 1.1, Scenario EN_NPi2020_900). Orange and black lines show scenarios drawn from the same model that follow the NDCs until 2030 and thereafter introduce action to stay within the same budget – in one case excluding net negative CO_2 emissions like before (orange lines; COFFEE 1.1., Scenario EN-INDCi2030_900) and in the other allowing for a temporary overshoot of the carbon budget until 2100 (black lines; COFFEE 1.1., Scenario EN-INDCi2030_900f). Light blue lines describe a scenario following the NDCs until 2030, and then aiming for a higher budget of 2300 $GtCO_2$ without overshoot (AIM/CGE 2.2, Scenario EN-INDCi2030_1200). It is drawn from another model which projects a lower anthropogenic non-CO_2 forcing contribution and therefore achieves about the same temperature outcome as the other two non-overshoot scenarios despite the higher CO_2 budget. Grey funnels include the trajectories from all scenarios that likely limit warming to 2°C (Category C3). Historical CO_2 emissions until 2019 are from Chapter SM.2.1 EDGAR v6.0.

The relationship between long-term climate goals and near term action is further constrained by social, technological, economic and political factors (Aghion et al. 2019; Mercure et al. 2019; van Sluisveld et al. 2018b; Cherp et al. 2018; Jewell and Cherp 2020; Trutnevyte et al. 2019b). These factors influence path dependency and transition speed (Vogt-Schilb et al. 2018; Pahle et al. 2018). While detailed integrated assessment modelling of global mitigation pathways accounts for technology inertia (Bertram et al. 2015a; Mercure et al. 2018) and technology innovation and diffusion (Wilson et al. 2013; van Sluisveld et al. 2018a; Luderer et al. 2021), there are limitations in capturing socio-technical and political drivers of innovation, diffusion and transition processes (Keppo et al. 2021; Gambhir et al. 2019; Hirt et al. 2020; Köhler et al. 2019). Mitigation pathways show a wide range of transition speeds that have been interrogated in the context of socio-technical inertia (Gambhir et al. 2017; Kefford et al. 2018; Kriegler et al. 2018a; Brutschin et al. 2021) vs. accelerating technological change and self-enforcing socio-economic developments (Creutzig et al. 2017; Zenghelis 2019) (Section 3.8). Diagnostic analysis of detailed IAMs found a lag of 8-20 years between the convergence of emissions pricing and the convergence of emissions response after a period of differentiated emission prices (Harmsen et al. 2021). This provides a measure of the inertia to changing policy signals in the model response. It is about half the timescale of 20-40 years observed for major energy transitions (Grubb et al. 2021). Hence, the mitigation pathways assessed here capture socio-technical inertia in reducing emissions, but the limited modelling of socio-political factors may alter the extent and persistence of this inertia.

3.5.2 Implications of near-term emission levels for keeping long-term climate goals within reach

The implications of near-term climate action for long-term climate outcomes can be explored by comparing mitigation pathways with different near-term emissions developments aiming for the same climate target (Vrontisi et al. 2018; Riahi et al. 2015; Roelfsema et al. 2020). A particular example is the comparison of cost-effective pathways with immediate action to limit warming to 1.5-2°C with mitigation pathways pursuing more moderate mitigation action until 2030. After the adoption of the Paris Agreement, near term action was often modelled to reflect conditional and unconditional elements of originally submitted NDCs (2015-2019) (Fawcett et al. 2015; Fujimori et al. 2016a; Kriegler et al. 2018a; Vrontisi et al. 2018; Roelfsema et al. 2020). The most recent modelling studies also include submission of updated NDCs or announcements of planned updates in the first half of 2021 (Network for Greening the Financial System 2021; Riahi et al. 2021). Emissions levels under current NDCs (see footnote 15) are assessed to range between 47–57 $GtCO_2$-eq in 2030 (Chapter 4.2.2). This assessed range corresponds well to 2030 emissions levels in 2°C mitigation pathways in the literature that are designed to follow the original or current NDCs until 2030[19]. 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 (44.5-57) GtCO2-eq (based on native model reporting) and 52 (46.5-56) GtCO2-eq, respectively (based on harmonized emissions data for climate assessment (Annex III part II section 2.4); median and 5th to 95th percentile). This close match allows a robust assessment of the implications of implementing current NDCs for post-2030 mitigation efforts and warming outcomes based on the literature and the AR6 scenarios database.

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) $GtCO_2$-eq in 2030 for limiting warming to 1.5°C with no or limited overshoot and 10-17 (7-14) $GtCO_2$-eq in 2030 for likely limiting warming to 2°C (Chapter 4, Cross-Chapter Box 2 in chapter 2). The emissions gap gives rise to a number of mitigation challenges (Rogelj et al. 2013a; Kriegler et al. 2013a, 2018b,a; Riahi et al. 2015; Luderer et al. 2013, 2018; Fujimori et al. 2016b; Fawcett et al. 2015; Strefler et al. 2018; Winning et al. 2019; UNEP 2020; SEI et al. 2020): (i) larger transitional challenges post-2030 to still remain under the warming limit (, in particular higher CO_2 emissions reduction rates and technology transition rates required during 2030-2050; (ii) larger lock-in into carbon-intensive infrastructure and increased risk of stranded fossil fuel assets (3.5.2.2); and (iii) larger reliance on CDR to reach net zero CO_2 more rapidly and compensate excess emissions in the second half of the century (3.5.2.1). All these factors exacerbate socio-economic strain of

FOOTNOTE [19] 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).

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

The challenges are illustrated in Table 3.6 and Figure 3.30, surveying global mitigation pathways in the literature that were collected in the AR6 scenarios database. There is a clear trend of increasing peak warming with increasing 2030 GHG emission levels (Figure 3.30a+b). In particular, there is no mitigation pathway designed to follow the NDCs until 2030 in 2030 that can limit warming to 1.5°C with no or limited overshoot. Our assessment confirms the finding of the IPCC Special Report on 1.5°C Warming for the case of current NDCs, including updates until 11 October 2021 that were assessed in the literature, that pathways following the NDCs until 2030 "*would not limit global warming to 1.5°C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030*" (SR1.5 SPM). This assessment is now more robust than in SR1.5 as it is based on a larger set of 1.5-2°C pathways with better representation of current trends and plans covering a wider range of post-2030 emissions developments. In particular, a recent multi-model study limiting peak cumulative CO_2 emissions for a wide range of carbon budgets and immediate vs NDC-type action until 2030 established a feasibility frontier for the existence of such pathways across participating models (Riahi et al. 2021).

2030 emissions levels in the NDC range also tighten the remaining space to likely limit warming 2°C. As shown in Figure 3.30b, the 67th percentile of peak warming reaches values above 1.7°C warming in pathways with 2030 emissions levels in this range. 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 0-0.8 $GtCO_2$-eq yr^{-1} to an average of 1.3-2.1 $GtCO_2$-eq yr^{-1} 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). Their average reduction rate of 0.6-1.4 $GtCO_2$ yr^{-1} would already be unprecedented at the global scale and with a few exceptions national scale for an extended period of time (Riahi et al. 2015). For comparison, the impact of COVID-19 on the global economy is projected to lead to a decline of ca. 2.5-3 GtCO2 of global CO_2 emissions from fossil fuel and industry in 2020 (Friedlingstein et al. 2020) (Chapter 2.2).

The increased post-2030 transition challenge in mitigation pathways with moderate near term action is also reflected in the timing of reaching net zero CO_2 emissions (Figure 3.30d and Table 3.6) (Cross-Chapter Box 3 in this chapter). As 2030 emission levels and the cumulated CO_2 emissions until 2030 increase, the remaining time for dropping to net zero CO_2 and staying within the remaining carbon budget shortens (Figure 3.29). This gives rise to an inverted v-shape of the lower bound on the year of reaching net zero as a function of 2030 emissions levels. Reaching low in 2030 facilitates reaching net zero early (left leg of the inverted v), but staying high until 2030 also requires to reach net zero CO_2 faster to compensate for higher emissions early on (right leg of the inverted v). Overall, there is a considerable spread of the timing of net zero CO_2 for any 2030 emissions level due to variation in the timing of spending the remaining carbon budget and the non-CO_2 warming contribution (Cross-Chapter Box 3 in this chapter).

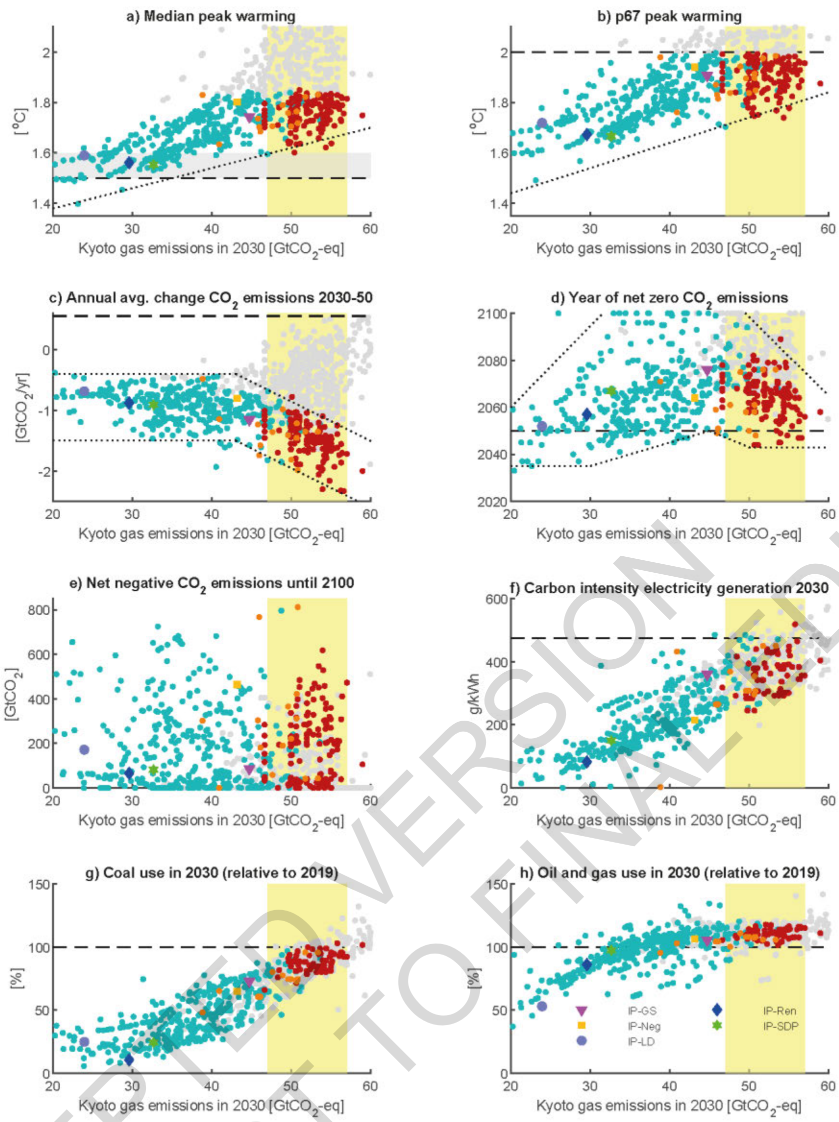

Figure 3.30: Relationship between level of global GHG emissions in 2030 and selected indicators as listed in the panel titles for scenarios collected in the AR6 scenario database. Emissions data based on harmonized emissions used for the climate assessment. All scenarios likely to limit warming to 2°C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

There is also a profound impact on the underlying transition of energy and land use (Table 3.6 and Figure 3.30f-h). Scenarios following NDCs until 2030 show a much smaller reduction in fossil fuel use, only half of the growth in renewable energy use, and a smaller reduction in CO_2 and CH_4 land use emissions in 2030 compared to immediate action scenarios. This is then followed by a much faster reduction of land use emissions and fossil fuels, and a larger increase of nuclear energy, bioenergy and non-biomass renewable energy during the medium term in order to get close to the levels of the immediate action pathways in 2050. This is combined with a larger amount of net negative CO2 emissions that are used to compensate the additional emissions before 2030. The faster transition during 2030-2050 is taking place from a greater investment in fossil fuel infrastructure and lower deployment of low carbon alternatives in 2030, adding to the socio-economic challenges to realize the higher transition rates (Section 3.5.2.2). Therefore, these pathways also show higher mitigation costs, particularly during the period 2030-2050, than immediate action scenarios (3.6.1, Figure 3.34d) (Liu et al. 2016; Vrontisi et al. 2018; Kriegler et al. 2018a).. Given these circumstances and the fact the modelling of socio-political and institutional constraints is limited in integrated assessment models (Keppo et al. 2021; Gambhir et al. 2019; Hirt et al. 2020; Köhler et al. 2019), the feasibility of realizing these scenarios is assessed to be lower (Gambhir et al. 2017; Napp et al. 2017; Brutschin et al. 2021) (cf. Section 3.8), increasing the risk of an overshoot of climate goals.

Table 3.6: Comparison of key scenario characteristics for four scenario classes (see Table 3.2): (i) immediate action to limit warming to 1.5°C with no or limited overshoot, (ii) near team action following the NDCs until 2030 and returning warming to below 1.5°C (50% chance) by 2100 with high overshoot, (iii) immediate action to likely limit warming to 2°C, and (iv) near term action following the NDCs until 2030 followed by post-2030 action to likely limit warming to 2°C. The classes (ii) and (iv) comprise the large majority of scenarios indicated by red dots, and the classes (i) and (iii) the scenarios depicted by blue dots in Figure 3.30. Shown are median and interquartile ranges (in brackets) for selected global indicators. Emissions ranges are based on harmonized emissions data for the climate assessment with the exception of land use CO2 emissions for which uncertainty in historic estimates is large. Numbers are 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_2 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_2 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_4 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 ($GtCO_2$)	665 (520,900)	670 (535,865)	605 (490,895)	535 (440,725)
of which BECCS ($GtCO_2$)	330 (250,560)	365 (280,590)	350 (240,455)	270 (240,400)
Cumulative net negative CO2 emissions until 2100 ($GtCO_2$)	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_2 emissions*

If near to medium term emissions developments deplete the remaining carbon budget, the associated warming limit will be overshot. 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_2 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_2 emissions in pathways limiting warming to 1.5-2°C climate goals varies widely, with some pathways not deploying net negative CO_2 emissions at all and others deploying up to -600 to -800 $GtCO_2$. The amount of net negative CO_2 emissions tends to increase with 2030 emissions levels (Figure 3.30e and Table 3.6). Studies confirmed the ability of net negative CO_2 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 CO2 removal and, with lower confidence, that the amount of cooling per unit CO2 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_2 emissions and the cooling response to net negative CO_2 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_2 emissions (Boysen et al. 2016).

Obtaining net negative CO_2 emissions requires massive deployment of carbon dioxide removal (CDR) in the second half of the century, on the order of 220 (160-370) GtCO2 for each 0.1°C degree of cooling (based on the assessment of the likely range of the transient response to cumulative CO_2 emissions in WGI Chap. 5.5, not taking into account potential asymmetries in the temperature response to CO_2 emissions and removals). CDR is assessed in detail in Chapter 12.3 of this report (see also Cross-Chapter Box 8 in Chapter 12). Here we only point to the finding that CDR ramp-up rates and absolute deployment levels are tightly limited by techno-economic, social, political, institutional and sustainability constraints (Smith et al. 2016; Boysen et al. 2017; Nemet et al. 2018; Fuss et al. 2018, 2020; Hilaire et al. 2019; Jia et al. 2019) (Chapter 12.3). CDR therefore cannot be deployed arbitrarily to compensate any degree of overshoot. A fraction of models was not able to compute pathways that would follow the mitigation ambition in unconditional and conditional NDCs until 2030 and return warming to below 1.5°C by 2100 (Luderer et al. 2018; Roelfsema et al. 2020; Riahi et al. 2021).There exists a three-way trade-off between near-term emissions developments until 2030, transitional challenges during 2030-50, and long-term CDR deployment post 2050 (Sanderson et al. 2016; Holz et al. 2018; Strefler et al. 2018). For example, Strefler et al. (2018) find that if CO_2 emission levels stay around 40 $GtCO_2$ until 2030, within the range of what is projected for current unconditional and conditional NDCs, rather than being halved to 20 $GtCO_2$ until 2030, CDR deployment in the second half of the century would have to increase by 50%-100%, depending on whether the 2030-2050 CO_2 emissions reduction rate is doubled from 6% to 12% or kept at 6% per year. This three-way trade-off has also been identified at the national level (Pan et al. 2020).

In addition to enabling a temporary budget overshoot by net negative CO_2 emissions in the second half of the century, CDR can also be used to compensate – on an annual basis - residual CO_2 emissions from sources that are difficult to eliminate and to reach net zero CO_2 emissions more rapidly if deployed before this point (Kriegler et al. 2013b; Rogelj et al. 2018a). This explains its continued deployment in pathways that exclude overshoot and net negative CO_2 emissions (Riahi et al. 2021). However, given the timescales that would likely be needed to ramp-up CDR to Gigaton scale (Nemet et al. 2018), it can be expected to only make a limited contribution to reaching net zero CO_2 as fast as possible. In the vast majority (95%) of 1.5-2°C mitigation pathways assessed in this report, cumulative CDR deployment did not exceed 100 $GtCO_2$ until mid-century. This adds to the risk of excessively relying on CDR to compensate for weak mitigation action until 2030 by either facilitating massive net CO_2 emissions reduction rates during 2030-2050 or allowing a high temporary overshoot of 1.5°C until the end of the century. If international burden sharing considerations are taken into account, the CDR penalty for weak action could increase further, in particular for developed countries (Fyson et al. 2020). Further assessment of CDR deployment in 1.5-2°C mitigation pathways is found in Section 3.4.7.

3.5.2.2 Carbon lock-in and stranded assets

There already exists a substantial and growing carbon lock-in today, as measured by committed emissions associated with existing long-lived infrastructure {Chapter 2.7, Figure 2.31}. If existing fossil-fuel infrastructure would continue to be operated as historically, they would entail CO_2 emissions exceeding the carbon budget for 1.5°C {Chapter 2.7.2, Figure 2.32}. However, owner-operators and societies may choose to retire existing infrastructure earlier than in the past, and committed emissions are thus contingent on the competitiveness of non-emitting alternative technologies and climate policy ambition. Therefore, in mitigation pathways, some infrastructure may become stranded assets. Stranded assets have been defined as "assets that have suffered from unanticipated or premature write-downs, devaluations or conversion to liabilities" (Caldecott 2017).

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

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

Many quantitative estimates of stranded assets along mitigation pathways have focused on fossil fuel power plants in pathways characterized by mitigation ambition until 2030 corresponding to the current NDCs followed by strengthened action afterwards to limit warming to 2°C or lower (Bertram et al. 2015a; Iyer et al. 2015b; Lane et al. 2016; Farfan and Breyer 2017; van Soest et al. 2017a; Luderer et al. 2018; Kriegler et al. 2018a; Cui et al. 2019; Saygin et al. 2019; SEI et al. 2020). Pathways following current NDCs until 2030 do not show a significant reduction of coal, oil and gas use (Figure 3.30f-h, Table 3.6) compared to immediate action pathways. Stranded coal power assets are evaluated to be higher by a factor of 2-3 if action is strengthened after 2030 rather than now (Iyer et al. 2015b; Cui et al. 2019). There is high agreement that the later climate policies are implemented, the higher the expected stranded assets and the societal, economic and political strain of strengthening action. Associated price increases for carbon-intensive goods and transitional macro-economic costs have been found to scale with the emissions gap in 2030 (Kriegler et al. 2013a). At the aggregate level of the whole global economy, Rozenberg et al. (2015) showed that each year of delaying the start of mitigation decreases the required CO_2 intensity of new production by 20-50 gCO_2/USD. Carbon lock-in can have a long-lasting effect on future emissions trajectories after 2030. Luderer et al. (2018) compared cost-effective pathways with immediate action to limit warming to 1.5-2°C with pathways following the NDCs until 2030 and adopting the pricing policy of the cost-effective pathways thereafter and found that the majority of additional CO_2 emissions from carbon lock-in occurs after 2030, reaching a cumulative amount of 290 (160–330) $GtCO_2$ by 2100 (2.7.2). Early action and avoidance of investments in new carbon-intensive assets can minimize these risks.

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

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

3.5.2.3 Global accelerated action towards long-term climate goals

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

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

One approach relies on augmenting initially moderate emissions pricing policies with robust anticipation of ratcheting up climate action in the future (Spencer et al. 2015). If announcements of strong future climate policies are perceived to be credible, they can help to prevent carbon lock-in as investors anticipating high future costs of GHG emissions would reduce investment into fossil fuel infrastructure, such as coal power plants (Bauer et al. 2018b). However, the effectiveness of such announcements strongly hinges on their credibility. If investors believe that policy makers could drop them if anticipatory action did not occur, they may not undertake such action.

Another approach relies on international cooperation to strengthen near term climate action. These studies build on international climate policy architectures that could incentivize a coalition of like-minded countries to raise their mitigation ambition beyond what is stated in their current NDC (Graichen et al. 2017). Examples are the idea of climate clubs characterized by harmonized carbon and technology markets (Pihl 2020; Nordhaus 2015; Keohane et al. 2017; Paroussos et al. 2019) and the Powering Past Coal Alliance (Jewell et al. 2019). Paroussos et al. (2019) find economic benefits of joining a climate club despite the associated higher mitigation effort, in particular due to access to technology and climate finance. Graichen et al. (2017) find an additional reduction of 5-11 $GtCO_2eq$ compared to the mitigation ambition in the NDCs from the successful implementation of international climate initiatives. Other studies assess benefits from international transfers of mitigation outcomes (Stua 2017; Edmonds et al. 2021). Edmonds et al. (2021) find economic gains from sharing NDC emissions reduction commitments compared to purely domestic implementation of NDCs. If reinvested in mitigation efforts, the study projects an additional reduction of 9 billion tonnes of CO_2 in 2030.

The most common approach relies on strengthening regulatory policies beyond current policy trends, also motivated by the finding that such policies have so far been employed more often than comprehensive carbon pricing (Roelfsema et al. 2018; Kriegler et al. 2018a; van Soest et al. 2021a; Fekete et al. 2021; IEA 2021a). Some studies have focused on generic regulatory policies such as low carbon support policies, fossil fuel sunset policies, and resource efficiency policies (Bertram et al. 2015b; Hatfield-Dodds et al. 2017). Bertram et al. (2015b) found that a moderate carbon price combined with a coal moratorium and ambitious low carbon support policies can limit efficiency losses until 2030 if emissions pricing is raised thereafter to limit warming to 2°C. They also showed that all three components are needed to achieve this outcome. Hatfield-Dodds et al. (2017) found that resource efficiency can lower 2050 emissions by an additional 15-20% while boosting near-term economic growth. The International Energy Agency (IEA 2021a) developed a detailed net zero scenario for the global energy sector characterized by a rapid phase out of fossil fuels, a massive clean energy and electrification push, and the stabilization of energy demand, leading to 10 $GtCO_2$ lower emissions from energy use in 2030 than in a scenario following the announced pledges.

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

Accelerated action pathways derived with this approach show considerable scope for narrowing the emissions gap between pathways reflecting the ambition level of the NDCs and cost-effective mitigation pathways in 2030. Kriegler et al. (2018a) find around 10 $GtCO_2eq$ lower emissions compared to original NDCs from a global roll-out of good practice plus net zero policies and a moderate increase in regionally differentiated carbon pricing. Fekete et al. (2021) show that global replication of sector progress in five major economies would reduce GHG emissions in 2030 by about 20% compared to a current policy scenario. These findings were found in good agreement with a recent model comparison study based on results from 9 integrated assessment models (van Soest et al. 2021a). Based on these three studies, implementing accelerated action in terms of a global roll out of regulatory and moderate pricing policies is assessed to lead to global GHG emissions of 47 (38-51) $GtCO_2$-eq in 2030 (median and 5th to 95th percentile based on 10 distinct modelled pathways). 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 3-9 GtCO2-eq. However, it does not close the emissions gap to immediate action pathways likely limiting warming to 2°C, and, based on our assessment in Section 3.5.2, emission levels above 40 $GtCO_2$-eq in 2030 still have a very low prospect for keeping limiting warming to 1.5°C with no or limited overshoot in reach.

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

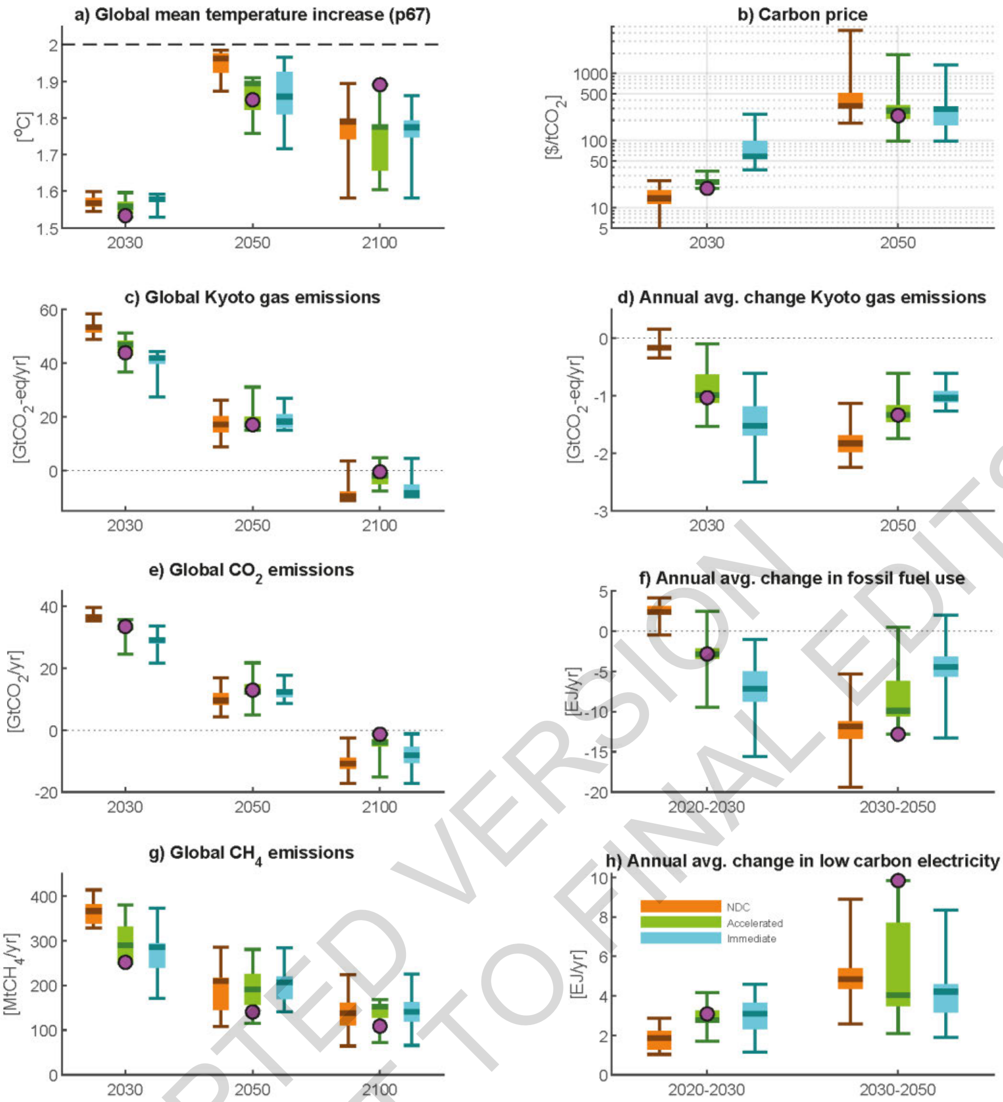

Figure 3.31: Comparison of (i) pathways with immediate action likely limiting warming to 2°C (Immediate, light blue), (ii) pathways following the NDCs until 2030 and aiming to likely stay below 2°C thereafter (NDC; orange) and (iii) pathways accelerating near term action until 2030 beyond NDC ambition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

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

A complete appraisal of economic effects and welfare effects at different temperature levels would include the macroeconomic impacts of investments in low-carbon solutions and structural change away from emitting activities, co-benefits and adverse side effects of mitigation, (avoided) climate damages, as well as (reduced) adaptation costs, with high temporal, spatial and social heterogeneity using a harmonized framework. If no such complete appraisal in a harmonized framework exists, key elements are emerging from the literature, and assessed in the following subsections: on aggregated economy-wide global mitigation costs (section 3.6.1), on the economic benefits of avoiding climate impacts (section 3.6.2), on economic benefits and costs associated with mitigation co-benefits and co-harms (section 3.6.3) and on the distribution of economic implications between economic sectors and actors (section 3.6.4).

3.6.1 Economy-wide implications of mitigation

3.6.1.1 Global economic effects of mitigation and carbon values in mitigation pathways

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

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

The marginal abatement cost of carbon, also called carbon price, is determined by the mitigation target under consideration: it describes the cost of reducing the last unit of emissions to reach the target at a given point in time. Total macro-economic mitigation costs (or gains) aggregate the economy-wide impacts of investments in low-carbon solutions and structural changes away from emitting activities. The total macro-economic effects of mitigation pathways are reported in terms of variations in economic output or consumption levels, measured against a Reference Scenario, also called Baseline, at various points in time or discounted over a given time period. Depending on the study, the Reference Scenario reflects specific assumptions about patterns of socio-economic development and assumes either no climate policies or the climate policies in place or planned at the time the study was carried out. When available in the AR6 scenarios database, this second type of Reference Scenario, with current policies, has been chosen for computation of mitigation costs. In the vast majority of studies that have produced the body of work on the cost of mitigation assessed here, and in particular in all studies that have submitted global scenarios to the AR6 scenarios database except (Schultes et al. 2021), the feedbacks of climate change impacts on the economic development pathways are not accounted for. This omission of climate impacts leads to overly optimistic economic projections in the reference scenarios, in particular in reference scenarios with no or limited mitigation action where the extent of global warming is the greatest. Mitigation cost estimates computed against no or limited policy reference scenarios therefore omit economic benefits brought by avoided climate change impact along mitigation pathways, and should be interpreted with care (Grant et al. 2020). When aggregate economic benefits from avoided climate change impacts are accounted for, mitigation is a welfare-enhancing strategy (see section 3.6.2).
If GDP or consumption in mitigation pathways are below the reference scenario levels, they are reported as losses or macro-economic costs. Such cost estimates give an indication on how economic activity slows relative to the reference scenario; they do not necessarily describe, in absolute terms, a reduction of economic output or consumption levels relative to previous years along the pathway. Aggregate mitigation costs depend strongly on the modelling framework used and the assumptions

about the reference scenario against which mitigation costs are measured, in particular whether the reference scenario is, or not, on the efficiency frontier of the economy. If the economy is assumed to be at the efficiency frontier in the reference scenario, mitigation inevitably leads to actual costs, at least in the short run until the production frontier evolves with technical and structural change. Starting from a reference scenario that is not on the efficiency frontier opens the possibility to simultaneously reduce emissions and obtain macroeconomic gains, depending on the design and implementation of mitigation policies. A number of factors can result in reference scenarios below the efficiency frontier, for instance distorting labour taxes and/or fossil fuel subsidies, misallocation or under-utilization of production factors such as involuntary unemployment, imperfect information or non-rational behaviours. Although these factors are pervasive, the modelling frameworks used to construct mitigation pathways are often limited in their ability to represent them (Köberle et al. 2021).

The absolute level of economic activity and welfare also strongly depends on the socioeconomic pathway assumptions regarding inter alia evolutions in demography, productivity, education levels, inequality and technical change and innovation. The GDP or consumption indicators reported in the database of scenarios, and synthesized below, represent the absolute level of aggregate economic activity or consumption but do not reflect welfare and well-being (Roberts et al. 2020), that notably depend on human needs satisfaction, distribution within society and inequality (see section 3.6.4).

Chapter 1 and Annex III give further elements on the economic concepts and on the modelling frameworks, including their limitations, used in this report, respectively.

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Estimates for the marginal abatement cost of carbon in mitigation pathways vary widely, depending on the modelling framework used and socioeconomic, technological and policy assumptions. However, it is robust across modelling frameworks that the marginal abatement cost of carbon increases for lower temperature categories, with a higher increase in the short-term than in the longer-term (Figure 3.32, left panel) (*high confidence*). The marginal abatement cost of carbon increases non-linearly with the decrease of CO_2 emissions level, but the uncertainty in the range of estimates also increases (Figure 3.33). Mitigation pathways with low-energy consumption patterns exhibit lower carbon values (Méjean et al. 2019; Meyer et al. 2021). In the context of the COVID-19 pandemic recovery, Kikstra et al. (2021a) also show that a low energy demand recovery scenario reduces carbon prices for a 1.5°C consistent pathway by 19% compared to a scenario with energy demand trends restored to pre-pandemic levels.

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

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

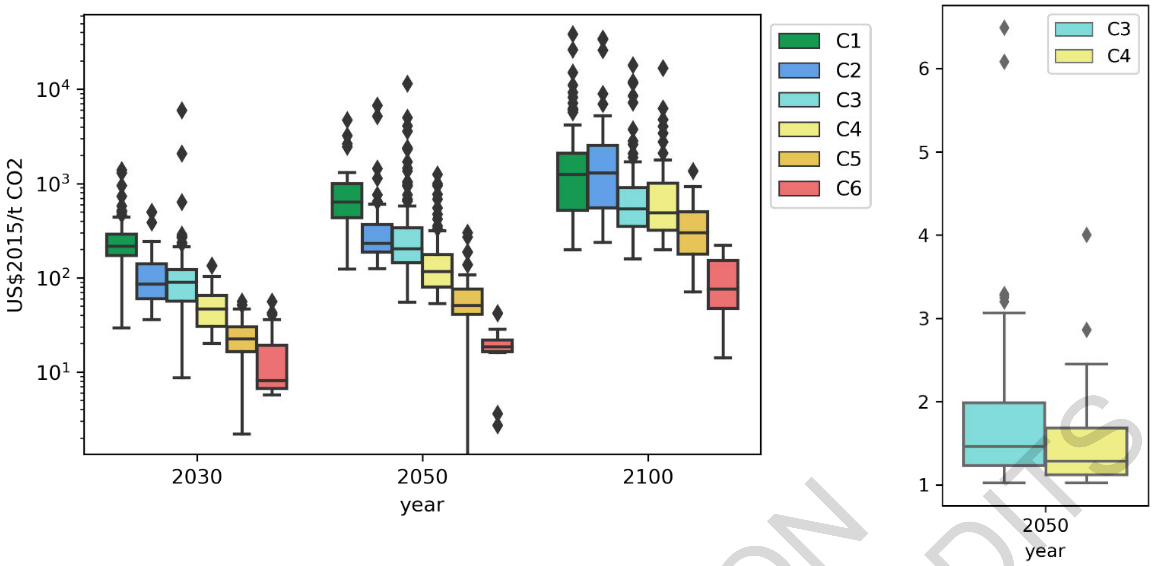

Figure 3.32: Marginal abatement cost of carbon in 2030, 2050 and 2100 for mitigation pathways with immediate global mitigation action (left panel), and ratio in 2050 between pathways that correspond to NDC in 2030 and strengthen action after 2030 and pathways with immediate global mitigation action,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

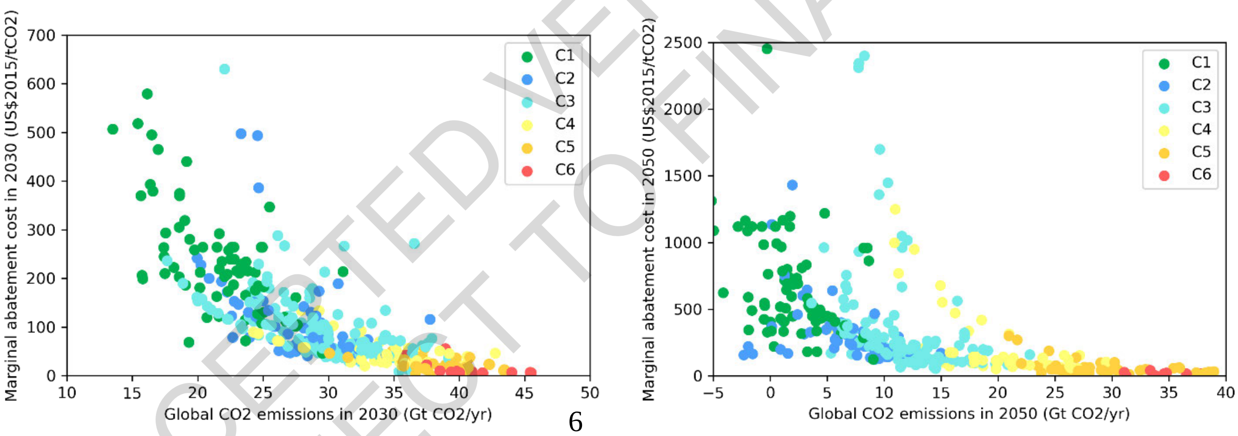

Figure 3.33: Marginal abatement cost of carbon with respect to CO_2 emissions for mitigation pathways with immediate global mitigation action, in 2030 (left panel) and 2050 (right panel).

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).

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

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

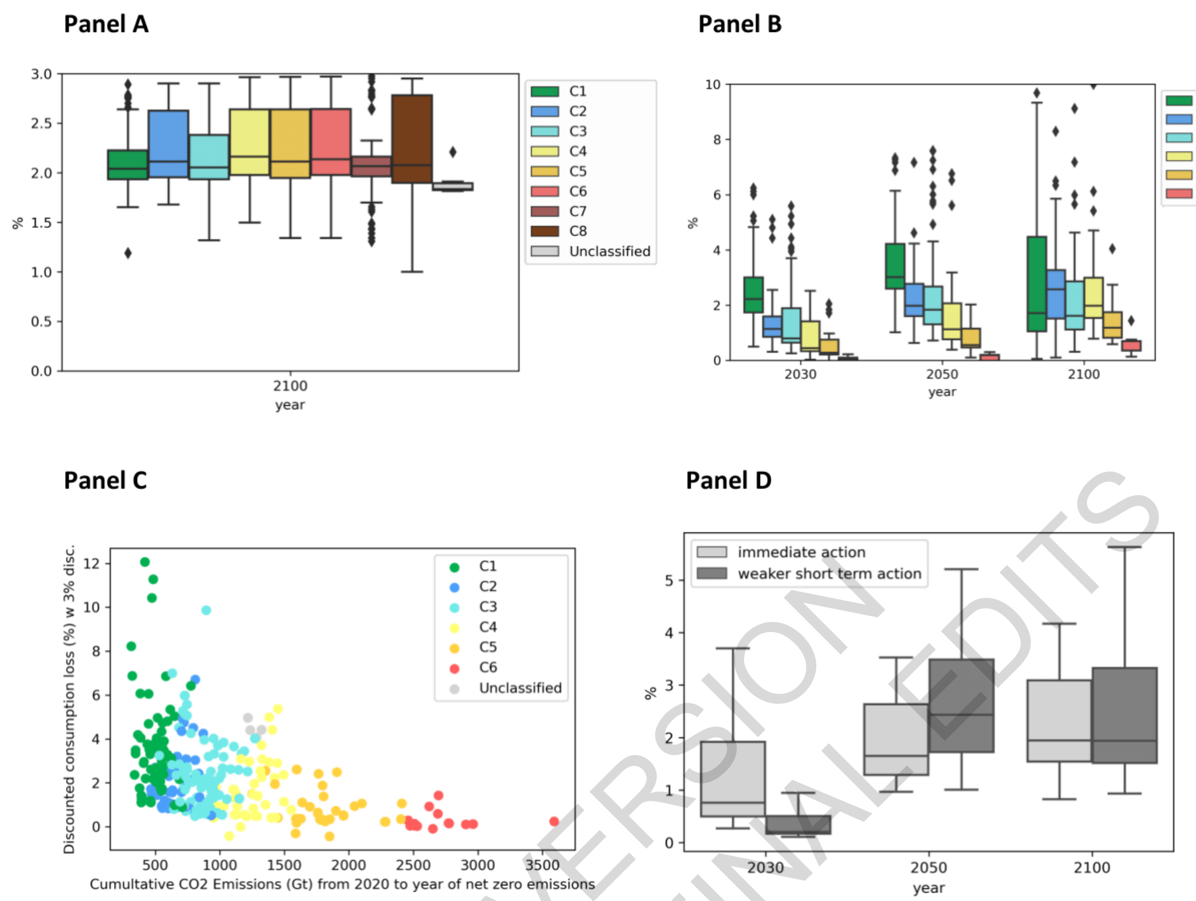

Figure 3.34: Panel (a): Mean annual global consumption growth rate over 2020-2100 for the mitigation pathways in the AR6 scenarios database. Panel (b): Global GDP loss compared to baselines (not accounting for climate change damages) in 2030, 2050 and 2100 for mitigation pathways with immediate global action. Panel (c): Total discounted consumption loss (with a 3% discount rate) in mitigation scenarios with respect to their corresponding baseline (not accounting for climate change damages) as a function of cumulative CO_2 emissions until date of net zero CO_2. Panel (d): Comparison of GDP losses compared to baselines (not accounting for climate change damages) in 2030, 2050 and 2100 for pairs of scenarios depicting immediate action pathways and delayed action pathways.

Mitigation pathways with early emissions reductions represent higher mitigation costs in the short run but bring long-term gains for the economy compared to delayed transition pathways (*high confidence*). Pathways with earlier mitigation action bring higher long-term GDP than pathways reaching the same end-of-century temperature with weaker early action (Figure 3.34, panel d). Comparing counterfactual history scenarios, Sanderson and O'Neill (2020) also find that delayed mitigation action leads to higher peak costs. Rogelj et al. (2019b) and Riahi et al. (2021) also show that pathways with earlier timing of net zero CO_2 lead to higher transition costs but lower long term mitigation costs, due to dynamic effects arising from lock-in avoidance and learning effects. For example, Riahi et al (2021) find that for a 2˚C target, the GDP losses (compared to a reference scenario without impacts from climate change) in 2100 are 5-70% lower in pathways that avoid net negative CO_2 emissions and temperature overshoot than in pathways with overshoot. Accounting also for climate change damage, van der Wijst et al. (2021a) show that avoiding net negative emissions leads to a small increase in total discounted mitigation costs over 2020-2100, between 5% and 14% in their medium assumptions, but does not increase mitigation costs when damages are high and when using a low discount rate, and becomes economically attractive if damages are not fully reversible. The modelled cost-optimal balance of mitigation action over time strongly depends on the discount rate used to compute or evaluate mitigation pathways: lower discount rates favour earlier mitigation, reducing both temperature overshoot and reliance on net negative carbon emissions (Emmerling et al. 2019; Riahi et al. 2021). Mitigation pathways with weak early action corresponding to NDCs in 2030 and strengthening action after 2030 to reach end-of-century temperature targets imply limited mitigation costs in 2030, compared to immediate global action pathways, but faster increase in costs post-2030, with implications for intergenerational equity (Aldy et al. 2016; Liu et al. 2016; Vrontisi et al. 2018). Emissions trading policies reduce global aggregate mitigation costs, in particular in the context of achieving NDCs (Fujimori et al. 2015, 2016a; Edmonds et al. 2021; Böhringer et al. 2021), and change the distribution of mitigation costs between regions and countries (see section 3.6.1.2).

3.6.1.2 Regional mitigation costs and effort-sharing regimes

The economic repercussions of mitigation policies vary across countries (Hof et al. 2017; Aldy et al. 2016): regional variations exist in institutions, economic and technological development, and mitigation opportunities. For a globally uniform carbon price, carbon intensive and energy exporting countries bear the highest economic costs because of a deeper transformation of their economies and of trade losses in the fossil markets (Stern et al. 2012; Tavoni et al. 2015; Böhringer et al. 2021). This finding is confirmed in Figure 3.35. Since carbon intensive countries are often poorer, uniform global carbon prices raises equity concerns (Tavoni et al. 2015). On the other hand, the climate economic benefits of mitigating climate change will be larger in poorer countries (Cross-Working Group Box 1). This reduces policy regressivity but does not eliminate it (Taconet et al. 2020; Gazzotti et al. 2021). Together with co-benefits, such as health benefits of improved air quality, the economic benefits of mitigating climate change are likely to outweigh mitigation costs in many regions (Li et al. 2018, 2019; Scovronick et al. 2021).

Regional policy costs depend on the evaluation framework (Budolfson et al. 2021), policy design, including revenue recycling, and on international coordination, especially among trade partners. By fostering technological change and finance, climate cooperation can generate economic benefits, both in large developing economies such as China and India (Paroussos et al. 2019) and industrialized countries such as Europe (Vrontisi et al. 2020). International coordination is a major driver of regional policy costs. Delayed participation in global mitigation efforts raises participation costs, especially in carbon intensive economies (Figure 3.35, right panel). Trading systems and transfers can deliver cost savings and improve equity (Rose et al. 2017a). On the other hand, measures that reduce imports of energy intensive goods such as carbon border tax adjustment may imply costs outside of the policy jurisdiction and have international equity repercussions, depending on how they are designed (Böhringer et al. 2012, 2017; Cosbey et al. 2019) (see also 13.6.6).

An equitable global emission trading scheme would require very large international financial transfers, in the order of several hundred billion USD per year (Tavoni et al. 2015; van den Berg et al. 2020; Bauer et al. 2020). The magnitude of transfers depends on the stringency of the climate goals and on the burden sharing principle. 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. International transfers also depend on the underlying socio-economic development (Leimbach and Giannousakis 2019), as these drive the mitigation costs of meeting the Paris Agreement (Rogelj et al. 2018b). By contrast, achieving equity without international markets would result in a large discrepancy in regional carbon prices, up to a factor (Bauer et al. 2020). The efficiency-sovereignty trade-off can be partly resolved by allowing for limited differentiation of regional carbon prices: moderate financial transfers substantially reduce inefficiencies by narrowing the carbon price spread (Bauer et al. 2020).

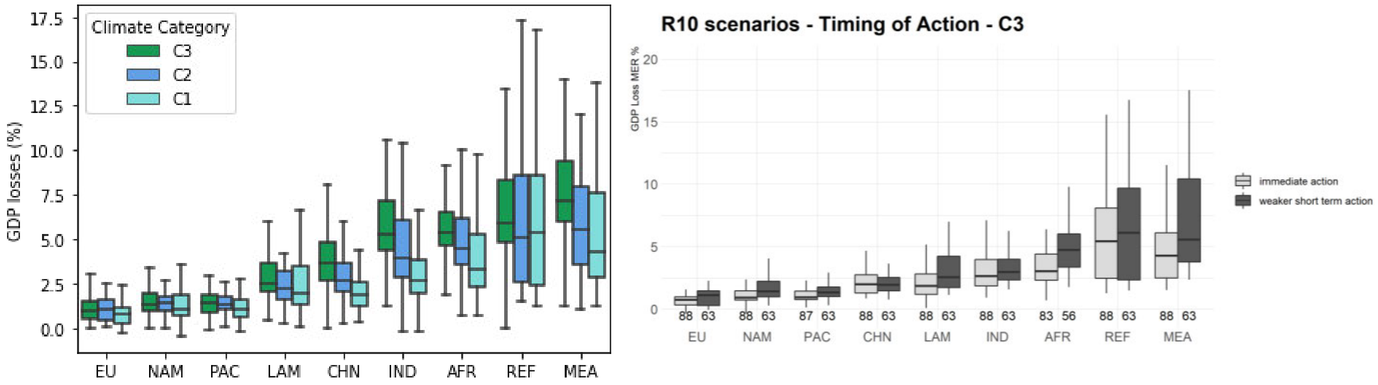

Figure 3.35: Left panel: Regional mitigation costs in the year 2050 (expressed as GDP losses between mitigation scenarios and corresponding baselines, not accounting for climate change damages), under the assumption of immediate global action with uniform global carbon pricing and no international transfers,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

3.6.1.3 Investments in mitigation pathways

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

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

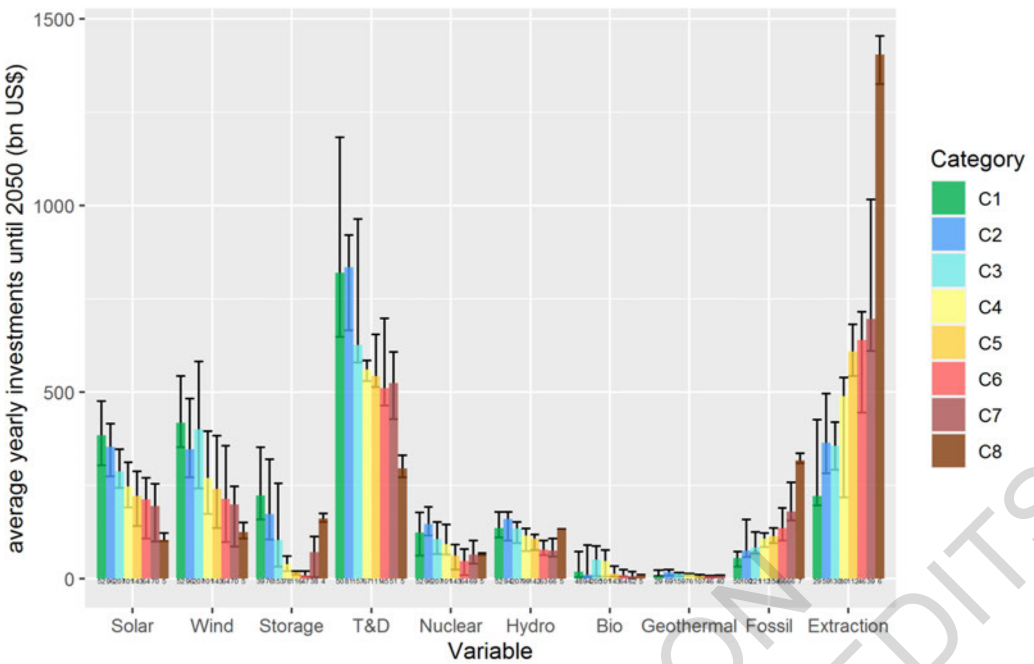

Figure 3.36: Global average yearly investments from 2023-2052 for 9 electricity supply subcomponents and for extraction of fossil fuels (in billion USD2015), in pathways by temperature categories. T&D: transmission and distribution of electricity. Bars show the median values (number of pathways at the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

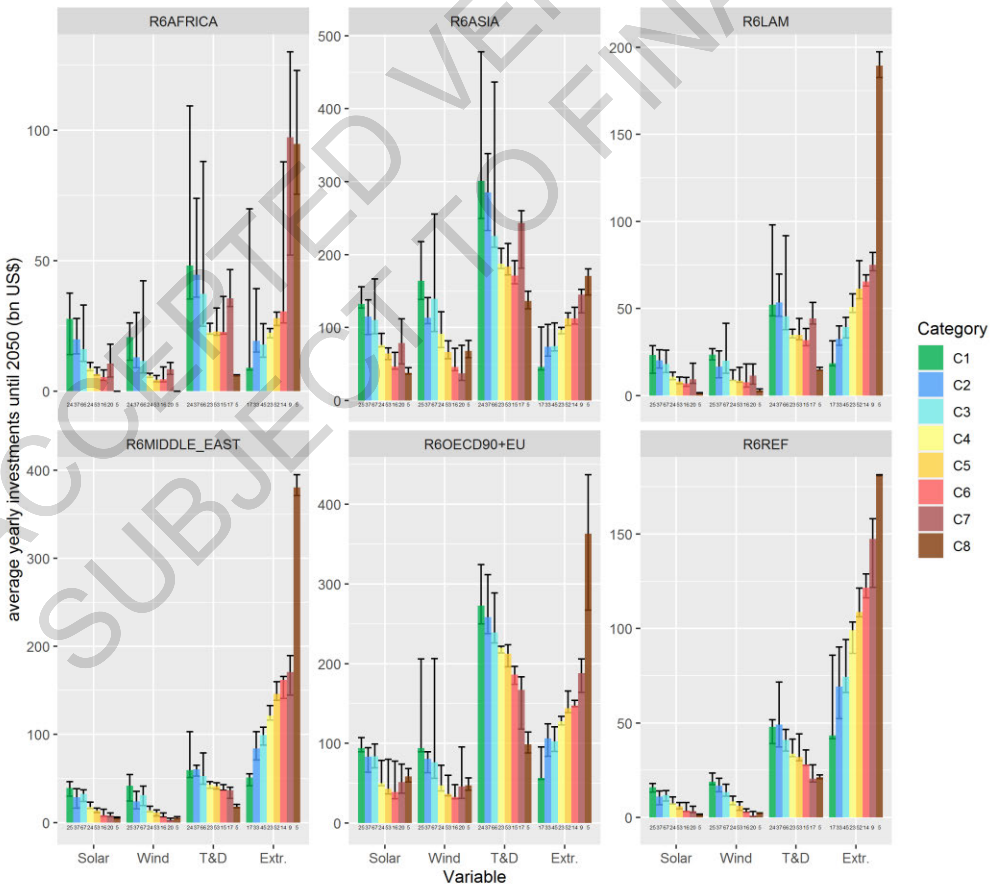

Figure 3.37: Average yearly investments from 2023-2052 for the four subcomponents of the energy system representing the larger amounts (in billion USD2015), by aggregate regions, in pathways by temperature categories. T&D: transmissions and distribution of electricity. Extr.: extraction of fossil

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

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

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

3.6.2 Economic benefits of avoiding climate changes impacts

START BOX HERE

Cross-Working Group Box 1: Economic benefits from avoided climate impacts along long-term mitigation pathways

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Mitigation reduces the extent of climate change and its impacts on ecosystems, infrastructure, and livelihoods. This box summarizes elements from the WGII report on aggregate climate change impacts and risks, putting them into the context of mitigation pathways. AR6 Working Group II provides an assessment of current lines of evidence regarding potential climate risks with future climate change, and therefore, the avoided risks from mitigating climate change. Regional and sectoral climate risks to physical and social systems are assessed (WGII Chapters 2-15). Over 100 of these are identified as Key Risks (KRs) and further synthesized by WGII Chapter 16 into eight overarching Representative Key Risks (RKRs) relating to low-lying coastal systems; terrestrial and ocean ecosystems; critical physical infrastructure, networks and services; living standards; human health; food security; water security; and peace and mobility (WGII 16.5.2). The RKR assessment finds that risks increase with global warming level, and also depend on socioeconomic development conditions, which shape exposure and vulnerability, and adaptation opportunities and responses. "Reasons For Concern", another WGII aggregate climate impacts risk framing, are also assessed to increase with climate change, with increasing risk for unique and threatened systems, extreme weather events, distribution of impacts, global aggregate impacts, and large-scale singular events (WGII Chapter 16). For human systems, in general, the poor and disadvantaged are found to have greater exposure level and vulnerability for a given hazard. With some increase in global average warming from today expected regardless of mitigation efforts, human and natural systems will be exposed to new conditions and additional adaptation will be needed (WGII Chapter 18). The range of dates for when a specific warming level could be reached depends on future global emissions, with significant overlap of ranges across emissions scenarios due to climate system response uncertainties (WGI Tables 4.2 and 4.5). The speed at which the climate changes is relevant to adaptation timing, possibilities, and net impacts.

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

Conceptually, the difference in aggregate economic impacts from climate change between two given temperature levels represents the aggregate economic benefits arising from avoided climate change impacts due to mitigation action. A subset of the studies whose estimates were evaluated by WGII (5 of 15) are used to derive illustrative estimates of aggregate economic benefits in 2100 arising from avoided climate change (Howard and Sterner 2017; Burke et al. 2018; Pretis et al. 2018; Kahn et al. 2019; Takakura et al. 2019). Burke et al. (2018), Pretis et al. (2018) and Kahn et al. (2019) are examples of statistical estimation of historical relationships between temperature and economic growth, whereas Takakura et al. (2019) is an example of structural modelling, which evaluates selected impact channels (impacts on agriculture productivity, undernourishment, heat-related mortality, labour productivity, cooling/heating demand, hydroelectric and thermal power generation capacity and fluvial flooding) with a general equilibrium model. Howard and Sterner (2017) and Rose et al. (2017b) estimate damage functions that can be used to compute the economic benefits of mitigation from avoiding a given temperature level for a lower one. Howard and Sterner (2017) estimate a damage function from a meta-analysis of aggregate economic impact studies, while Rose et al. (2017b) derive global functions by temperature and socioeconomic drivers from stylized aggregate Cost-Benefit-Analysis integrated assessment models using diagnostic experiments. Cross-Working Group Box 1 Figure 1 summarizes the global aggregate economic benefits in 2100 of avoided climate change impacts from individual studies corresponding to shifting from a higher temperature category (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. Benefits are positive and increase with the temperature gap for any given study, and this result is robust across socioeconomic scenarios. The Figure provides evidence of a wide range of quantifications, and illustrates the important differences associated with methods. Panel a puts the studies used to calculate aggregate economic benefits arising from avoided impacts into the context of the broader set of studies assessed in WGII (WGII Cross-Working Group Box Economic, 16.6.2). However, economic benefits in 2100 arising from avoided impacts cannot be directly computed from damage estimates across this broader set of studies, due to inconsistencies - different socioeconomic assumptions, scenario designs, and counterfactual reference scenarios across studies. Furthermore, these types of estimates cannot be readily compared to mitigation cost estimates. The comparison would require a framework that ensures consistency in assumptions and dynamics and allows for consideration of benefits and costs along the entire pathway.

Cross-Working Group Box 1 Figure 1: Global aggregate economic benefits of mitigation from avoided climate change impacts in 2100 corresponding to shifting from a higher temperature category (4°C (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 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 WGII CWGB ECONOMIC Figure 1, showing global aggregate economic impact estimates (% global GDP loss relative to GDP without additional climate change) by temperature change level. All estimates are shown in grey. Estimates used for the computation of estimated benefits in 2100 in Panel b are coloured for the selected studies, which provide results for different temperature change levels. See the WGII Chapter 16 box for discussion and assessment of the estimates in Panel a and the differences in methodologies. For B18 and T19, median estimates in the cluster are considered. Shape distinguishes the baseline scenarios. Temperature ranges are highlighted. HS17 estimates are based on their preferred model - 50th percentile of non-catastrophic damage. Panel b shows the implied aggregate economic benefits in 2100 of a lower temperature increase. Economic benefits for point estimates are computed as a difference, while economic benefits from the curve HS17 are computed as ranges from the segment differences.

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

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

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

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

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

Comparing economic costs and benefits of mitigation raises a number of methodological and fundamental difficulties. Monetizing the full range of climate change impacts is extremely hard, if not impossible (WGII chapter 16), as is aggregating costs and benefits over time and across individuals when values are heterogeneous (AR5, WGIII chapter 3; this assessment, Chapter 1). Other approaches should thus be considered in supplement for decision making (Chapter 1, section 1.7), in particular cost-effectiveness approaches that analyse how to achieve a defined mitigation objective at least cost or while also reaching other societal goals (Koomey 2013; Kaufman et al. 2020; Köberle et al. 2021; Stern and Stiglitz 2021). In cost effectiveness studies too, incorporating benefits from avoided climate damages influences the results and leads to more stringent mitigation in the short-term (Drouet et al. 2021; Schultes et al. 2021).

3.6.3 Aggregate economic implication of mitigation co-benefits and trade-offs

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

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

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

3.6.4 Structural change, employment and distributional issues along mitigation pathways

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

3.6.4.1 Economic structural change and employment in long-term mitigation pathways

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

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

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

3.6.4.2 Distributional implications of long-term mitigation pathways

Mitigation policies can have important distributive effects between and within countries, either reducing or increasing economic inequality and poverty, depending on policy instruments design and implementation (see section 3.6.1.2 for an assessment of the distribution of mitigation costs across regions in mitigation pathways, section 3.7, Box 3.6 and chapter 4 section 4.2.2.6 for an assessment of the fairness and ambition of NDCs, and section 4.5 for an assessment of national mitigation pathways along the criteria of equity, including just transition, as well as chapter 17, section 17.4.5 for equity in a just transition). For instance, emissions taxation has important distributive effects, both between and within income groups (Klenert et al. 2018; Cronin et al. 2018b; Pizer and Sexton 2019; Douenne 2020; Steckel et al. 2021). These effects are more significant in some sectors, such as transport, and depend on country-specific consumption structures (Dorband et al. 2019; Fullerton and Muehlegger 2019; Ohlendorf et al. 2021). However, revenues from emissions taxation can be used to lessen their regressive distributional impacts or even turn the policy into a progressive policy reducing inequality and/or leading to gains for lower income households (Cameron et al. 2016; Jakob and Steckel 2016; Fremstad and Paul 2019; Fujimori et al. 2020b; Böhringer et al. 2021; Steckel et al. 2021; Soergel et al. 2021b; Budolfson et al. 2021). Mitigation policies may affect the poorest through effects on energy and food prices (Hasegawa et al. 2015; Fujimori et al. 2019). Markkanen and Anger-Kraavi (2019) and Lamb et al. (2020) synthesize evidence from the existing literature on social co-impacts of climate change mitigation policy and their implications for inequality. They show that most policies can compound or lessen inequalities depending on contextual factors, policy design and policy implementation, but that negative inequality impacts of climate policies can be mitigated (and possibly even prevented), when distributive and procedural justice are taken into consideration in all stages of policy making, including policy planning, development and implementation, and when focusing on the carbon intensity of lifestyles, sufficiency and equity, wellbeing and decent living standards for all (see also 13.6).

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

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

3.7 Sustainable development, mitigation and avoided impacts

3.7.1 Synthesis findings on mitigation and sustainable development

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

This section covers the long-term interconnection of SD and mitigation, taking forward the holistic vision of SD described in the SDGs (Brandi 2015; Leal Filho et al. 2018). Recent studies have explored the aggregated impact of mitigation for multiple sustainable development dimensions (Hasegawa et al. 2014; Bertram et al. 2018; Grubler et al. 2018; McCollum et al. 2018b; Fuso Nerini et al. 2018; van Vuuren et al. 2019; Soergel et al. 2021a). For instance, Figure 3.38 shows selected mitigation co-benefits and trade-offs based on a subset of models and scenarios, since so far many IAMs do not have a comprehensive coverage of sustainable development goals (Rao et al. 2017a; van Soest et al. 2019). Figure 3.38 shows that mitigation likely leads to increased forest cover (SDG 15) and reduced mortality from ambient PM2.5 pollution (SDG 3) compared to reference scenarios. However, mitigation policies can also cause higher food prices and an increased population at risk of hunger (SDG 2) and relying on solid fuels (SDG 3 and SDG 7) as side effects. These trade-offs can be compensated through targeted support measures and/or additional SD policies (Cameron et al. 2016; Bertram et al. 2018; Fujimori et al. 2019; Soergel et al. 2021a).

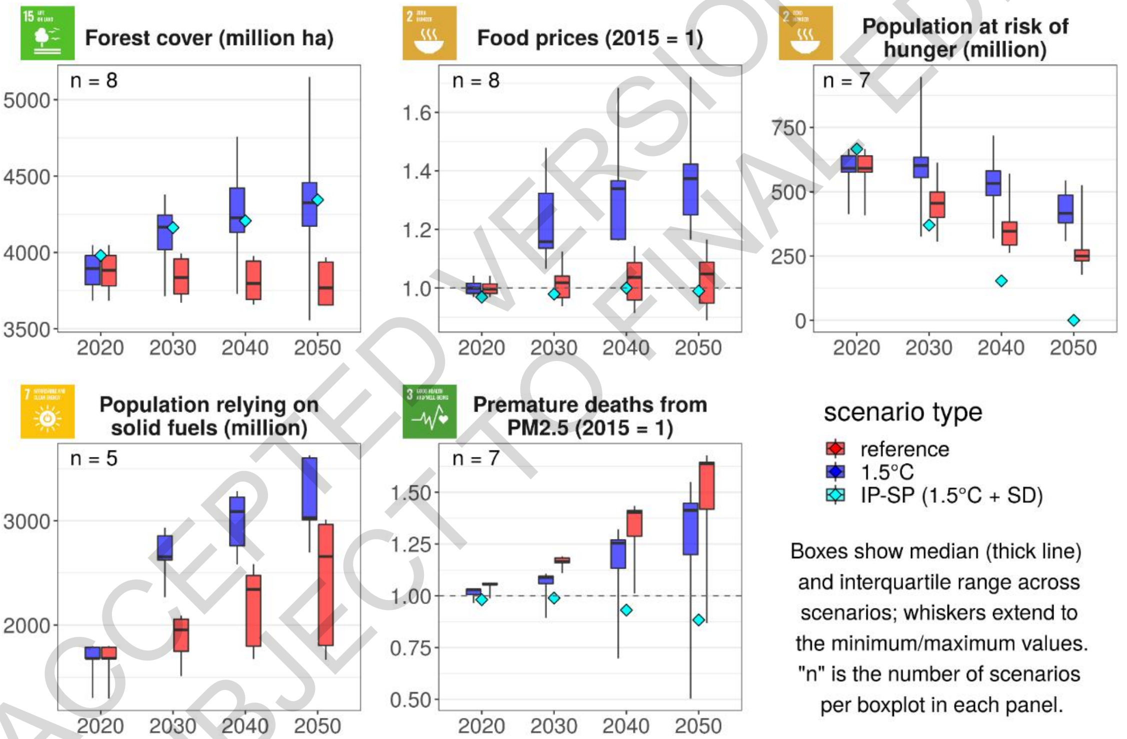


Figure 3.38: Effect of climate change mitigation on different dimensions of sustainable development: shown are mitigation scenarios compatible with 1.5°C target (blue) and reference scenarios (red). Blue boxplots contain scenarios that include narrow mitigation policies from different studies (see below). This is compared to a sustainable development scenario (*SP*, Soergel et al. (2021a), cyan diamonds) integrating mitigation and SD policies (e.g., zero hunger in 2050 by assumption). Scenario sources for boxplots: single scenarios from i) Fujimori et al. (2020a); ii) Soergel et al. (2021a); multi-model scenario set from CD-LINKS (McCollum et al. 2018b; Roelfsema et al. 2020; Fujimori et al. 2019). For associated methods, see also Cameron et al. (2016), Rafaj et al. (2021). The reference scenario for (Fujimori et al. 2020a) is no-policy baseline; for all other studies, it includes current climate policies. In the "Food prices" and "Risk of hunger" panels, scenarios from CD-LINKS include a price cap of 200 USD/tCO_2eq for land-use emissions (Fujimori et al. 2019). For the other indicators, CD-LINKS scenarios without price cap Roelfsema et al. (2020) are used due to SDG indicator availability. In the "Premature deaths" panel, a well-below 2°C scenario from Fujimori et al. (2020a) is used in place of a 1.5°C scenario due to data availability, and all scenarios are indexed to their 2015 values due to a spread in reported levels between models. SDG icons were created by the United Nations.

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

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

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

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

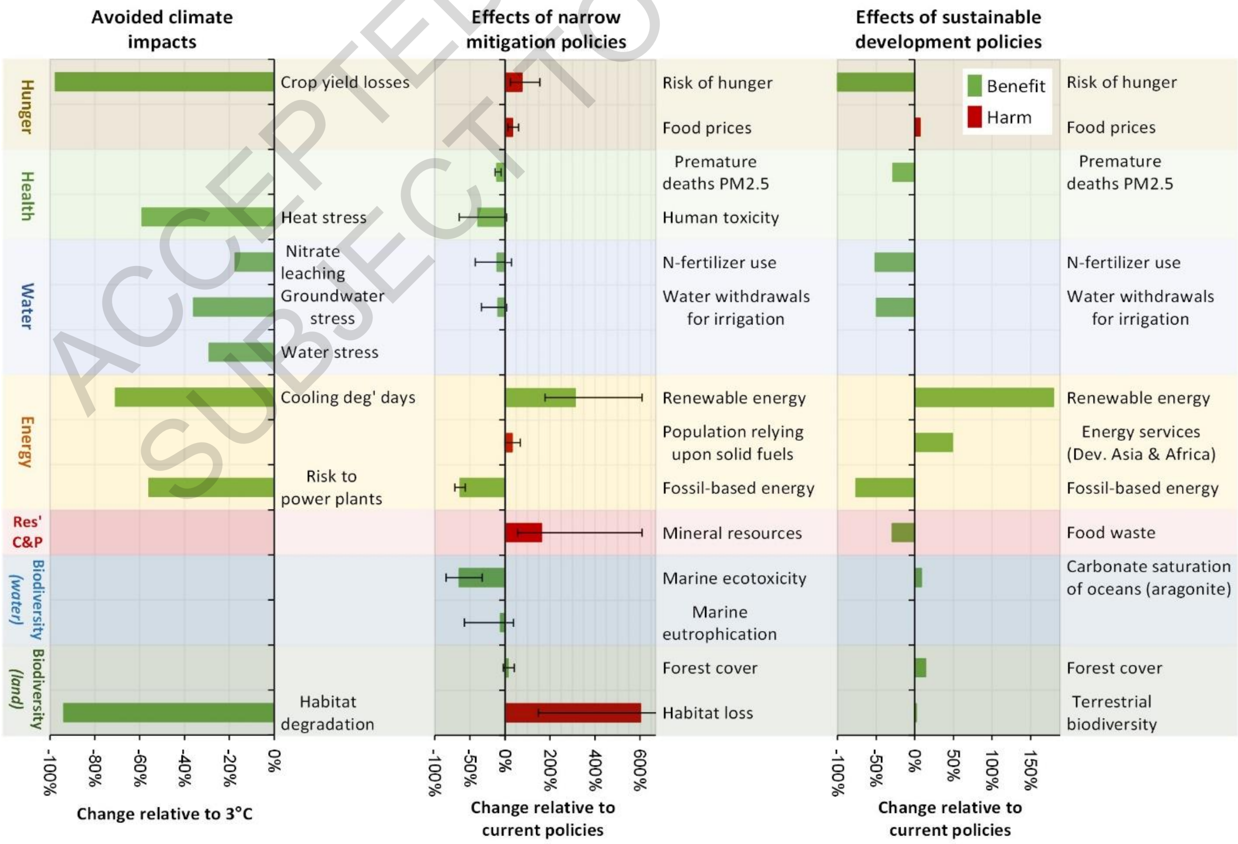


Figure 3.39: Sustainable development effects of mitigation to 1.5°C. Left: benefits of mitigation from avoided impacts. Middle: sustainability co-benefits and trade-offs of narrow mitigation policies (averaged over multiple models). Right: sustainability co-benefits and trade-offs of mitigation policies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

3.7.1.1 Policies combining mitigation and sustainable development

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

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

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

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

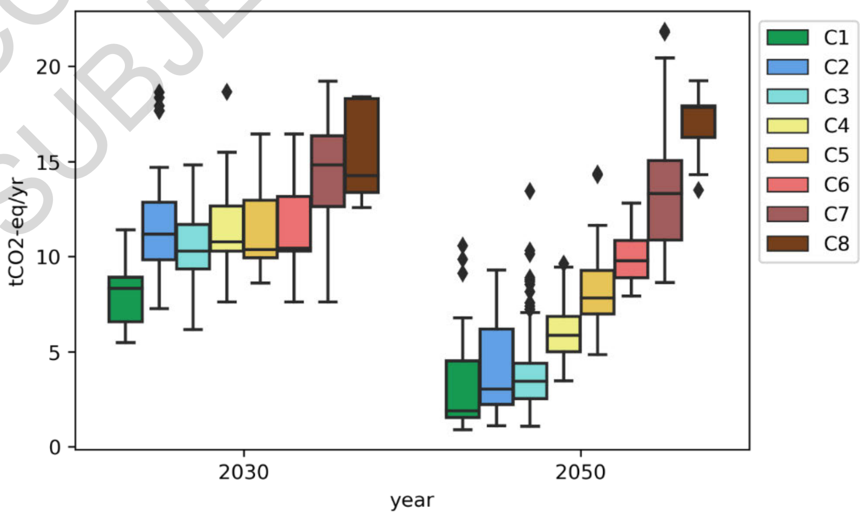
START BOX HERE

Box 3.6 Poverty and Inequality

There is high confidence *(medium evidence, high agreement)* that the eradication of extreme poverty and universal access to energy can be achieved without resulting in significant greenhouse gas emissions (Tait and Winkler 2012; Pachauri 2014; Chakravarty and Tavoni 2013; Rao 2014; Pachauri et al. 2013; Hubacek et al. 2017b; Poblete-Cazenave et al. 2021). There is also high agreement in the literature that a focus on wellbeing and decent living standards for all can reduce disparities in access to basic needs for services concurrently with climate mitigation (Chapter 5, 5.2). Mitigation pathways in which national redistribution of carbon pricing revenues is combined with international climate finance, achieve poverty reduction globally (Fujimori et al. 2020b; Soergel et al. 2021b). Carbon pricing revenues in mitigation pathways consistent with limiting temperature increase to 2°C could also contribute to finance investment needs for basic infrastructure (Jakob et al. 2016) and SDGs achievement (Franks et al. 2018).

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

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



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

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

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

3.7.2 Food

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

3.7.2.1 Benefits of avoided climate impacts along mitigation pathways

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

3.7.2.2 Implications of mitigation efforts along pathways

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

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

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

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

3.7.3 Water

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

3.7.3.1 Benefits of avoided climate impacts along mitigation pathways

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

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

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

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

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

3.7.3.2 Implications of mitigation efforts along pathways

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

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

3.7.4 Energy

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

3.7.4.1 Benefits of avoided climate impacts along mitigation pathways

Climate change alters the production of energy through changes in temperature (hydropower, fossil fuel, nuclear, solar, bioenergy, transmission and pipelines), precipitation (hydropower, fossil fuel, nuclear, bioenergy), windiness (wind, wave), and cloudiness (solar) *(high confidence)*. Increases in temperature reduce efficiencies of thermal power plants (e.g., fossil fuel and nuclear plants) with air-cooled condensers by 0.4-0.7% ºC increase in ambient temperature (Cronin et al. 2018a; Yalew, S. G. et al. 2020; Simioni and Schaeffer 2019). Potentials and costs for renewable energy technologies are also affected by climate change, though with considerable regional variation and uncertainty (Gernaat et al. 2021). Biofuel yields could increase or decrease depending on the level of warming, changes in precipitation, and the effect of CO_2 fertilization (Calvin et al. 2013; Kyle et al. 2014; Gernaat et al. 2021). Coastal energy facilities could potentially be impacted by sea-level rise (Brown et al. 2014).

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

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

3.7.4.2 Implications of mitigation efforts along pathways

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

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

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

3.7.5 Health

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

3.7.5.1 Benefits of avoided climate impacts along mitigation pathways

The human health chapter of the WGII contribution to the AR6 concluded that climate change is increasingly affecting a growing number of health outcomes, with negative net impacts at the global scale and positive only in a few limited situations. There are few estimates of economic costs of increases in climate-sensitive health outcomes. In the U.S. in 2012, the financial burden in terms of deaths, hospitalizations, and emergency department visits for ten climate-sensitive events across 11 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

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

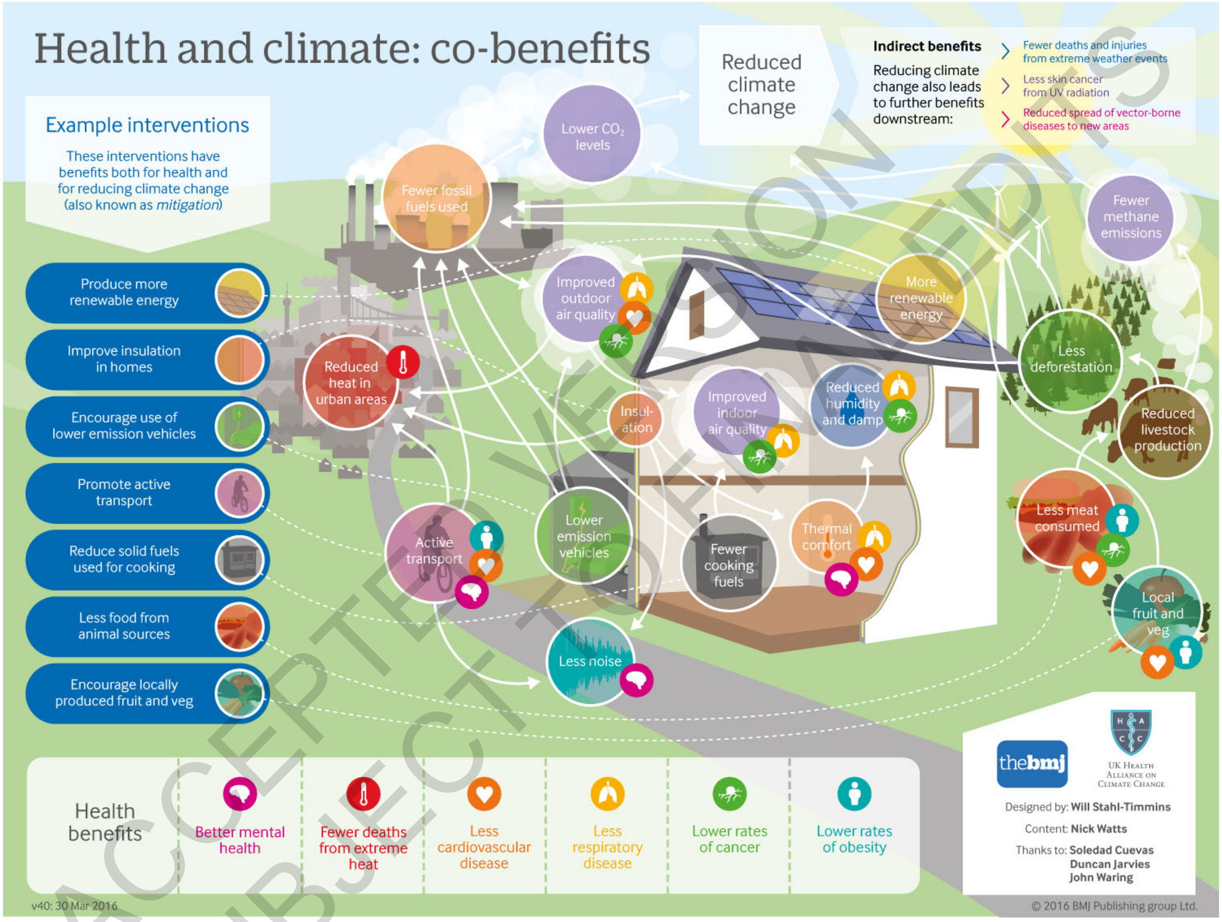

Figure 3.40: Diagram showing the co-benefits between health and mitigation (Iacobucci 2016)

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

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

Cost-benefit analyses for climate mitigation in urban settings that do not account for health may underestimate the potential cost savings and benefits (Hess et al. 2020). The net health benefits of controlling air pollution as part of climate mitigation efforts could reach trillions of dollars annually, depending on the air quality policies adopted globally (Markandya et al. 2018; Scovronick et al. 2019b). Air pollution reductions resulting from meeting the Paris Agreement targets were estimated to provide health co-benefits-to-mitigation ratios of between 1.4 and 2.5 (Markandya et al. 2018). In Asia, the benefit of air pollution reduction through mitigation measures were estimated to reduce premature mortality by 0.79 million, with an associated health benefit of USD2.8 trillion versus mitigation costs of USD840 billion, equating to 6% and 2% of GDP, respectively (Xie et al. 2018). Similarly, stabilizing radiative forcing to 3.4 W/m^2 in South Korea could cost USD1.3-8.5 billion in 2050 and could lead to a USD23.5 billion cost reduction from the combined benefits of avoided premature mortality, health expenditures, and lost work hours (Kim et al. 2020). The health co-benefits related to physical exercise and reduced air pollution largely offset the costs of implementing low CO_2 emitting urban mobility strategies in three Austrian cities (Wolkinger et al. 2018).

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

3.7.6 Biodiversity (land and water)

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

3.7.6.1 Benefits of avoided climate impacts along mitigation pathways

3.7.6.1.1 Terrestrial and freshwater aquatic ecosystems

Climate change is a major driver of species extinction and terrestrial and freshwater ecosystems destruction (see WGII Chapter 2) *(high confidence)*. Analysis shows that approximately half of all species with long-term records have shifted their ranges in elevation and about two thirds have advanced their timing of spring events (Parmesan and Hanley 2015). Under 3.2 °C warming, 49% of insects, 44% of plants and 26% of vertebrates are projected to be at risk of extinction. At 2°C, this falls to 18% of insects, 16% of plants and 8% of vertebrates and at 1.5°C, to 6% of insects, 8% of plants and 4% of vertebrates (Warren et al. 2018). Incidents of migration of invasive species, including pests and diseases, are also attributable to climate change, with negative impacts on food security and vector-borne diseases. Moreover, if climate change reduces crop yields, cropland may expand – a primary driver of biodiversity loss – in order to meet food demand (Molotoks et al. 2020). Land restoration and halting land degradation under all mitigation scenarios has the potential for synergy between mitigation and adaptation.

3.7.6.1.2 Marine and coastal ecosystems

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

3.7.6.2 Implications of mitigation efforts along pathways

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

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

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

3.7.7 Cities and infrastructure

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

3.7.7.1 Benefits of avoided climate impacts along mitigation pathways

By 2100, urban population will be almost double and more urban areas will be built (Jiang and O'Neill 2017), although Covid-19 may modify these trends (Kii 2021). Urbanization will amplify projected air temperature changes in cities, including amplifying heat waves (see WGI Chapter 10, Box 10.3). Benefits of climate mitigation in urban areas include reducing heat, air pollution and flooding. Industrial infrastructure and production-consumption supply networks also benefit from avoided impacts.

3.7.7.2 Implications of mitigation efforts along pathways

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

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

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

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

3.8 Feasibility of socio/techno/economic transitions

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

3.8.1 Feasibility frameworks for the low carbon transition and scenarios

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

Regarding scenarios, the feasibility 'what' question is the one most commonly dealt with in the literature, though most of the studies have focused on expanding low carbon system, and yet political constraints might arise mostly from phasing out fossil fuel-based ones (Spencer et al. 2018; Fattouh et al. 2019). The 'when and where' dimension can also be related to the scenario assessment, but only insofar the models generating them can differentiate time and geographical contextual factors. Distinguishing mitigation potential by regional institutional capacity has a significant influence on the costs of stabilizing climate (Iyer et al. 2015c). The 'whom' question is the most difficult to capture by scenarios, given the multitude of actors involved as well as their complex interactions. The focus of socio-technical transition sciences on the co-evolutionary processes can shed light on the dynamics of feasibility (Nielsen et al. 2020).

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

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

3.8.2 Feasibility appraisal of low carbon scenarios

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

3.8.2.1 Model solvability

In order to be generated, scenarios must be coherent with the constraints and assumptions embedded in the models (i.e., deployment potential of given technologies, physical and geological limits) and in the scenario design (i.e., carbon budget). Sometimes, models cannot solve specific scenarios. This provides a first, coarse indication of feasibility concerns. Specific vetting criteria can be imposed, such as carbon price values above which scenarios should not be reported, as in Clarke et al. (2009). However, model solvability raises issues of aggregation in model ensemble. Since model solving is not a random process, but a function of the characteristics of the models, analysing only reported outcomes leads to statistical biases (Tavoni and Tol 2010).

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

3.8.2.2 Scenario feasibility

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

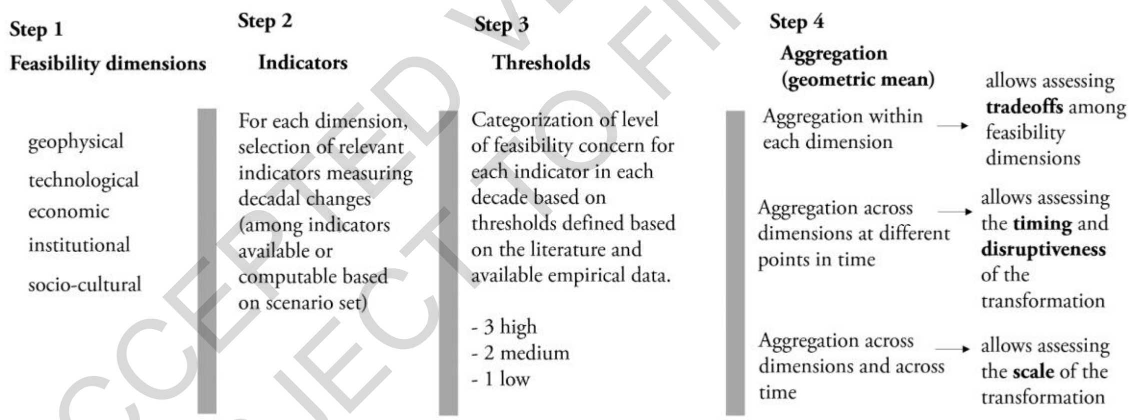

Figure 3.41: Steps involved in evaluating the feasibility of scenarios

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

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

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

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

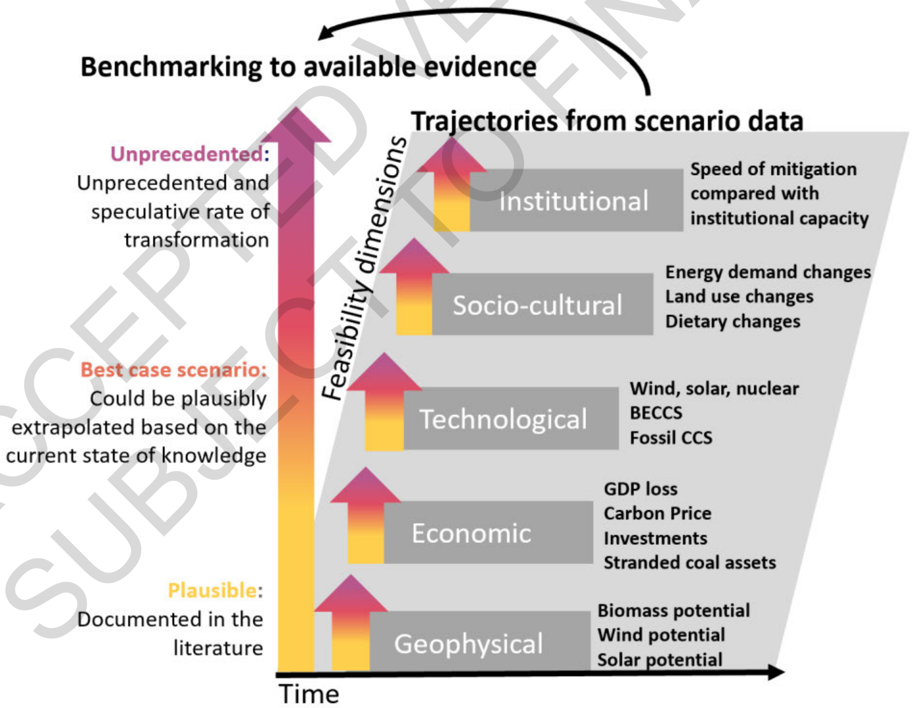

Figure 3.42: Example of multi-dimensional feasibility analysis and indicators used in the IPCC AR6 scenarios. The approach defines relevant indicators characterizing the key dimensions of feasibility. Indicators capture the timing, scale and disruptiveness challenges. Low, medium and high feasibility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

In Figure 3.43, we show the results of applying the methodology of Brutschin et al. (2021) to the AR6 scenarios database. The charts highlight the dynamic nature of feasibility risks, which are mostly concentrated in the decades before mid-century except for geophysical risks driven by CO_2 removals later in the century. Different dimensions pose differentiated challenges: for example, institutional feasibility challenges appear to be the most relevant, in line with the qualitative literature. Thus, feasibility concerns might be particularly relevant in countries with weaker institutional capacity. The Figure also highlights the key role of policy and technology, as enabling factors. In particular (Panel B), internationally coordinated and immediate emission reductions allow to smooth out feasibility concerns and reduce long term challenges compared to delayed policy action, as a result of a more gradual transition and lower requirements of CO_2 removals. For the same climate objective, different illustrative mitigation pathways entail somewhat different degrees and distributions of implementation challenges (panel C).

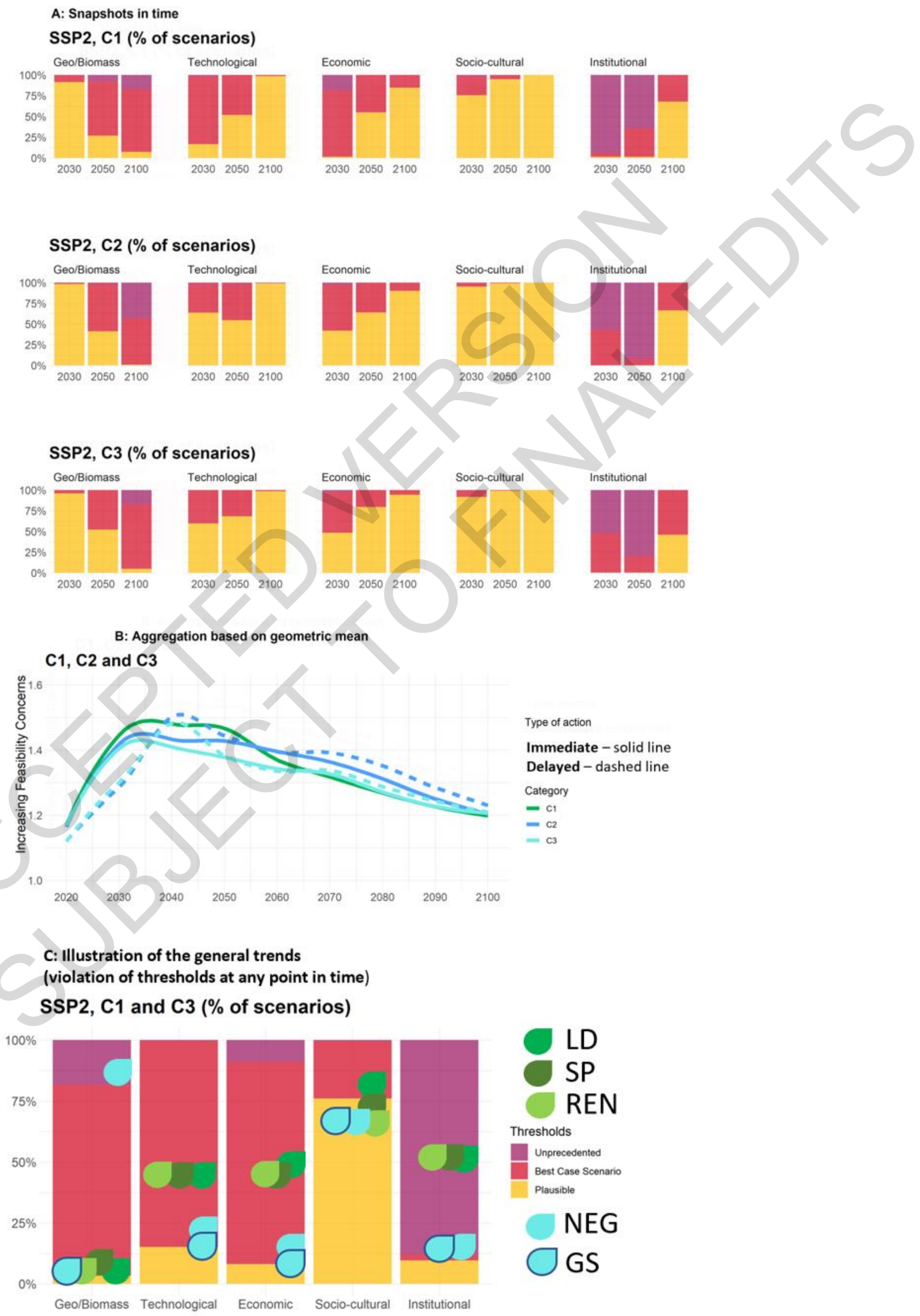

Figure 3.43: Feasibility characteristics of the Paris-consistent scenarios in AR6 scenarios database, applying the methodology by : Feasibility corridors for the AR6 scenarios database, applying the methodology by (Brutschin et al. 2021). Panel A: the fraction of scenarios falling within 3 categories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

3.8.3 Feasibility in the light of socio-technical transitions

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

Other elements of feasibility relate to social justice, which could be essential to enhance the political and public acceptability of the low carbon transition. Reviewing the literature, one study finds that employing social justice as an orienting principle can increase the political feasibility of low carbon policies (Patterson et al. 2018). Three elements are identified as key: i) protecting vulnerable people from climate change impacts, ii), protecting people from disruptions of transformation, iii), enhancing 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_2 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_2 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 the mitigation potential of a given sector. There is an increasing focus in IAM studies on SDGs (Section 3.7), with some studies reporting the implications of mitigation pathways on SDGs (e.g., Bennich et al. (2020)) and others using achieving SDGs as a constraint on the scenario itself (van Vuuren et al. 2015; Soergel et al. 2021a). However, IAMs are still limited in the SDGs they represent, often focusing on energy, water, air pollution and land. On the economic side, the majority of the models report information on marginal costs (i.e., carbon price). Only a subset provides full economic implications measured by either economic activity or welfare. Also often missing, is detail about economic inequality within countries or large aggregate regions.

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

Frequently Asked Questions (FAQs)

FAQ 3.1 – Is it possible to stabilize warming without net negative CO_2 and GHG emissions?

Yes. Achieving net zero CO2 emissions and sustaining them into the future is sufficient to stabilize the CO_2-induced warming signal which scales with the cumulative net amount of CO_2 emissions. At the same time, the warming signal of non-CO_2 GHGs can be stabilized or reduced by declining emissions that lead to stable or slightly declining concentrations in the atmosphere. For short-lived GHGs with atmospheric lifetimes of less than 20 years, this is achieved when residual emissions are reduced to levels that are lower than the natural removal of these gases in the atmosphere. Taken together, mitigation pathways that bring CO_2 emissions to net zero and sustain it, while strongly reducing non-CO_2 GHGs to levels that stabilize or decline their aggregate warming contribution, will stabilize warming without using net negative CO_2 emissions and with positive overall GHG emissions when aggregated using GWP100. A considerable fraction of pathways limiting warming to 1.5°C with no or limited overshoot and likely limiting warming to 2°C, respectively, do not or only marginally (<10 $GtCO_2$ cumulative until 2100) deploy net negative CO_2 emissions (26% and 46%, respectively) and do not reach net zero GHG emissions by the end of the century (48% and 70%, respectively). This is no longer the case in pathways that return warming to 1.5°C after a high overshoot (typically > 0.1°C). All of these pathways deploy net negative emissions on the order of 330 (26-623 $GtCO_2$) (median and 5^{th}-95^{th} percentile) and 87% achieve net negative GHGs emissions in AR6 GWP-100 before the end of the century. Hence, global net negative CO_2 emissions, and net zero or net negative GHG emissions, are only needed to decline, not to stabilize global warming. The deployment of carbon dioxide removal (CDR) is distinct from the deployment of net negative CO_2 emissions, because it is also used to neutralize residual CO_2 emissions to achieve and sustain net zero CO_2 emissions. CDR deployment can be considerable in pathways without net negative emissions and all pathways limiting warming to 1.5°C use it to some extent.

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

Halting global warming in the long term requires, at a minimum, that no additional CO_2 emissions from human activities are added to the atmosphere (i.e., CO_2 emissions must reach "net" zero). Given that CO_2 emissions constitute the dominant human influence on global climate, global net zero CO_2 emissions are a prerequisite for stabilizing warming at any level. However, CO_2 is not the only greenhouse gas that contributes to global warming and reducing emissions of other greenhouse gases alongside CO_2 towards net zero emissions of all GHGs would lower the level at which global temperature would peak. The temperature implications of net zero GHG emissions depend on the bundle of gases that is being considered, and the emissions metric used to calculate aggregated GHG emissions and removals. If reached and sustained, global net zero GHG emissions using the 100-year Global Warming Potential (GWP-100) will lead to gradually declining global temperature.

Not all emissions can be avoided. Achieving net zero CO_2 emissions globally therefore requires deep emissions cuts across all sectors and regions, along with active removal of CO_2 from the atmosphere to balance remaining emissions that may be too difficult, too costly or impossible to abate at that time. Achieving global net zero GHG emissions would require, in addition, deep reductions of non-CO_2 emissions and additional CO_2 removals to balance remaining non-CO_2 emissions.

Not all regions and sectors must reach net zero CO_2 or GHG emissions individually to achieve global net zero CO_2 or GHG emissions, respectively; instead, positive emissions in one sector or region can be compensated by net negative emissions from another sector or region. The time each sector or region reaches net zero CO_2 or GHG emissions depends on the mitigation options available, the cost of those options, and the policies implemented (including any consideration of equity or fairness). Most modelled pathways that likely limit warming to 2°C above pre-industrial levels and below use land-based CO_2 removal such as afforestation/reforestation and BECCS to achieve net zero CO_2 and net zero GHG emissions even while some CO_2 and non-CO_2 emissions continue to occur. Pathways with more demand-side interventions that limit the amount of energy we use, or where the diet that we consume is changed, can achieve net zero CO_2, or net zero GHG emissions with less carbon dioxide removal. All available studies require at least some kind of carbon dioxide removal to reach net zero; that is, there are no studies where absolute zero GHG or even CO_2 emissions are reached by deep emissions reductions alone.

Total GHG emissions are greater than emissions of CO_2 only; reaching net zero CO_2 emissions therefore occurs earlier, by up to several decades, than net zero GHG emissions in all modelled pathways. In most modelled pathways that likely limit warming to 2°C above pre-industrial levels and below in the most cost-effective way, the AFOLU and energy supply sectors reach net zero CO_2 emissions several decades earlier than other sectors; however, many pathways show much reduced, but still positive net GHG emissions in the AFOLU sector in 2100.

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

IAMs are used to develop a wide range of scenarios describing future trajectories for greenhouse gas emissions based on a wide set of assumptions regarding socio-economic development, technological changes, political development and climate policy. Typically, the IAM-based scenarios can be divided into a) reference scenarios (describing possible trajectories in the absence of new stringent climate policies) and b) mitigation scenarios (describing the impact of various climate policy assumptions). Reference scenarios typically result in high emissions and, subsequently, high levels of climate change (in the order of 2.5-4 °C during the 21st century). The purpose of such reference scenarios is to explore the consequences of climate change and act as a reference for mitigation scenarios. The possible emission levels for reference scenarios diverge from stabilising and even slowly declining emissions (e.g., for current policy scenarios or SSP1) to very high emission levels (e.g., SSP5 and RCP8.5). The latter leads to nearly 5 °C of warming by the end of the century for medium climate sensitivity. 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. This means that reaching emissions levels as high as RCP8.5 has become less likely. Still, high emissions cannot be ruled out for many reasons, including political factors and, for instance, higher than anticipated population and economic growth. 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). Therefore, their median climate impacts might also materialise while following a lower emission path (e.g., Hausfather and Betts (2020)). All-in-all, this means that high-end scenarios have become considerably less likely since AR5 but cannot be ruled out. High-end scenarios (like RCP8.5) can be very useful to explore high-end risks of climate change but are not typical 'business-as-usual" projections and should therefore not be presented as such.

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