Modelling assumptions rather than peak warming determine CO_2 removal needs in 1.5°C pathways

Carl-Friedrich Schleussner[1,2]

1 Climate Analytics, Berlin, Germany
2 Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys) and the Geography Department, Humboldt-Universität zu Berlin, Berlin, Germany

Greenhouse gas emission pathways that are aligned with the goals of the Paris Agreement generally deploy some kind of carbon dioxide removal, but the scale of deployment varies greatly between different pathways. In particular, pathways associated with limiting warming to 1.5°C are often linked to large scale deployment of carbon removal raising questions with regard to their plausibility and sustainability. However, the categorization applied in the Special Report on Global Warming of 1.5°C (SR15) of the Intergovernmental Panel on Climate Change (IPCC), on which these assessments are based, group together emission pathways with very different long-term assumptions. Here I show that the scale of CDR deployed depends much less on peak warming, and therefore the chance to limit warming to 1.5°C, than on the long-term assumptions in emission scenarios. Limiting warming to 1.5°C might thus depend less on large scale CDR deployment than often assumed.

The Paris Agreement temperature goal of *"holding the increase in global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels"*[1] sets the objective for climate policy and climate action. The most detailed assessment of emission pathways and associated mitigation requirements to date is provided in the IPCC SR15[2]. The report found that achieving the 1.5°C long-term limit of the Paris Agreement is still within reach but requires stringent near-term mitigation action and about halving global greenhouse gas emissions until 2030 [2]. The IPCC SR15 has assessed a wide range of different greenhouse gas emission pathways and has found that 1.5°C is attainable under different assumptions of future socio-economic development and technology deployment[3]. More recently, analysis of post-COVID19 economic stimulus has outlined the potential for a green recovery towards a 1.5°C compatible trajectory[4,5]. The chances of achieving certain warming targets, however, are not just dependent on emission reductions, but also subject to geophysical uncertainty with regard to the response of the climate system that remain considerable [6].

Table 1| Pathway characteristics of emission pathways categorized as "as likely as not" (or 'no or low overshoot') 1.5°C pathways in the IPCC SR15*. Based on Table 2.SM.11 and 2.SM.12 and own analysis. Exceedance Probabilities are provided as in the SR15 based on the MAGICC6 model. Values shown: median (25th to 75th percentile) across scenarios.*

Pathway Category	2100 Probability level	MAGICC Peak Exceedance Probability	MAGICC 2100 Exceedance Probability	MAGICC Peak Exceedance Probability 2°C	Cumulative net CO_2 removal (Gt CO_2)	Number of Scenarios
Below 1.5°C		P(1.5°C) ≤ 0.5		0.05 (0.05,0.05)	380 (270,470)	9
1.5°C low overshoot	Below 1.5°C in 2100	0.5 < P(1.5°C) ≤ 0.67	0.34 < P(1.5°C in 2100) ≤ 0.5	0.1 (0.09,0.12)	170 (100,380)	10
	Likely below in 2100	0.5 < P(1.5°C) ≤ 0.67	P(1.5°C in 2100) ≤ 0.34	0.1 (0.09,0.12)	380 (300,420)	34

A meaningful categorization of emission pathways in the context of the goals of the Paris Agreement needs to consider these geophysical uncertainties. The pre-Paris goal of "below 2°C" was commonly interpreted as a "likely" (66% following IPCC uncertainty guidance) chance of not exceeding a global mean temperature increase of 2°C above pre-industrial levels[7]. The Paris Agreement language is strengthened to "well below 2°C", implying a higher probability of not exceeding 2°C. A plausible interpretation of the "well below 2°C" language would be a "very likely" or 90% probability of not exceeding that warming level [8].

The IPCC SR15 has identified no emission pathways in the literature that provide a *likely* (66%) chance to keep the global mean temperature increase to less than 1.5°C above pre-industrial levels [2]. However, it provides an assessment and mitigation benchmarks for pathways that are "as likely as not" (between 33% and 66% chance) to limit warming to 1.5°C. These pathways are subsumed in the 'low or no overshoot' pathway category (for further details on the scenario categorization see Table 1). These 'low or no overshoot' pathways simultaneously provide a "very likely" (>=90%) chance to hold warming to "well below 2°C". Emission pathways with such characteristics can thus be considered fully Paris Agreement compatible. To improve readability the shorthand "1.5°C pathways" is used for these "as likely as not" 1.5°C pathways. The IPCC SR15 also includes a pathway category of so-called 'high overshoot' 1.5°C pathways. However, high overshoot pathways are "likely" (>66% chance) to exceed 1.5°C and are thus excluded from the analysis presented here.

1.5°C scenarios are characterized by the need for rapid near-term emission reductions and subsequent CO_2 removal to balance out residual CO_2 emissions (Figure 1). After reaching net zero CO_2 emissions around mid-century, CO_2 emissions become net-negative (Figure 1a). Some level of CO_2 removal from the atmosphere is required to further balance out the remaining non-CO_2 emissions and to achieve net-zero greenhouse gas emissions expressed in Article 4 of the Paris Agreement[7]. However, most 1.5°C pathways go beyond that and achieve even net-negative greenhouse gas emissions[3]. The SR15 1.5°C pathway category includes three subtypes (see Table 1) that are illustrated in Figure 1b.

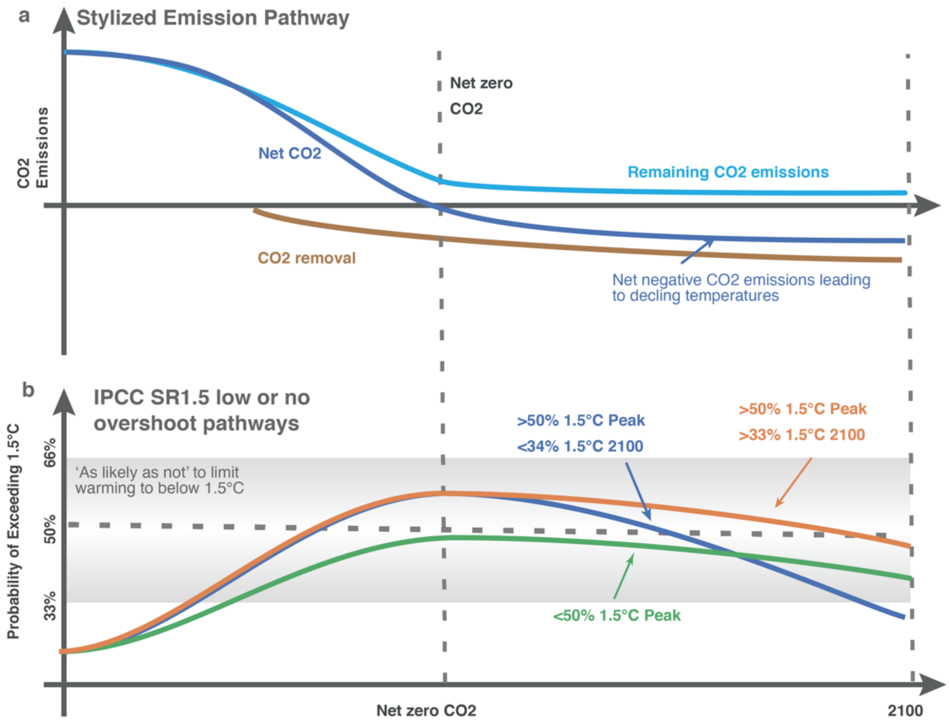

Figure 1| Illustrations of characteristics of as likely as not 1.5°C pathways. a, *Stylized CO_2 emissions over the 21st century. CO_2 removal is deployed to balance remaining CO_2 emissions and then to achieve net negative CO_2 emissions leading to a long-term temperature decline.* ***b****, Illustrative 1.5°C pathways for the pathway classification in Table 1. All pathways are "as likely as not" to limit warming to 1.5°C, but differ in terms of their peak and 2100 exceedance probability assumptions.*

Out of 53 "as likely as not" 1.5°C pathways, only 9 limit median (50%) warming to below 1.5°C throughout the 21st century (<50% 1.5°C peak). The median warming estimate in the other so-called 'low overshoot' pathways exceeds 1.5°C by around 0.1°C before getting below 1.5°C by the end of the century. However, the majority of pathways (34) goes substantially beyond that and strives to achieve a better than likely (66%) chance to limit warming to below 1.5°C in 2100 (>50% 1.5°C peak, <34% 1.5°C in 2100). This corresponds to a median warming of around 1.3°C - a substantial reduction in global mean temperature after peak warming of around 1.6°C. Applying a simple equivalence in terms of the Transient Climate Response to Emissions (TCRE), a median temperature reduction of 0.3°C requires about 700 Gt of net CO_2 removal (assuming a TCRE of 0.44 °C per 1000 Gt CO_2 as in [9]). This is an oversimplification for various reasons. For example, TCRE might be asymmetrical due to non-linear feedback effects in the earth system response, and effects of non-CO_2 forcers also need to be considered. Nonetheless, this back-of-the-envelope calculation provides an estimate of the consequences of scenario assumptions for the need of negative CO_2 emissions.

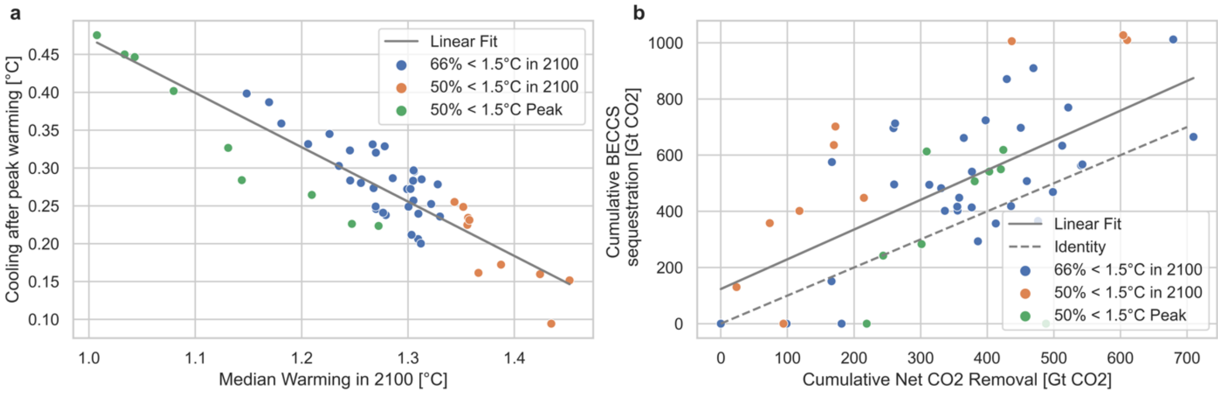

Figure 2| **Warming and CO_2 removal characteristics of 1.5°C pathways.** ***a***, *Median cooling after peak warming compared to median warming outcomes in 2100 for different 1.5°C scenario categories. Note that the probability of limiting warming to below 1.5°C (the basis for scenario categorization) and median warming estimates are interdependent. Pathways with a 66% of limiting warming to below 1.5°C show a median 2100 warming of around 1.3°C or less.* ***b,*** *Interdependencies of the cumulative net CO_2 removal after reaching net-zero CO_2 and the cumulative CO_2 sequestration through bioenergy with carbon capture and storage (BECCSS) over the 21st century. An identity line and a linear fit (after removing outliers) are provided to enhance readability.*

This substantial net-negative deployment is the result of *a priori* scenario design in integrated assessment models (IAMs), for example to meet the RCP1.9 forcing level in 2100 [10]. In response to criticism of a scenario design focusing on 2100 outcomes rather than on more near-term and policy relevant objectives such as peak warming a new scenario logic for the Paris Agreement long-term temperature goal has been suggested[11]. In the following, I will illustrate the interdependencies between net negative emissions and peak vs. 2100 warming outcomes in 1.5°C scenarios provided in the IPCC SR15 database.

Results

The year when net-zero CO_2 emissions are reached approximately determines the timing of peak warming[11] (around mid-century in most 1.5°C pathways). Subsequent end of century warming outcomes for all 1.5°C pathways are lower than peak warming (compare Figure 2a). Depending on the pathway assumptions, a cooling of up to 0.5°C relative to peak warming levels is projected in some scenarios. Median cooling across the ensemble is around 0.3°C with 50% <1.5°C in 2100 pathways showing lower cooling. Given that peak warming is reached around 2050, this implies median cooling rates of about 0.05°C per decade on average after net zero, or a quarter of the current warming rate of around 0.2°C per decade [2].

Besides effects of non-CO_2 forcers, cooling in such pathways is achieved through net removal of CO_2 from the atmosphere after reaching net zero CO_2 emissions (compare Figure 2b). The total net-removal of CO_2 from the atmosphere strongly depends on the scenario assumptions. However, in general the net CO_2 removal is higher for scenarios that achieve warming a higher probability of limiting warming to 1.5°C in 2100. The ensemble median net CO_2 removal in 66% below 1.5°C in 2100 pathways is 380 Gt CO_2, more than twice the estimate for the 50% below 1.5°C in 2100 category (compare Table 1).

Achieving net CO_2 removal requires the deployment of techniques that actively remove CO_2 from the atmosphere. Different Carbon Dioxide Removal (CDR) options, their potentials and sustainability limitations have been discussed extensively in ref. [12]. While various CDR technologies exist, Bioenergy and Carbon Capture and Storage (BECCS) as well as afforestation and reforestation are two options to achieve carbon dioxide removal commonly

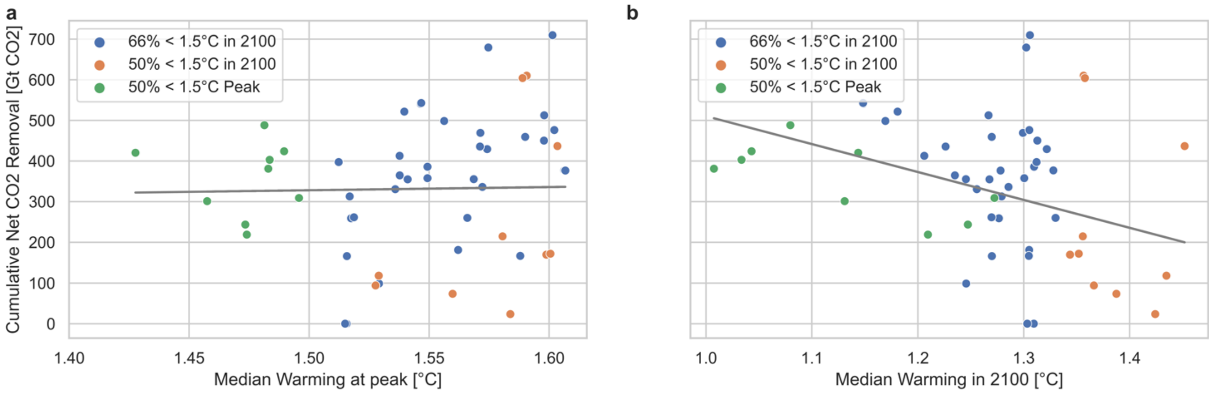

Figure 3| Cumulative net CO_2 removal versus different warming benchmarks over the 21st century. ***a***, *the median peak warming and* ***b***, *the median 2100 warming for 1.5°C scenarios. A linear trend line is added for illustration purposes (outliers removed).*

implemented in Integrated Assessment Models (IAMs) that provide these emission pathways. The cumulative net CO_2 removal vs. the total sequestration by BECCS is shown in Figure 2b. Although BECCS deployment varies widely between the scenarios, a clear trend of BECCS deployment vs. net CO_2 removal is evident. On average, the BECCs deployment in 1.5°C scenarios almost linearly follows the total need for net CO_2 removal with an offset of around 180 Gt CO_2 linked to compensation of residual CO_2 emissions through BECCS (compare Figure 1a).

All 1.5°C scenarios show a similar peak warming of around 1.5-1.6°C above pre-industrial levels. However, they vary widely in terms of their 2100 warming outcome. It is thus not surprising that the total net CO_2 removal in 1.5°C pathways shows little dependency on the peak warming (see Figure 3a), but more robustly depends on end-of-century warming outcomes (Figure 3b). This becomes even more apparent when assessing CO_2 removal vs. cooling after peak warming (Figure 4a). For comparison, a simple TCRE-based estimate of the cooling inferred by CO_2 removal is added to Figure 4a[9]. Despite the clear limitations of the TCRE-based approach, it is remarkable how closely the linear trend across the emission pathway ensemble follows the TCRE cooling trajectory. Cooling in emission pathways is generally higher than what would be implied by CO_2 removal only. It appears that across the model ensemble, an additional cooling of around 0.15°C results from changes in the non-CO_2 forcing (compare Figure 4a). The importance of non-CO_2 forcing is illustrated by some outlier emission pathways that achieve very high (low) cooling for comparably low (high) net CO_2 removal.

Linked to the median cooling after peak warming is the 1.5°C exceedance probability in 2100. It appears that the lower the exceedance probability (that is, the better the chances of not exceeding 1.5°C), the more net CO_2 removal is required (compare Figure 4b). Some 50% <1.5°C peak scenarios even achieve a "very likely" (>90%) probability of limiting warming to 1.5°C in 2100.

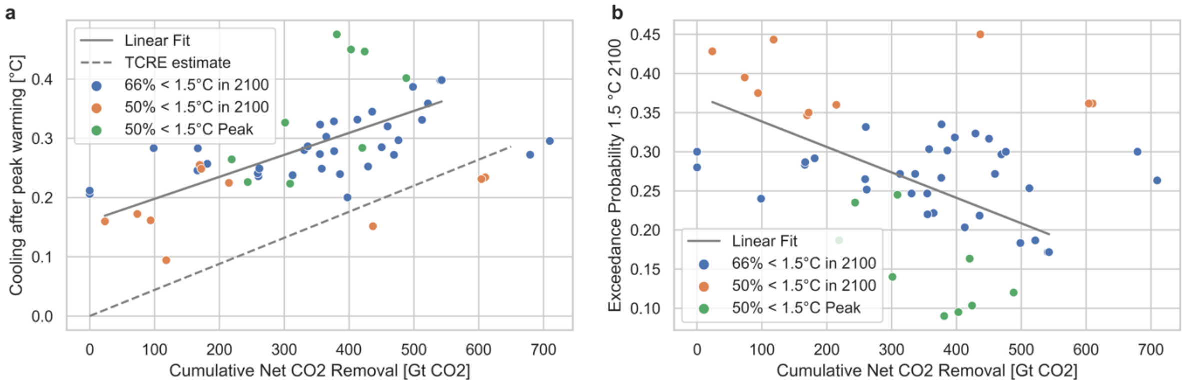

***Figure 4: Cumulative net CO_2 removal and 2100 pathway assumptions. a**, the median cooling after peak warming until 2100 and **b**, the 1.5°C exceedance probability in 2100. A linear trend line is added for illustration purposes (outliers removed). In panel **a**, a TCRE-based estimate of the cooling inferred by the CO_2 removal is added for comparison (dashed line).*

Discussion

The long-term temperature goal of the Paris Agreement might be understood as establishing a temperature increase of 1.5°C above pre-industrial levels as the upper limit that should not be exceeded, or allowing for a temporary overshoot of 1.5°C while always holding warming to 'well below 2°C' [13]. The "as likely as not" below 1.5°C category subsumes emission pathways that cater to both these interpretations of the long-term temperature goal (no overshoot and temporary overshoot). However, there is no policy guidance to when temperatures should be brought back below 1.5°C or with what probability. Implications of scenario assumptions such as setting 2100 as the cut-off year or requiring a 66% below 1.5°C probability in 2100 thus need to be carefully analyzed and communicated. In particular, when they have far reaching consequences like implying the need for hundreds of gigatons of carbon dioxide removal.

Although more stringent near-term emission reductions limit the dependencies on long-term removal [14], the analysis presented here underscores that post peak-warming assumptions largely define CDR requirements in 1.5°C pathways. Future CDR deployment raises fundamental questions of equity and fairness both intergenerationally as well internationally [14]. Bottom up sustainability assessments have identified potential of between 0.5-5 Gt CO_2 per year of CDR in 2050 based on BECCS[2], which in turn implies a limit to the cumulative BECCS CDR potential of the order of 250 Gt CO_2 over the 21st century. There is ample evidence that large-scale deployment of negative emission technologies exceeding such levels would come with substantial side-effects in terms of land and water requirements, subsequent biodiversity implications etc. not to speak of the economic financing needs of a sector up to a quarter of the size of the current fossil fuel industry [12,15–18]. Potential benefits of decreasing temperatures need to be put in perspective with the potential negative consequences of large scale CDR.

Warming versus impact reversibility

The long-term temperature goal of the Paris Agreement is not set to achieve a certain temperature limit. Much more, it aims to "*significantly reduce the risks and impacts of climate change*" based on an extensive assessment of climate impacts at different warming levels as part of the 2013-2015 Review [19]. Whether the impacts after an overshoot are the same than in a no-overshoot scenario is not established [20,21], but it seems unlikely given that a multi-decadal exceedance of a certain warming level will infer potentially irreversible impacts on vulnerable systems [22]. For time-lagged physical systems, this interdependency can be made explicit. An overshoot of 1.5°C of 50 years will infer about 20cm long-term sea-level rise in 2300 and potentially substantially more if irreversible thresholds of ice sheets are crossed [23]. The risks and impacts of climate change at 1.5°C are high for many systems and reducing temperatures again will reduce those risks in the long run. But as shown above, even large scale CO_2 removal will not achieve reversal rates of much more than 0.05°C per decade. Whether or not this is fast enough to avoid the crossing of critical thresholds for vulnerable systems is not clear. In any case, limiting peak warming is arguably more important for reducing risks and impacts of climate change than the pace of long-term cooling. This notwithstanding, a temperature reduction might still be desirable in the light of severe long term climate impacts such as a multi-meter sea level rise commitment [24].

Peak warming dependent removal needs

The physical considerations underlying the probability assessments also need to be revisited. Assuming higher probabilities for non-exceedance of warming levels is warranted based on the still considerable uncertainties of the climate response [6,25]. These uncertainties are linked to different components of the earth system incorporating both the climate system as well as the carbon cycle, and need to consider different timescales (i.e. fast responding atmospheric feedbacks and a slow oceanic response). However, estimates of the warming response can be expected to be further constrained as science progresses, and certainly when net zero CO_2 emissions and peak warming are reached. The warming commitment beyond net zero CO_2 is equally still uncertain (both long-term cooling and warming are possible), but the current best estimate is that the zero emissions commitment is close to zero [26]. Arguably, at peak warming humanity will have an improved understanding of what is required to achieve the long-term 1.5°C limit compared to today. Different outcomes are plausible under 1.5°C pathways:

1) Warming never exceeds 1.5°C. Either as the result of emission reductions aligned with below 1.5°C peak warming pathways in the literature (compare Table 1), or as the result of a climate response that turns out to be lower than the current central estimate. The uncertainty range around the warming response and in particular its lower bound has been narrowed in the recent literature compared to the AR5-based estimates provided here[6,25], but a lower warming outcome cannot be ruled out. In both cases, no net CO_2 removals would be required to limit warming to 1.5°C.
2) Warming turns out to be around the current median estimate. Peak temperatures reach around 1.6°C. In this case, returning to below 1.5°C only requires the reduction of around 0.1°C. Based on the SR15 scenarios, this might be achievable with non-CO_2 reductions alone (compare Figure 4a), but if this was to be achieved by CO_2 removal alone, it would imply around 220 Gt CO_2 of net removal. Much less than what is assumed in most 1.5°C pathways (compare Table 1 and Figure 2b) and plausibly consistent with sustainability considerations of BECCS deployment[27].
3) Warming turns out to be above the current estimate, 1.5°C will likely be exceeded. In terms of the reversibility and CO_2 removal implications of such a high warming outcome understanding the reason for a higher warming response is important. If it is for example the result of an atmospheric response with limited memory such as cloud feedbacks as e.g. in the latest generation of climate models [28], then CO_2 removals might be as effective in bringing down global mean temperature as emissions are to increase it. In this case, CDR needs would not be higher than in case

2). This is different if the origin of a high warming outcome is linked to non-CO_2 forcing responses such as aerosol-related cooling or non-CO_2 greenhouse gases. A higher warming outcome as a result of different non-CO_2 responses would require substantially more CO_2 removal to balance. Lastly, high warming could also be related to long-term earth system feedbacks[29], or a stronger carbon cycle responses for example related to emissions from permafrost [30]. Such an earth system response might require net anthropogenic CO_2 removal just to balance earth system induced warming and could render effective temperature decline infeasible. However, in such scenarios the need for CO_2 removal would not arise from the objective to bring temperatures down to below 1.5°C again, but rather from limiting further temperature rise after achieving net zero emissions.

This non-exhaustive list illustrates different plausible scenarios that could arise after net zero CO_2 emissions are achieved aligned with 1.5°C pathways. The need for subsequent net CO_2 removal beyond what is required to achieve net zero greenhouse gases in line with the Paris Agreement strongly depends on the earth system uncertainties at play. In the light of these potential different outcomes, prescribing the need for a 66% below 1.5°C probability based on today's estimates for the end of the century seems premature, even more as this in turn prescribes the need for peak and (substantial) decline scenarios. The amount of CDR deployment and net removal in 1.5°C pathways differs substantially between the different scenarios (compare Figure 2b). An improved understanding of the assumptions underlying those deployments and the role of non-CO_2 forcers and other factors is urgently required in order to improve scenario modelling to incorporate social and environmental constraints. It is, however, important to highlight that these assumptions do not appear to be the result of achieving certain warming limits (compare Figure 3a).

Conclusions

This analysis illustrates that the need for net CO_2 removal in 1.5°C scenarios in the IPCC report is not primarily linked to the peak warming outcome and therefore the ability of securing an 'as likely as not' chance of limiting warming to 1.5°C. Much more, it systematically depends on the assumptions made after peak warming is reached and is linked to the scenario design in IAMs that provided those pathways. In order to avoid misunderstandings, the implications of such model assumptions need to be transparently assessed and communicated. This is even more relevant as these assumptions effectively constitute pure value judgements. Whether or not a 66% below 1.5°C probability after overshoot (or cooling of ~0.3°C from peak warming) is societally desirable, by when it should be accomplished, and at what societal and ecosystem costs, requires a broad societal discourse and informed decision making. Other research has shown that CDR deployment in emission pathways may also be linked to other value judgments made in modelling, i.e. the choice of the discount rate [31].

It might be questioned if the scenario categorization used in the IPCC SR15 and subsequent literature does provide the necessary transparency in this regard. Or if bundling very different long-term warming outcomes into a common category has rather led to an impression that long-term CO_2 removal needs are directly linked to certain (peak) warming outcomes. Moving forward, an alternative scenario logic can help to improve transparency in the scenario design [11].

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Methods

The analysis presented is based on the IPCC SR15 database retrieved from ref [32]. Based on standard output provided in the database, the scenario classification as in ref. [3] is applied across the scenarios, warming outcomes and exceedance probabilities are derived based on the MAGICC6 model as provided in the SR15. Cumulative net negative CO_2 emissions are derived as the difference between the cumulative CO2 emissions from 2016 to net zero CO_2 emissions and cumulative CO2 emissions until 2100.

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