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Pathways limiting warming to 1.5°C: a tale of turning around in no time?

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We explore the feasibility of limiting global warming to 1.5°C without overshoot and without the deployment of carbon dioxide removal (CDR) technologies. For this purpose, we perform a sensitivity analysis of four generic emissions reduction measures to identify a lower bound on future CO_2 emissions from fossil fuel combustion and industrial processes. Final energy demand reductions and electrification of energy end uses as well as decarbonization of electricity and non-electric energy supply are all considered. We find the lower bound of cumulative fossil fuel and industry CO_2 emissions to be 570 $GtCO_2$ for the period 2016–2100, around 250 $GtCO_2$ lower than the lower end of available 1.5°C mitigation pathways generated with integrated assessment models. Estimates of 1.5°C-consistent CO_2 budgets are highly uncertain and range between 100 and 900 $GtCO_2$ from 2016 onwards. Based on our sensitivity analysis, limiting warming to 1.5°C will require CDR or terrestrial net carbon uptake if 1.5°C-consistent budgets are smaller than 650 $GtCO_2$. The earlier CDR is deployed, the more it neutralizes post-2020 emissions rather than producing net negative emissions. Nevertheless, if the 1.5°C budget is smaller than 550 $GtCO_2$, temporary overshoot of the 1.5°C limit becomes unavoidable if CDR cannot be ramped up faster than to 4 $GtCO_2$ in 2040 and 10 $GtCO_2$ in 2050.

This article is part of the theme issue 'The Paris Agreement: understanding the physical and social challenges for a warming world of 1.5°C above pre-industrial levels'.

1. Introduction

The Paris Agreement is heralded as a breakthrough in international climate policy. It sets up a process to combine nationally determined contributions (NDCs) to a global response to climate change which is consistent with the long-term goal of limiting warming to well below 2°C. It also strengthens the long-term ambition to limit warming to 1.5°C. The remaining emissions budget under the 1.5°C limit, however, appears prohibitively small. Nations are not on track to even meet a 2°C limit [1–3]. Naturally, the question emerges whether limiting warming to 1.5°C is feasible at all and, if so, under which conditions this could be achieved. By now, the literature has provided some answers to these questions. A few studies have conducted sensitivity analyses of emissions profiles consistent with 1.5°C, highlighting the combined need for deep emissions reductions and carbon dioxide removal (CDR) [4,5]. Several studies have explored 1.5°C pathways with integrated assessment models (IAMs) describing the coupled energy–land–economy–climate system [6–9]. All of these pathways rely heavily on CDR from the atmosphere to accelerate the phase-out of anthropogenic CO_2 emissions until mid-century and thereafter establish net negative emissions to return cumulative CO_2 emissions to levels consistent with the remaining 1.5°C budget by the end of century. These pathways overshoot 1.5°C during the twenty-first century and provide a median probability of returning to below 1.5°C warming by 2100. They share similar characteristics in terms of mitigation strategy to 2°C pathways, i.e. early decarbonization of electricity generation combined with reduced energy demand, accelerated electrification of energy services, replacement of fossil fuel use in energy end-use sectors by biofuels and to a more limited degree hydrogen, and compensation of residual fossil fuel use with CDR [1,10,11]. However, these transitions are accelerated in 1.5°C pathways such that net zero CO_2 emissions are reached around mid-century, around 20 years earlier than in 2°C pathways [7].

A host of questions still remain. Is such acceleration feasible or can the transition proceed even faster than projected in available 1.5°C pathways? Are pathways conceivable with less overshoot or less CDR deployment, which typically exceeds 500 $GtCO_2$ over the century in available 1.5°C pathways? Are there alternative mitigation options not fully captured in current pathway modelling that would alter the shape and CDR reliance of 1.5°C pathways? To explore these questions, our analysis starts from two important insights. First, the question of feasibility cannot directly be answered because the concept of feasibility itself cannot be clearly defined. Several attempts to elaborate the concept [10,12,13] demonstrate the difficulties involved. Obviously, model feasibility cannot directly be related to real-world feasibility as models may be able to generate pathways that cannot be implemented in practice and vice versa. Different layers of feasibility—physical, technical, socio-economic and sociopolitical—help to break down the concept in a more meaningful way, but still leave enough overlap and room for interpretation to make the question of feasibility intractable. We, therefore, restrict ourselves to an analysis of the conditions that would need to be met for the identification of 1.5°C pathways without substantial overshoot or CDR deployment.

Second, exploring the lower bound of anthropogenic CO_2 emissions brings us into deeply uncertain territory about the future development of emissions drivers, technology and society

[14–17]. Will electric airliners come into reach 50 years from now? Will nuclear fusion finally make good on its promise to become a commercial energy source by then? These are just two examples of unanswerable questions on future innovation which are relevant for the assessment of 1.5°C pathways. In the face of such deep uncertainty, available pathway modelling takes the most tenable position of relying on the range of technologies and their learning rates described in the literature rather than introducing unspecified backstop technologies or fictional proposals. To go beyond this, it is useful to abstract from the details of individual pathways and associated technology portfolios. Such an approach of reduced granularity in long-term forecasts was suggested by Morgan & Keith [18] to explore high-level implications for long-term emissions strategies in the presence of deep uncertainty. Here we compare 1.5°C pathways with back-of-the-envelope projections of key determinants of future anthropogenic fossil fuel use and assumptions of CDR deployment to explore the following question: to what extent is overshoot and CDR needed in 1.5°C pathways? In this context, we will also ask whether energy demand-side options that are traditionally less well represented in IAMs than energy supply-side mitigation options have the potential to change the current perspective on 1.5°C pathways in the literature.

The study is presented in four sections. The next section discusses the 1.5°C carbon budget and the general structure of 1.5°C pathways. Section 3 introduces our emissions decomposition approach and the associated sensitivity analysis of supply- and demand-side mitigation measures. Section 4 presents the results for the lower end of anthropogenic CO_2 emissions in the twenty-first century and the implications for overshoot and CDR requirements. Section 5 concludes.

2. Carbon budget and emissions pathways for limiting warming to 1.5°C

(a) The 1.5°C carbon budget

The amount of cumulative CO_2 emissions into the atmosphere is a critical indicator for the investigation of temperature overshoot in mitigation pathways. CO_2 is the most prevalent anthropogenic greenhouse gas (GHG). Owing to its longevity in the atmosphere and the exchange of heat between ocean and atmosphere, the warming from a pulse of CO_2 emissions remains important over multiple centuries. Warming from CO_2 emissions accumulates linearly over time, and a warming limit can be associated with a finite carbon emissions budget [19]. The size of the carbon budget is governed by the transient climate response to cumulative CO_2 emissions (TCRE) which is estimated to be likely in the range of 0.2–0.7°C per 1000 $GtCO_2$ (0.8–2.5°C per 1000 GtC) [20]. TCRE estimates vary between models and methods, with the median of the CMIP5 Earth system model ensemble located around 0.45°C per 1000 $GtCO_2$ and the median from historical observations estimated to be 0.37°C per 1000 $GtCO_2$ [21]. The linear relationship between cumulative emissions and temperature increase holds for warming from CO_2 only until the time of peak warming (and peak cumulative CO_2 emissions) and for cumulative CO_2 emissions up to 7000 $GtCO_2$ [20].

A policy-relevant carbon budget for future CO_2 emissions needs to take into account also anthropogenic emissions of other GHGs and forcing agents. A multi-forcer perspective is particularly relevant for stringent mitigation pathways which project an increasing share of non-CO_2 forcing over time due to limited reduction potentials, in particular for methane and nitrous oxide emissions in the agricultural sector [22]. Carbon budgets in multi-forcer contexts are usually estimated on the basis of available multi-gas emissions scenarios fed into Earth system models or reduced-form climate models as, e.g., used in IAMs [23,24]. This has given rise to different concepts of carbon budgets depending on the choice of scenario [25] and increased the complexity of the carbon budget approach considerably.

The TCRE estimates can still be applied in a multi-gas context if the warming from non-CO_2 climate forcers is subtracted from the overall warming signal. Non-CO_2 warming at the time of peak warming has been estimated to be in the range of 0.4–0.6°C in 2°C pathways [25],

Table 1. Remaining carbon budgets from 2016 onwards for limiting warming to 1.5°C and 2°C with 50% probability as a function of the additional warming from non-CO_2 gases at the time of peak CO_2 warming and two different TCRE estimates [21]. Budgets from 2016 onwards were calculated assuming 2090 $GtCO_2$ emitted by 2016 (1890 $GtCO_2$ emitted by 2011 [20] and 200 $GtCO_2$ emitted during 2011–2015 [26]). (Online version in colour.)

		1.5°C limit		**2°C limit**	
TCRE	**Non-CO_2 warming**	0.3°C	0.5°C	0.4°C	0.6°C
0.45°C per 1000 $GtCO_2$		580 $GtCO_2$	130 $GtCO_2$	1470 $GtCO_2$	1020 $GtCO_2$
0.37°C per 1000 $GtCO_2$		1150 $GtCO_2$	610 $GtCO_2$	2230 $GtCO_2$	1690 $GtCO_2$

and can be lower in 1.5°C pathways. The uncertainty about the TCRE and non-CO_2 warming leads to considerable uncertainty about the actual carbon budget for limiting warming to 1.5°C (table 1). Current 1.5°C budgets discussed in the climate policy context are heavily influenced by extrapolations of the multi-gas budget estimates derived in the Fifth Assessment Report of the IPCC [20]. Those extrapolations based on the RCP2.6 or RCP8.5 multi-gas emissions trajectories suggest a residual budget of only approximately 100 GtCO2 from 2016 onwards. Recently, a study claimed that the likely 1.5°C budget could be as high as 730–880 $GtCO_2$. This was based on the fact that the amount of cumulative CO_2 emissions to reach current warming levels as backcasted by Earth system models was lower than empirical estimates of CO_2 emissions, and thus the amount of CO_2 emissions to reach 1.5°C might actually be higher than originally suggested [27]. Given all this uncertainty, we consider a large range of 1.5°C budgets for our analysis here.

Available 1.5°C pathways tend to lead to peak warming above 1.5°C and return to median 1.5°C temperature values by 2100. The resulting ‘return budgets’ for the period 2016–2100 are expected to be lower than the peak budgets for CO_2 emissions trajectories that peak temperature at 1.5°C due to hysteresis in the temperature response to net negative emissions [28,29]. Available estimates for 2016–2100 budgets in a class of 1.5°C pathways with temporary overshoot including pathways that fall below 1.5°C in 2100 range from −110 to 110 $GtCO_2$ [30] and 0 to 220 $GtCO_2$ [7]. Further research will be needed to narrow down the uncertainty about the remaining carbon budget for both limiting peak warming to 1.5°C and returning warming to 1.5°C after a peak.

(b) Evolution of CO_2 emissions in 1.5°C pathways

To set up our analysis, we start with an assessment of the main emissions drivers and reduction potentials in 1.5°C mitigation pathways in the literature. Figure 1 depicts the example of a pair of 1.5°C (SSP2–1.9) and 2°C (SSP2–2.6) scenarios developed with the IAM framework REMIND-MAgPIE [8,31]. The anthropogenic CO_2 emissions are separated into four components:

1. gross CO_2 emissions from fossil fuel power plants in the power sector, not including oxidized fossil carbon captured and sequestered underground by carbon capture and storage (CCS) technologies,
2. gross CO_2 emissions from fossil fuel combustion outside the power sector and from industrial processes, not including oxidized fossil carbon captured and sequestered underground by CCS technologies,
3. net CO_2 emissions from agriculture, forestry and other land uses, including terrestrial CDR by measures such as afforestation, soil carbon enrichment and land restoration, and
4. CDR by energy and industrial applications, most prominently application of bioenergy with CCS, known as bioenergy with carbon capture and storage (BECCS) [32]. Other measures such as bio-based plastics, direct air capture and mineralization of atmospheric carbon are also conceivable in this category, although they have been rarely included in pathway modelling to date.

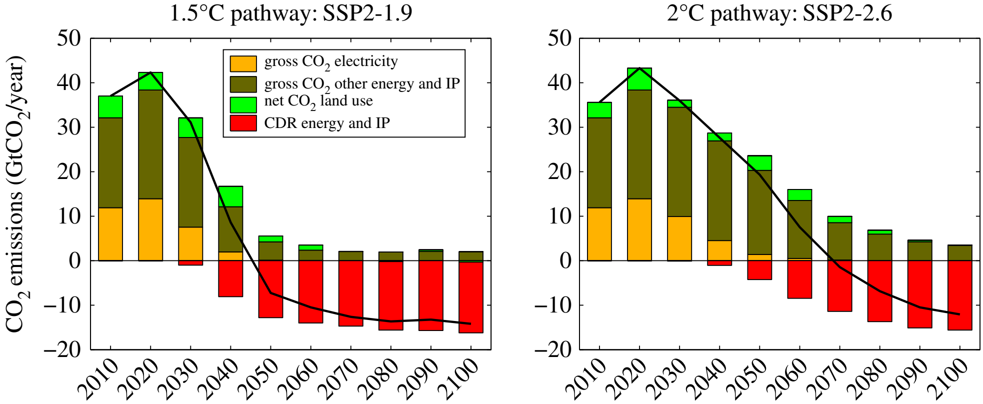

Figure 1. Example of 1.5°C (1.9 W m^{-2}) and 2°C pathways (2.6 W m^{-2}) derived from the REMIND-MAgPIE model under assumptions described by Shared Socio-economic Pathway 2 (SSP2) [31]. (Online version in colour.)

As shown in figure 1, power sector CO_2 emissions are phased out and other fossil fuel and industry (FFI)-related CO_2 emissions are greatly reduced [8–11,33]. Some residual CO_2 emissions from fossil fuel use remain and are compensated by industrial and energy sector CDR. Moreover, an additional amount of CDR leads to net negative CO_2 emissions compensating for remaining non-CO_2 emissions particularly from the land-use sector as well as for earlier CO_2 emissions that exceeded the available CO_2 budget. The overshoot of the 1.5°C temperature limit is determined by the cumulative amount of net negative emissions that return the amount of CO_2 emitted over the twenty-first century to values consistent with the long-term climate target. In the selected model scenarios in figure 1, net land-use CO_2 emissions are comparatively small and mostly occur in the first half of the twenty-first century. Other models have shown a significant contribution of afforestation to augment and substitute CDR via BECCS in the energy sector [8,17,34].

The sectoral pattern of emission reductions has a similar stucture in 1.5°C and 2°C pathways but the transition is accelerated in 1.5°C pathways (figure 1). Carbon neutrality is reached before mid-century rather than around 2070; CO_2 emissions from energy end use are reduced earlier and deeper, and energy sector CDR is deployed earlier at scale [7]. Despite the acceleration, the 1.5°C pathway still overshoots the 1.5°C target at the time of the temperature peak. To further limit the overshoot, the fossil fuel and industrial process (FFI) CO_2 emissions in the first half of the century would need to be reduced even faster or CDR would need to be deployed at scale even earlier to compensate residual emissions before the point of carbon neutrality is reached.

3. Material and methods

(a) General approach and decomposition of anthropogenic CO_2 emissions

Based on this assessment, we proceed in three steps to identify conditions for the existence of 1.5°C pathways that do not rely on substantial CDR deployment or do not lead to temporary overshoot of 1.5°C.

1. Conduct a sensitivity analysis to explore the lower end of gross anthropogenic CO_2 emissions into the atmosphere before any CDR is applied (see [9] for such an analysis based on a set of IAM pathways).
2. Combine this with assumptions about the upper end of the pace and extent of CDR deployment [5].
3. Compare the resulting cumulative CO2 emissions over the twenty-first century with estimates about the CO_2 budget consistent with limiting warming to 1.5°C.

With regard to the first step, we investigate the maximum speed at which the gross FFI CO_2 could be brought down to their minimum level. To explore the possibility of obtaining FFI CO_2 emissions below the range of available 1.5°C pathways in the literature [7–9], we employ a simple decomposition of FFI CO_2 emissions that allows us to conduct a sensitivity analysis of the central supply- and demand-side measures driving the emissions reductions:

$$\mathrm{CO_2FFI}(t) = \mathrm{FE}(t)\mathrm{ES}(t)\mathrm{CI}_{\mathrm{elec}}(t) + \mathrm{FE}(t)(1 - \mathrm{ES}(t))\mathrm{CI}_{\text{non-elec}}(t),$$

where CO_2 FFI is the CO_2 emissions from fossil fuel combustion and industrial processes (FFI), FE is the final energy demand, ES is the electricity share in the final energy mix, $\mathrm{CI}_{\mathrm{elec}}$ is the carbon intensity of electricity delivered to the consumer, and $\mathrm{CI}_{\text{non-elec}}$ is the average carbon intensity of other energy carriers delivered to the consumer (solids, liquids, gases, hydrogen, heat, including emissions from the primary to secondary energy conversion process) and of industrial processing.

The two central supply-side measures are the reduction of carbon intensity in the electricity and other sectors (§3c). The two central demand-side measures are the reduction of final energy demand and the electrification of energy use in the industry, transport and buildings sectors (§3d), because the electricity sector will be decarbonized first in deep mitigation pathways (figure 2). In the following, we will introduce the variations of $\mathrm{CI}_{\mathrm{elec}}$ (four cases), $\mathrm{CI}_{\text{non-elec}}$ (four cases), ES (five cases) and FE (four cases) that are considered in our sensitivity analysis. They will then be combined to 320 trajectories spanning the low end of gross anthropogenic FFI CO_2 emissions during the twenty-first century.

(b) The concept of limiting cases

To derive an estimate on the maximum speed of CO_2 emissions reductions, we introduce the concept of limiting cases for the deployment of CDR (step 2 above) and the central supply- and demand-side measures (step 1 above). This necessarily includes a subjective element as experts will have diverging views on what is still feasible and what would no longer be feasible. Here we conceptualize the limiting case as something only a minority of experts would still consider feasible. With regard to our analysis, this implies firmer ground for the potential finding that overshoot is required for limiting warming to 1.5°C because emissions are unlikely to turn out lower to avoid overshoot; and less firmer ground for the potential opposite finding because emissions may turn out higher causing overshoot even though it was avoided in the limiting case.

The sensitivity cases including the limiting cases are described in simple terms of a schedule of benchmark values for selected points in time and growth rates for the periods in between. This should allow them to be used easily as benchmarks for detailed sector decarbonization studies. Our numerical specifications of the limiting cases will be informed guesses based on the available literature and mitigation pathway data (see §§3b and 3c). No formal expert elicitation was attempted for this analysis.

We estimate the upper end of the speed at which CDR deployment can be ramped up [5] based on a limiting case of massive CDR deployment. It is described by a logistic growth function which is typical for technology diffusion processes [35]. Here we assume a maximum capacity level of 20 $GtCO_2$/year, half of it reached by 2050 and a growth from 5% to 95% of maximum capacity from 2030 to 2070. This amounts to an initial growth of CDR deployment of approximately 15% per year. The deployment limit is described by post-2020 CDR ramp-ups to 1, 4, 10, 16, 19 and a maximum of 20 $GtCO_2$/year in 2030, 2040, 2050, 2060, 2070 and 2080, respectively (figure S2 in the electronic supplementary material). A CDR deployment along this limiting case would result in approximately 1000 $GtCO_2$ removed from the atmosphere over the period from 2021 to 2100. Given our treatment of AFOLU (agriculture, forestry and other land use) CO_2 emissions above, CDR in our case has to be understood as including engineered and natural net terrestrial carbon uptake. Nevertheless, 1000 $GtCO_2$ cumulatively and 20 $GtCO_2$ annually are very large deployment levels that would be very challenging to reach. There are strong sustainability concerns associated with CDR at much lower levels [36].

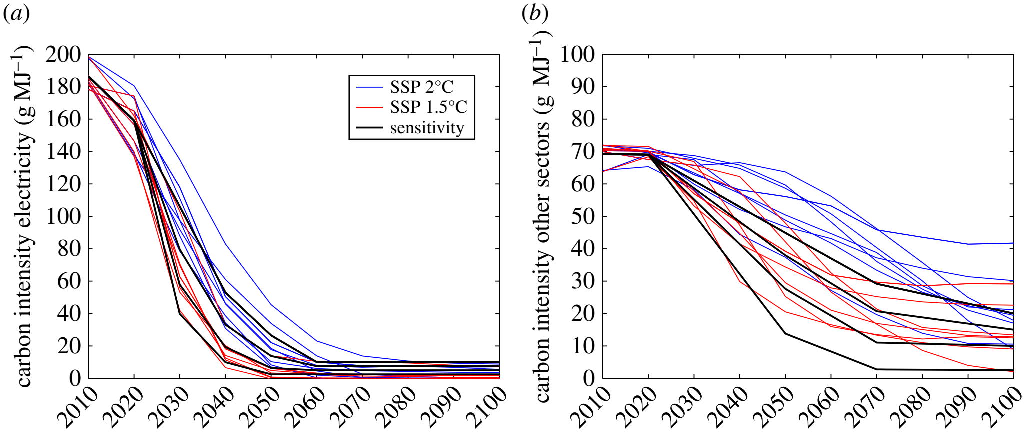

Figure 2. Carbon intensity of electricity generation (*a*) and fuel use in other sectors (*b*) for an ensemble of 1.5°C and 2°C pathways derived from integrated assessment models (SSP1-1.9, SSP2-1.9, SSP1-2.6, SSP2-2.6 from the AIM, IMAGE, MESSAGE-GLOBIOM and REMIND-MAgPIE models). Black lines denote the stylized carbon intensity cases developed for the sensitivity analysis in this paper. (Online version in colour.)

(c) Sensitivity analysis of supply-side emissions reduction measures

The recently published IAM pathways developed across the variation of shared socio-economic pathways (SSPs) [37,38] provide a unique resource to simultaneously investigate the dependence of deep mitigation pathways on the choice of climate target as well as on socio-economic development assumptions including societal factors and consumption patterns captured in the SSP narratives ([17]; see [8] for the SSP-based 1.5°C pathways; data available at https://secure.iiasa.ac.at/web-apps/ene/SspDb). They, therefore, give a good estimate of the range of deployments of supply- and demand-side emissions reductions measures in the recent mitigation pathway literature hinting at what could constitute a limiting case. For example, SSP1 (sustainability) is a world with a peak and decline in population, rapid convergence of *per capita* income at high levels, resource- and energy-efficient consumption and preferences for clean and renewable energy. By contrast, SSP2 (middle of the road) has higher population growth, slower and regionally differentiated income growth and mixed patterns in energy and resource use, retaining a considerable reliance on fossil fuels [17,33]. Here we use 2°C pathways (SSP1-2.6 and SSP2-2.6, peaking and declining radiative forcing to 2.6 $\mathrm{W\,m^{-2}}$ in 2100 [17]) and 1.5°C pathways (SSP1-1.9 and SSP2-1.9, peaking and declining to 1.9 $\mathrm{W\,m^{-2}}$ in 2100 [8]) from this set.

Figure 2 shows the reduction of carbon intensity for electricity generation and other energy carriers in 1.5°C and 2°C pathways developed by four global IAMs, AIM [39], IMAGE [40], MESSAGE-GLOBIOM [41] and REMIND-MAgPIE [31]. The range from the SSP-based deep mitigation scenarios is contrasted with a bottom-up sensitivity analysis of possible carbon intensity reductions. To ensure consistency with current global trends in the sensitivity analysis, the projection of carbon intensity up to 2020 followed the mean of the SSP-based pathways (global average reductions from approx. 190 g CO_2/MJ in 2010 to approx. 160 g CO_2/MJ in 2020 for electricity generation and stable at approx. 70 g CO_2/MJ over the period 2010–2020 for the other sectors). Beyond 2020, four different scenarios of decarbonization speed and depth were assumed for both cases. In the case of electricity generation, carbon intensity was assumed to be reduced by a factor of 1.5 (to 110 g CO_2/MJ) up to a factor of 4 (40 g CO_2/MJ) by 2030, and by an additional factor of 4 (to 30 g CO_2/MJ) up to a factor of 16 (2.5 g CO_2/MJ) by mid-century. Long-term carbon intensity floors were assumed to range between 10 gCO_2/MJ and 2.5 gCO_2/MJ. To put these numbers into context, a power mix with such low carbon intensities could only entertain a negligible amount of fossil fuel-fired power generation without CCS. And even with CCS, coal-fired power plants with a 99% CO_2 capture rate would barely reach the 10 gCO_2/MJ standard, and neither gas nor coal plants with CCS would be able to reach 2.5 g CO_2/MJ. The sensitivity cases thus all imply an almost complete phase-out of fossil fuel use in the electricity sector, as robustly shown in deep mitigation pathways [8,33]. As can be seen in figure 2, the assumed sensitivity cases cover the range of speeds and depths of power sector decarbonization in SSP-based 1.5°C pathways. As IAMs have a detailed representation of the electricity sector and its decarbonization potential [11], we take the radical transition of the sector projected in the lowest 1.5°C pathway in figure 2 as a limiting case.

For the sensitivity analysis of global average carbon intensity reductions of other energy carriers and industrial processes, we assumed a linear decline of 35%, 45%, 60%, 80% of carbon intensity from 2020 until 2050 and again from 2050 until 2070, followed by a linear extrapolation to end-of-century values of 20, 15, 10 and 2.5 gCO_2/MJ, respectively. The more linear decline compared to the power sector captures the fact that the use of solids, gases and liquids in energy end-use sectors is harder and slower to decarbonize. CCS in the industry sector and replacement of fossil fuels with biomass, hydrogen and carbon-neutral synthetic fuels are among the main decarbonization options here. As shown in figure 2, the upper three decarbonization cases approximately cover the range of SSP-based 1.5°C pathways, while the lower case falls below this range. In this assumed limiting case, the carbon intensity of the non-electric fuel mix is reduced by a factor of 5 by 2050 and a factor of 25 by 2070, falling to negligible levels within 50 years. The case was constructed to reflect the fact that most IAMs of the current generation, including those analysed here, do not include a number of breakthrough technologies that could help to decarbonize non-electric fuels faster and deeper. This includes the production of carbon-neutral liquids and gases, e.g. algae-based biofuels [42] and synthetic fuels generated from renewable based Power-to-X technologies and CO_2 captured from the atmosphere [43,44].

(d) Sensitivity analysis of demand-side emissions reduction measures

Figure 3 shows final energy demand in the 1.5°C and 2°C SSP-based pathways from the four IAMs. In contrast to carbon intensity, there is a large and overlapping spread of energy demand developments in both sets of pathways (300–700 EJ/year by the end of century, i.e. 75% to 175% of present day levels). This is due to the widely varying assumptions about population and economic growth as well as resource efficiency and consumption patterns in the SSPs. On the lower end marked by the sustainability narrative of SSP1, energy demand stabilizes below present-day levels in the second half of the century despite an eightfold increase in average global *per capita* income. This shows that the mitigation pathway literature includes low-energy-demand scenarios [10,12,17] independently of the fact that demand-side mitigation measures are less well represented in IAMs. It can be seen that 1.5°C pathways show a transitory drop in energy demand triggered by the disruptive implementation of strong carbon pricing policies after 2020.

For the back-of-the-envelope sensitivity analysis of future final energy demand, we develop separate projections for future gross domestic product (GDP) growth and energy intensity of economic activity. In the SSP-based pathways, the global gross world product (GWP) measured in units of purchasing power parity (PPP) grows at approximately 4% per year in the period 2010–2020 and at an average of approximately 2.3% per year over the century in SSP1 and SSP2 [45]. Both SSPs reach similar end-of-century GWP values of 540 trillion dollars (SSP2) to 565 trillion dollars (SSP1), but with very different population levels of 9 billion (SSP2) and 6.8 billion (SSP1), respectively. An intermediate GWP trajectory between SSP1 and SSP2 can be derived by assuming that economic growth falls to a third of its 2020 value by the end of the century[1].

The sensitivity analysis is introduced on the level of energy intensity measured as final energy per unit of GWP in PPP. In the SSP-based mitigation pathways shown in figure 3, energy intensity is projected to improve by an annual average of 2.7% during the period 2010–2020, close to the rate observed over the previous decade [46]. Energy intensity improvements, however, are boosted further by a carbon pricing shock in the post-2020 transition period, before they decline

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[1] Economic growth rate $g_Y(t > 2020) = 4\%/(1+(t-2020)/40))$.

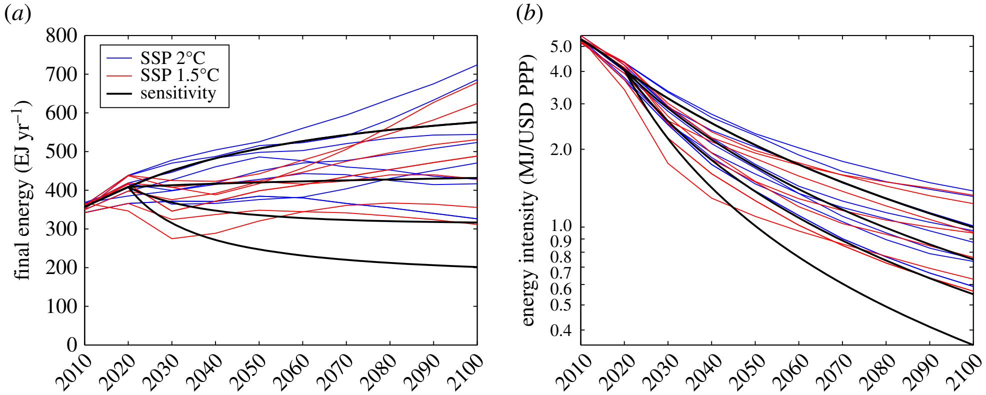

Figure 3. Global final energy demand (*a*) and underlying energy intensity improvements per unit of GDP (*b*) for an ensemble of 1.5°C and 2°C pathways derived from integrated assessment models (SSP1-1.9, SSP2-1.9, SSP1-2.6, SSP2-2.6 from the AIM, IMAGE, MESSAGE-GLOBIOM and REMIND-MAgPIE models). Black lines denote the stylized energy intensity and final energy demand cases developed for the sensitivity analysis in this paper. (Online version in colour.)

to lower improvement rates in the second half of the century due to increasing technology limits at increasingly high energy efficiency levels. Here we assume that post-2020 energy intensity improvement rates reduce by a factor of 2.3 to 5 until 2100 and are chosen such that end-of-century intensities of 0.35, 0.55, 0.75 and 1.0 MJ/USD are reached (compared to 4.1 MJ/USD projected by the SSP scenarios for 2020). This yields improvement rates in the year 2020 ranging from a dramatic 7.7% in the lowest case to 2.7% in the highest case, falling to 1.5% and 1.2%, respectively, in the year 2100. The lower end of this range presents a continuation of recent trends. The limiting case at the high end of the range goes far beyond the pace of energy intensity improvements observed over the past half decade, suggesting that fundamental and transformative changes are required to achieve it.

Such a boost only seems plausible if energy efficiency potentials identified in the literature are fully realized, but achieved earlier than anticipated by the respective studies. For the buildings sector, strict building codes and deep retrofitting can reduce specific energy requirements per floor space to less than a third of current levels [47], and achieve savings in total final energy for heating in excess of 50% compared to a reference scenario continuing current policy trends [48]. For transportation, both efficiency improvements in internal combustion engines as well as the introduction of electric engines, which are characterized by an about threefold higher final energy efficiency, are estimated to yield demand reductions of up to 50% relative to reference levels [9,49]. Efficiency potential in industry is estimated to be more modest. A recent study estimated that broad adoption of energy efficiency improvement measures could yield an additional decrease of energy intensity by 24% until 2050 relative to the reference level [50]. Similarly, the International Energy Agency estimates a potential for reducing energy intensity by 30% until 2060 [48]. Material efficiency, i.e. providing material services with lower levels of material production through light-weighting, higher recycling and substitution could provide further energy demand reductions, but is thus far under-researched [51]. This bottom-up assessment indicates that overall reductions of final energy demand across sectors to less than half of the present value will be extremely challenging. The limiting case we consider here describes such a development.

As shown in figure 3, the upper three energy demand sensitivity cases cover the range of demand projections from the SSP-based 1.5°C and 2°C pathways. The limiting case is defined by a radical energy demand reduction scenario falling well below the available 1.5°C pathways before mid-century. It reaches a final energy demand of 200 EJ in 2100, only half of current levels. Recently, a low-energy-demand scenario for sustainable development was proposed which constitutes the lowest energy demand projection for the twenty-first century to date [52]. Our limiting case still falls slightly below this scenario. Reaching such low levels with

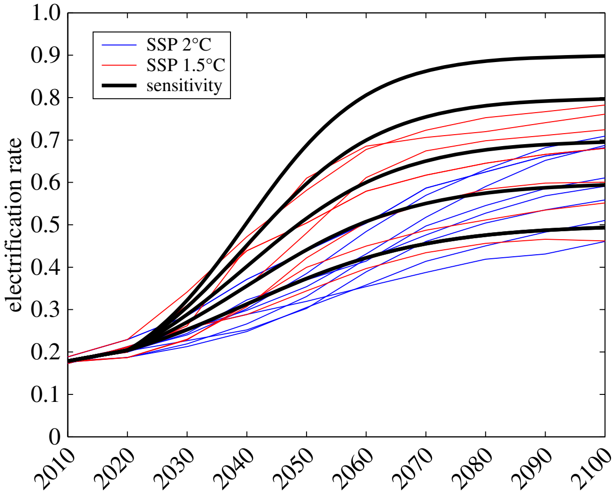

Figure 4. Electrification of final energy for an ensemble of 1.5°C and 2°C pathways derived from integrated assessment models (SSP1-1.9, SSP2-1.9, SSP1-2.6, SSP2-2.6 from the AIM, IMAGE, MESSAGE-GLOBIOM and REMIND-MAgPIE models). Black lines denote the stylized electrification rates developed for the sensitivity analysis in this paper. (Online version in colour.)

continued economic development would require a highly energy-efficient world with a much better conversion ratio between final and useful energy than today [53]. Such a scenario also has to assume that potential drivers of energy demand in the future like exponentially increasing computing needs will not play a large role.

The electrification of energy demand in the transport, buildings and industry sectors amplifies the emissions reduction gains from a rapid decarbonization of the electricity mix. Accelerating electrification is, therefore, an important demand-side measure in deep mitigation pathways. SSP-based pathways project a modest increase of the electricity share in the final energy demand across all sectors from 18% in 2010 to 20% in 2020 followed by a substantial acceleration to 35–60% in 2050 (figure 4). As increasing electrification approaches technical limits, the electrification rate slows again towards the end of the century, reaching 45–80% in SSP-based 1.5°C pathways. Our sensitivity analysis emulates the logistic growth of electrifying energy end use in the mitigation pathways using the following formula for electricity share ES(t) over time:

$$\mathrm{ES}(t > 2020) = \frac{\mathrm{ES}_{\mathrm{max}} - c}{(1 + \exp(-g(t - 2040))} + c,$$

with maximum electricity share $\mathrm{ES}_{\mathrm{max}}$ ranging between 50% and 90% in steps of 10%, and the time period during which electricity share increases by a factor 2.7 (Euler's number) varying between 15 and 10 years in steps of 1.25 years. The constant c is chosen such that the electricity share in 2020 matches the mean value from the SSP-based pathways.

Figure 4 shows that the lower four cases cover the range of electricity shares in 1.5°C pathways. In addition, we include a strong electrification scenario which goes above the 1.5°C pathways after 2030, reaching electricity shares of 70% in 2050, 80% in 2060 and 90% by 2100. Future non-electric energy demand is projected to be dominated by the industry and transportation sectors, while end uses in the buildings sector are more amenable to electrification [9,48]. A very high electricity share by mid-century thus hinges critically on overcoming electrification barriers in these two sectors. For transportation, aviation is likely to continue to rely on hydrocarbon fuels. Slowing the growth of air-based transport is, therefore, crucial for enabling high shares of electricity in transport energy demand. In the case of surface freight transport, large-scale electrification seems challenging but increasingly plausible given concepts for battery electric trucks or catenary electric truck systems [54]. Rapid progress in battery technology would also foster widespread adoption of electric vehicles for road passenger transport. Steel production, the most energy-intensive industry sector, can largely be electrified, albeit at relatively high costs. Many other industrial processes require medium to very high temperature heat [48]. While not suitable for highly efficient heat pumps, most of these processes can still be electrified, albeit, again, at relatively high costs. Despite these challenges, Blesl & Kessler estimate in a case study for Germany that around two-thirds of process heat requirements can be electrified [55]. Taken together, reaching a 90% electricity share across the transport, industry and buildings sector as assumed in our limiting case will be extremely challenging.

4. Results

(a) Lower bound on CO_2 energy and industrial process emissions in the twenty-first century

The sensitivity analysis of central emissions reduction measures on the supply and demand side generates a set of FFI CO_2 emissions trajectories for deep mitigation pathways. In this way, the sensitivity analysis enables us to analyse the range of residual FFI CO_2 emissions in deep mitigation pathways beyond what has been derived with IAMs. Of particular interest is the lower bound of residual emissions that is directly relevant for the question whether limiting warming to 1.5°C without overshoot is still possible.

Figure 5 compares the sensitivity range with the FFI CO_2 emissions from the SSP-based 1.5°C and 2°C pathways. The inclusion of cases with deeper reductions in final energy and deeper decarbonization of non-electric energy supply as well as higher electrification in the energy end-use sectors leads to a lower end of emission projections that falls below the 1.5°C pathways from the literature. Lowest emissions in the sensitivity analysis are 14.8 $GtCO_2$ in 2030, 5.7 $GtCO_2$ in 2040, 1.5 $GtCO_2$ in 2050 and a residual 0.5 $GtCO_2$ after 2080. The lowest values from the set of 1.5°C pathways are 18.4 $GtCO_2$ in 2030, 8.9 $GtCO_2$ in 2040, 4.2 $GtCO_2$ in 2050, 2.0 $GtCO_2$ in 2080 and 0.5 $GtCO_2$ in 2100. Deeper emissions reductions in the limiting case occur in particular in the period 2040–2060, the time span in which carbon neutrality needs to be reached in 1.5°C pathways. The emission values can be compared with the benchmark values of 20 $GtCO_2$ in 2030, 10 $GtCO_2$ in 2040 and 5 $GtCO_2$ in 2050 put forward as a roadmap for rapid decarbonization [56]. This is close to the emissions levels of the lowest SSP 1.5°C pathways derived from IAMs, but still 3–5 $GtCO_2$ per year above our limiting case.

The lowest sensitivity case results in 570 $GtCO_2$ of gross cumulative emissions from fossil fuel combustion and industrial processes for the period 2016–2100, compared to 820 $GtCO_2$ in the lowest 1.5°C pathway. This implies around 250 $GtCO_2$ are saved by raising the ambition level of final energy demand reduction, non-electric energy decarbonization and end use electrification to its limits. We recall that this lower bound was generated as the product of all four limiting cases of mitigation measures, and thus would be extremely challenging to realize given our concept of limiting case (see §3b). The cumulative amount of CO_2 emissions can be compared with the emissions commitment from existing and planned fossil fuel infrastructure. Existing infrastructure has been estimated to carry a carbon commitment of 500 ± 200 $GtCO_2$, with approximately 180 $GtCO_2$ already emitted by 2016 [57]. Emissions commitments from coal-fired power plants built until the end of 2016 are estimated to add roughly 200 $GtCO_2$ with a further 100–150 $GtCO_2$ from plants under construction or planned in the pipeline [58]. Taken together, this already reaches or even surpasses the amount of fossil CO_2 emissions in the limiting case, indicating that it would entail abandoning existing or planned fossil fuel infrastructure.

Low final energy demand has the strongest effect on limiting future emissions among the assumed variations in the four generic emissions reduction measures, followed by the decarbonization of non-electric energy supply (electronic supplementary material, figure S1). While the full variation of all assumptions yields a range of 570–1610 $GtCO_2$ for 2016–2100, fixing final energy demand to the limiting case and varying only the other three factors reduces the range to 570–980 $GtCO_2$. If non-electric energy decarbonization is fixed to the limiting case, the range is reduced to 570–1210 $GtCO_2$. If both are fixed to their limiting cases, while the other

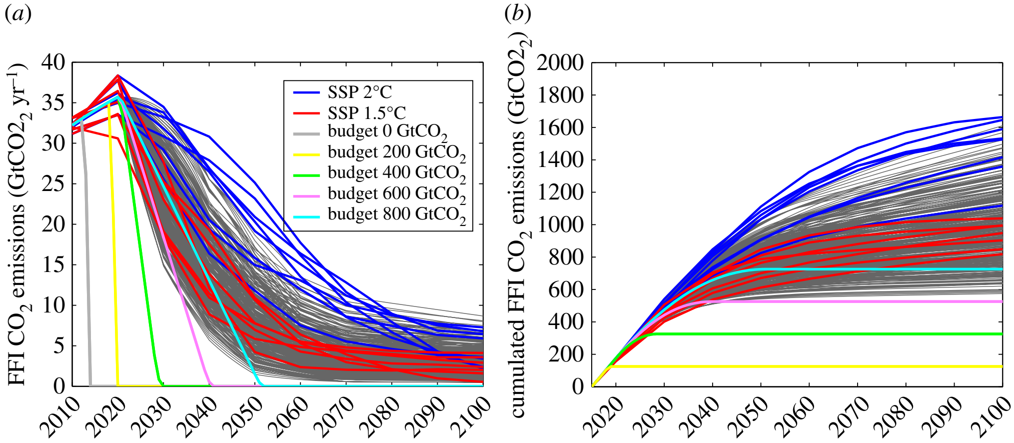

Figure 5. Gross CO$_2$ emissions from fossil fuel combustion and industrial processes (FFI) over the twenty-first century ((*a*) annual emission rates, (*b*) cumulated). Shown are results from 1.5°C and 2°C pathways derived from integrated assessment models (SSP1-1.9, SSP2-1.9, SSP1-2.6, SSP2-2.6 from the AIM, IMAGE, MESSAGE-GLOBIOM and REMIND-MAgPIE models) and the combination of all 320 sensitivity cases for final energy demand, electrification, and carbon intensities of electricity and non-electric energy production. Coloured lines describe CO$_2$ budgets (reduced by an assumed 75 GtCO$_2$ land-use emissions from 2016 until the time land use ceases to be a CO$_2$ emissions source).

two are freely varied, we find a range of 570–810 GtCO$_2$. Thus, breakthroughs in decarbonizing non-electric energy use and radical energy demand reductions [52] have the largest potential to deepen emissions reductions beyond what is projected in 1.5°C pathways in the literature. These findings are due to the fact that aggressive power sector decarbonization is already foreseen in these scenarios, and that the variation covered in the sensitivity analysis was small compared to the other measures.

(b) CDR deployment and overshoot

To assess the implications of our sensitivity analysis for the question of overshooting 1.5°C, the range of cumulative CO$_2$ emissions from fossil fuel combustion and industrial processes needs to be related to the range of remaining CO$_2$ emissions budgets for staying below 1.5°C discussed in §2a. We assume that land-use CO$_2$ emissions after 2020 can be effectively limited to a cumulative amount of 50 GtCO$_2$, which is on the low end of values from the SSP-based 1.5°C pathways. Assuming that during 2016–2020 another 25 Gt of CO$_2$ emissions will be emitted from land use, our sensitivity analysis finds a range of 650–1680 Gt gross anthropogenic CO$_2$ emissions during the period 2016–2100. This range does not take into account net negative land-use emissions that would occur if land turned into a natural or engineered carbon sink. It also does not take into account CDR from the atmosphere to the geological or ocean reservoir. Such measures would not be required if the gross CO$_2$ emissions remained within the 1.5°C budget throughout the twenty-first century. This is only the case for the overlap in ranges above 650 GtCO$_2$, i.e. for low gross FFI CO$_2$ emissions close to the limiting case and high estimates of the remaining 1.5°C budget [27]. Thus very deep FFI CO$_2$ emissions reductions drawing on all levers from final energy demand to carbon intensity reductions may still be able to limit warming to 1.5°C without overshoot if and only if the 1.5°C budget turns out to be at the upper end of the estimated range. However, this finding needs to be qualified by the fact that our limiting case of FFI CO$_2$ emissions has been constructed to make it unlikely that emissions could be even lower, at the expense of the likelihood that it actually can be achieved. So the overlap might be vanishing small, even if the 1.5°C budget is high. If it is not high, CDR will become indispensable to limit warming to 1.5°C.

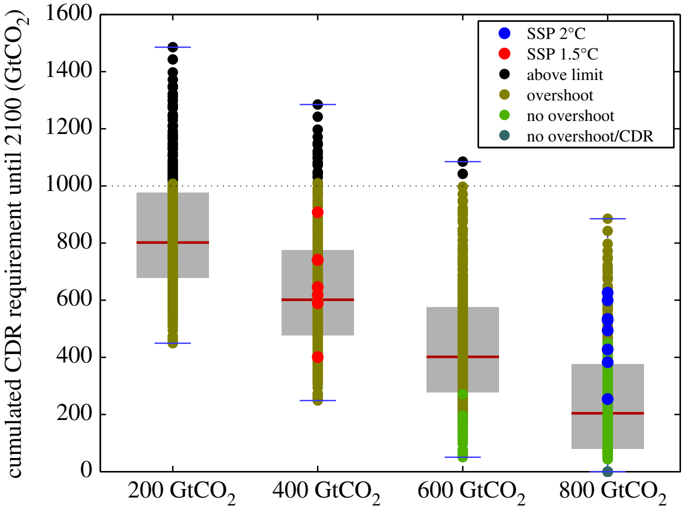

Figure 6. CDR requirements to limit warming to 1.5°C for the 320 FFI CO_2 emissions projections from the sensitivity analysis under different assumptions about the remaining 1.5°C CO_2 budget from 2016 onwards. Red and blue dots indicate the actual cumulative amount of CDR realized in SSP-based 1.5°C and 2°C pathways.

CDR can be used for both neutralizing or reducing emissions to avoid overshoot as well as for returning the budget to 1.5°C-consistent values, i.e. producing overshoot. In the recent discussion of CDR deployment triggered by the mitigation pathway assessment in the 5th Assessment Report of the IPCC [1], CDR, often called 'negative emissions', has frequently been used synonymously with net negative emissions, but the two are not the same. To elucidate the scope of CDR to achieve the 1.5°C limit with and without overshoot, we add our limiting case of massive CDR deployment introduced in §3b to our analysis. The amount of overshoot and net negative emissions is limited the most if CDR is brought in as early as possible to neutralize as much as possible residual CO_2 emissions before mid-century [59]. Our limiting case allows for up to 100 $GtCO_2$ CDR until mid-century, which in principle could be deployed to reduce net cumulative CO_2 emissions to 550–1040 $GtCO_2$, assuming that further CDR would be deployed to compensate any residual CO_2 emissions after mid-century. The low end of this range describes the lower limit for the 1.5°C budget that would need to remain to still avoid overshoot. If the 1.5°C budget from 2016 onwards is smaller than 550 $GtCO_2$, overshoot becomes inevitable according to our analysis of limiting cases.

We turn the analysis around by calculating the CDR requirement to limit warming to 1.5°C as a function of the remaining 1.5°C budget and gross anthropogenic CO_2 emissions from our sensitivity analysis. In principle, the optimal shape of CDR deployment depends on whether residual CO_2 emissions should be compensated as much as possible and, therefore, the amount of net negative emissions be minimized, whether annual CDR levels should be kept as low as possible or whether technology ramp-up should proceed as smoothly as possible (electronic supplementary material, figure S2). All these criteria can be supported on the grounds of limiting sustainability impacts of CDR deployment. In the first case, the goal is to limit the amount of temperature overshoot as much as possible; in the second case, the goal is to minimize the size of the CDR industry and the annual CO_2 flows produced by it; and in the last case, the goal is to reduce institutional challenges to ramp-up and maintain a large-scale CDR sector. In our analysis, we have chosen the optimal CDR path such that overshoot is avoided if it can be, and such that it minimizes annual CDR deployment if overshoot is inevitable (electronic supplementary material, figure S2).

Figure 6 shows the resulting CDR requirements as a function of four budgets from 200 to 800 $GtCO_2$ and the sensitivity cases for gross FFI CO_2 emissions. For the lower two budgets of

200 and 400 $GtCO_2$, a significant share of sensitivity cases would require CDR in excess of the limiting case to return to 1.5°C by the end of the century. In these cases, 1.5°C could be already out of reach until 2100 even with CDR and overshoot. The majority of cases can return to 1.5°C with substantial CDR deployment. Here, there is a direct trade-off: the lower the remaining FFI CO_2 emissions are, the lower is the CDR requirement. For the high budget of 800 $GtCO_2$, there is a substantial share of cases where overshoot can be avoided with early CDR deployment and even a few cases (near the limiting case) where overshoot and CDR can be avoided altogether to stay below 1.5°C.

5. Conclusion

The answer to the question whether it is still possible to limit warming to 1.5°C without overshoot and CDR depends strongly on the remaining 1.5°C budget from 2016 onwards. For a 1.5°C CO_2 budget up to 550 $GtCO_2$, overshoot will be inevitable; CDR will be required to return to the 1.5°C limit if the limiting cases formulated in our analysis hold. For budgets between 550 and 650 $GtCO_2$, we find CDR trajectories that allow to stay below 1.5°C without overshoot in the steepest FFI CO_2 emissions reduction cases. For budgets of 650 $GtCO_2$ and higher, the steepest emissions reduction cases are sufficient to limit warming to 1.5°C without CDR deployment. However, these steepest cases are based on limiting cases for carbon intensity improvements of electricity and non-electric energy supply, electrification of energy end use, final energy demand reductions, and CDR deployment. They are designed to describe outer bounds beyond which developments are very unlikely. But they themselves may also be unlikely to obtain, with the exception of power sector decarbonization. Thus the passage to limiting warming to 1.5°C can further narrow if socio-economic, political and sustainable development considerations are taken into account. The benchmark values provided by the limiting cases will be a useful device to connect to bottom-up assessments of deep decarbonization pathways in individual sectors. Limiting warming to 1.5°C is an enormous challenge. To tackle this challenge, every tonne of CO_2 that is not emitted into the atmosphere counts. In the scenarios analysed here 200 $GtCO_2$, a third of the CO_2 budget in the limiting case, are already used up until 2020. This calls for a parallel approach to strengthen action as quickly as possible and at the same time invest in the development of critical mitigation options like carbon-neutral liquids and radical energy efficiency measures that will be needed to reach carbon neutrality.

Data Accessibility. The data of the SSP-based IAM scenarios are available at https://secure.iiasa.ac.at/web-apps/ene/SspDb. The data of the sensitivity cases are provided in the supplementary material.

Competing interests. We declare we have no competing interests.

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