needs to make up its slow start by (i) rapid reductions mid-century and (ii) 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 stabilisation compared to current emissions, respectively.

3.3 Emission Pathways, Including Socio-economic, Carbon Budget and Climate Responses Uncertainties

3.3.1 Socio-economic Drivers of Emissions Scenarios

Greenhouse gas (GHG) 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 (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 (Figure 3.9a). 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 these differences, 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 3.9c). 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; Hickel and Kallis 2020; Kallis et al. 2020; Hickel et al. 2021; Keyßer and Lenzen 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.

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 AR6 Scenarios Database, Figure 3.9b). 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

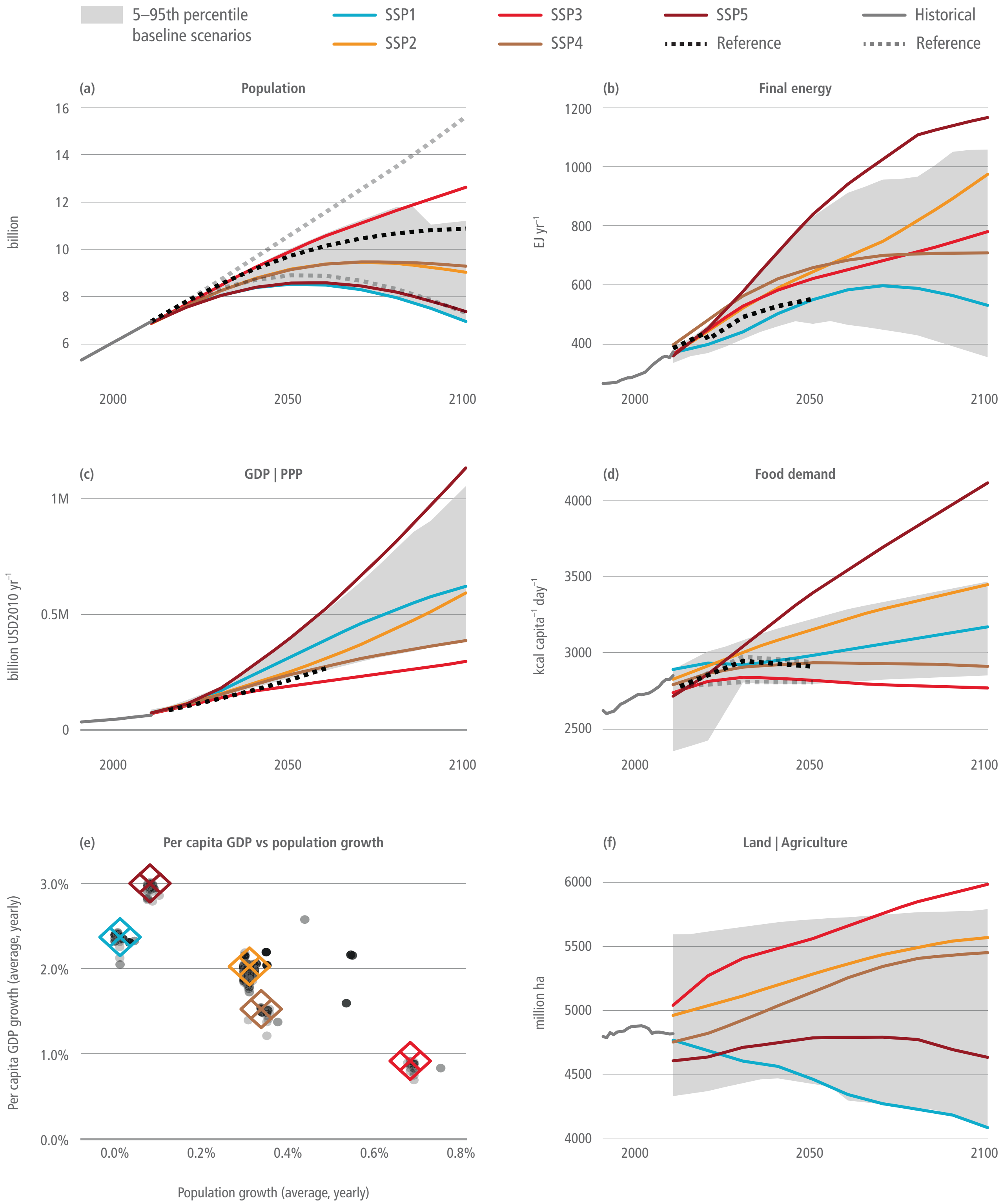

Figure 3.9 | Trends in key scenario characteristics and driving forces as included in the SSP scenarios (showing 5–95th percentiles of the reference scenarios as included in the database in grey shading). Reference (dotted lines) refers to the UN low-, medium- and high-population scenarios (UN 2019),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

pathways, their energy efficiency improvement rates are considerably above the historic range of around 2% (Gütschow et al. 2018; Jeffery et al. 2018; Vrontisi et al. 2018; Haberl et al. 2020; Roelfsema et al. 2020; Giarola et al. 2021; Höhne et al. 2021; IEA 2021a; Höhne et al. 2021; Sognnaes 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 (Figure 3.9d). However, it should be noted that there are large differences in dietary composition across the scenarios (from more meat-intensive in scenarios such as 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 (Figure 3.9f). Typically, changes in land use are less drastic than some other parameters (in fact, the 5–95th percentile database range is almost stable). Agriculture land is projected to increase in SSP3, SSP2, and SSP4 – it is 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 the impact of COVID-19 (Box 3.2).

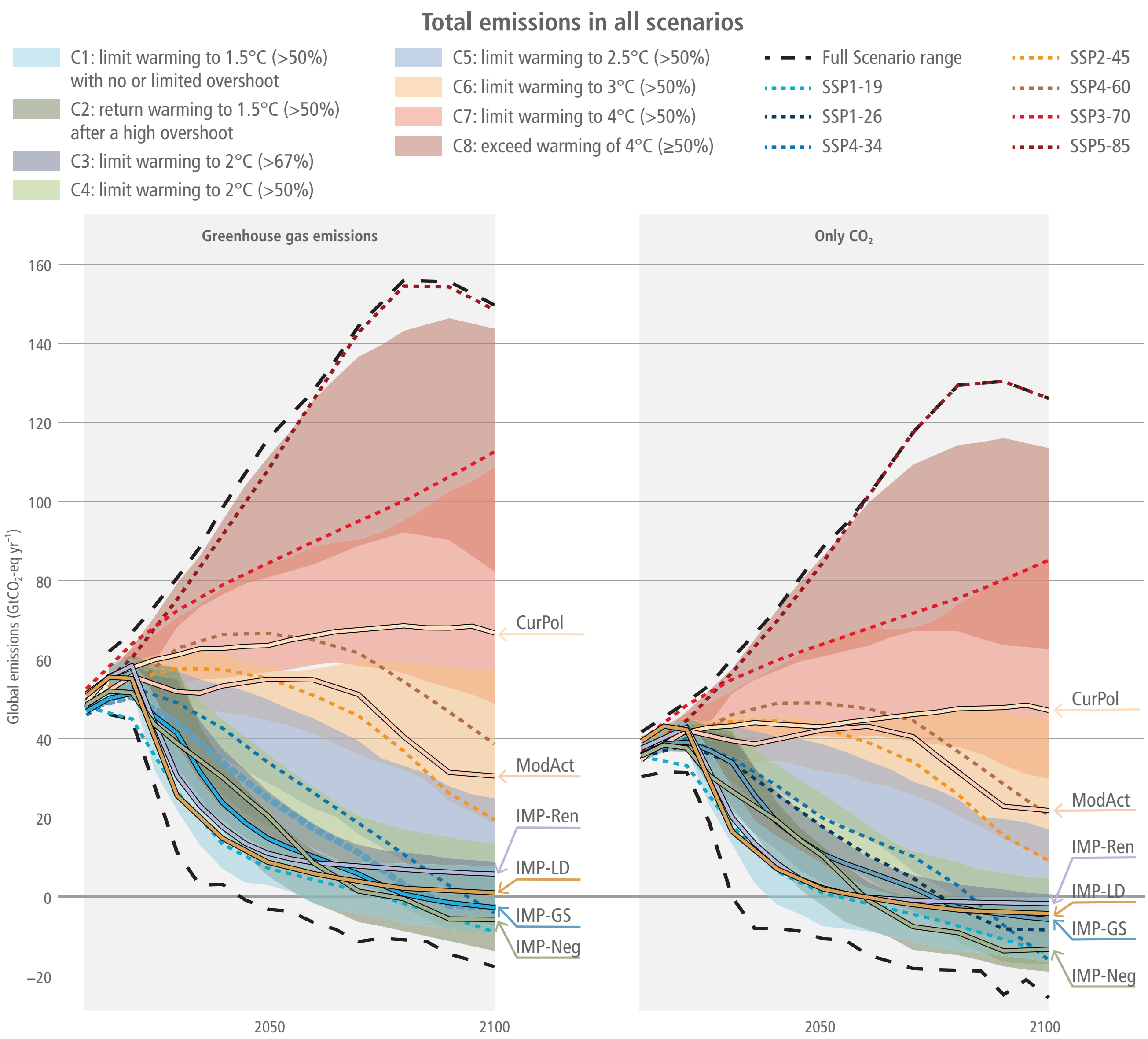

Figure 3.10 | Total emissions profiles in the scenarios based on climate category for GHGs (AR6 GWP-100) and CO_2. The Illustrative mitigation pathways (IMPs) are also indicated.

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% (Section 4.2.2.4 and Table 4.SM.2) lower than 2019 levels (Forster et al. 2020; Friedlingstein et al. 2020; Liu et al. 2020c; BP 2021; Crippa et al. 2021; IEA 2021; Le Quéré et al. 2021). 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 emissions 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 (Andrijevic et al. 2020b; Hepburn et al. 2020; Pianta et al. 2021). 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 (Bertram et al. 2021; Kikstra et al. 2021a; Pollitt et al. 2021; Rochedo et al. 2021; Shan et al. 202). 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 limit warming to 2°C (>67%) 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.

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 (Höhne et al. 2021; IEA 2021a; Jeffery et al. 2018; Gütschow et al. 2018). Based on the assessment in Chapter 4, reference pathways consistent with the implementation and trend from implemented policies until the end of 2020 are associated with increased GHG emissions from 59 (53–65) $GtCO_2$-eq yr^{-1} in 2019 to 54–60 $GtCO_2$-eq yr^{-1} by 2030 and to 47–67 $GtCO_2$-eq yr^{-1} by 2050 (Figure 3.6). Pathways with these near-term emissions characteristics lead to a median global warming of 2.2°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 socio-economic, technological, and policy assumptions (Giarola et al. 2021) found a 2.2°C–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 lead to a median range of 2.9°C–3.2°C in 2100 for current policies and 2.4°C–2.9°C in 2100 for 2030 pledges (Höhne et al. 2021). The median spread of 1°C across these studies (2.2°C–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 1.5°C 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 to 40 years before total GHG emissions reach net zero. The main reason is that scenarios reduce non-CO_2 greenhouse gas emissions less than CO_2 due to a limited mitigation potential (Section 3.3.2.2). Figure 3.10 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.

Figure 3.11 shows the possible consequences of the different scenario categories for global mean temperature calculated using a reduced complexity model (RCM) calibrated to the IPCC AR6 WGI assessment (see Annex III.II.2.5 of this report and Cross-Chapter Box 7.1 in AR6 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 *more likely than not* be in the range from 2.2°C to 3.5°C, warming up to 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 (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

Box 3.3 | The Likelihood of High-end Emissions Scenarios

At the time the Representative Concentration Pathways (RCPs) were published, they included three scenarios that could represent emission developments in the absence of climate policy: RCP4.5, RCP6 and RCP8.5, described as, respectively, low, medium and high-end scenarios in the absence of strong climate policy (van Vuuren et al. 2011). RCP8.5 was described as representative of the top 5% scenarios in the literature. The SSPs-based set of scenarios covered the RCP forcing levels, adding a new low scenario (at 1.9 W m^{-2}). 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 (Section 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 (AR6 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 realise 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 the C5–C7 categories included in this assessment.

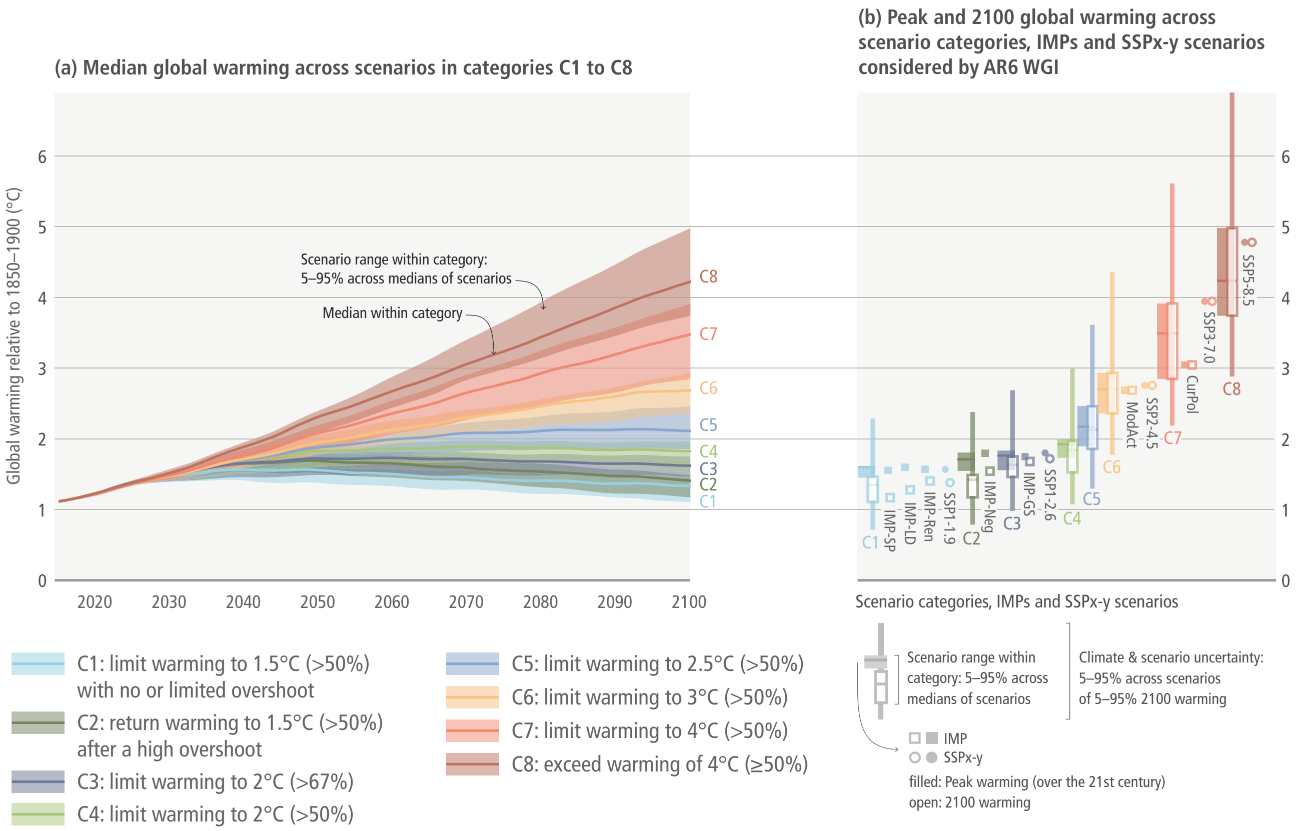

Figure 3.11 | Global mean temperature outcome of the ensemble of scenarios included in the climate categories C1–C8 (based on a reduced complexity model – RCM – calibrated to the WGI assessment, both in terms of future and historic warming). The left panel shows the ranges of scenario uncertainty (shaded 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).

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 *IMP-LD* and *IMP-Ren*) (Figure 3.10). In addition to the temperature caused by the range of scenarios in each category (main panel), climate uncertainties also contribute to a range of temperature outcomes (including uncertainties regarding the carbon cycle, climate sensitivity, and the rate of change, see AR6 WGI). The bars on the right of Figure 3.11 show the uncertainty range for each category (combining scenario and climate uncertainty). While the C1 category *more likely than not* limits warming to 1.5°C (>50%) by the end of the century, even with such a scenario, warming above 2°C cannot be excluded (95th percentile). The uncertainty range for the highest emission categories (C7) implies that these scenarios could lead to a warming above 6°C.

3.3.2.2 The Role of Carbon Dioxide and Other Greenhouse Gases

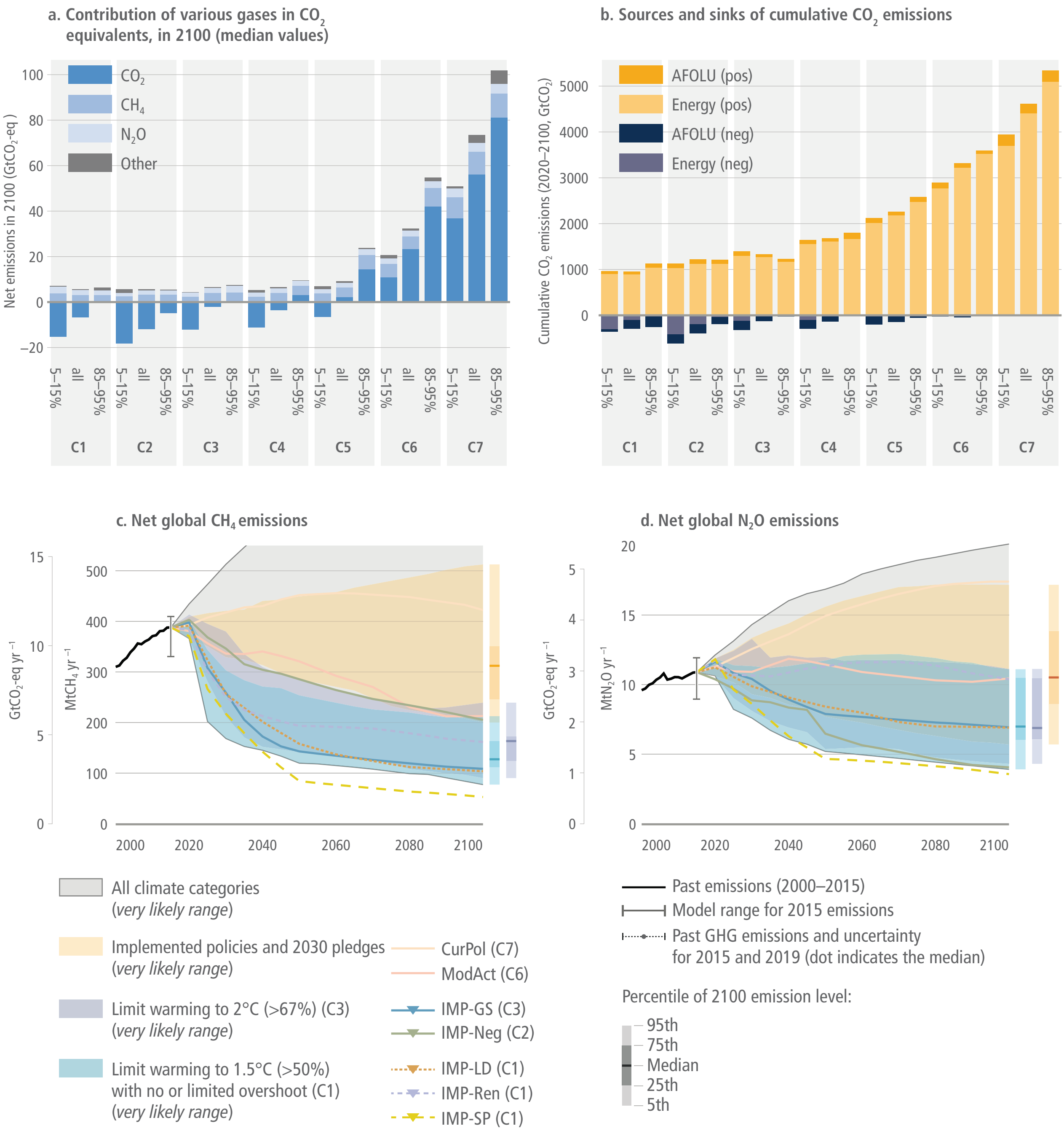

Figure 3.12 | (a) The role of CO_2 and other greenhouse gases. Emission in CO_2-eq in 2100 (using AR6 GWP-100) (other = halogenated gases) and **(b)** cumulative CO_2 emissions in the 2020–2100 period. Panels **(c)** and **(d)** show the development of CH_4 and N_2O emissions over time. Energy emissions 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.

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 (CDR) is still playing a role in compensating for remaining positive emissions in hard-to-abate sectors.

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 measures related to manure management, see also Chapter 7 and 11). However, technical potential estimates become 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, therefore reducing livestock (Stehfest et al. 2009; Willett et al. 2019; Ivanova et al. 2020) (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 (AR6 WGI, Figure SPM.2) (Shindell et al. 2012). These forcers consist of (i) substances contributing to warming, such as methane, black carbon and tropospheric ozone, and (ii) 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 (Takemura and Suzuki 2019; Smith et al. 2020b) (see also AR6 WGI 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) (Box 3.4). A more detailed discussion can be found in AR6 WGI Chapters 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 (GWPs) 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 2.1 in Chapter 2 of this report, and AR6 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 in Chapter 3). Depending on the metric, the value attributed to reducing short-lived forcers such as methane can be lower in the near term (e.g., in the case of GTP) or higher (GWP with a 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 that limit warming to 2°C (>67%) or lower (Box 2.1).

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 (Allen et al. 2009; Matthews et al. 2009; Meinshausen et al. 2009; MacDougall and Friedlingstein 2015). This is illustrated in Figure 3.13, which plots the cumulative CO_2 emissions against the projected outcome for global mean temperature, both until peak temperature and through to end of century (or 2100). The deviations from a 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-CO_2 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 $GtCO_2$ (AR6 WGI Chapter 5, Section 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 (Collins et al. 2018; van Vuuren et al. 2018) (see also AR6 WGI, Chapters 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.