# Modelling assumptions rather than peak warming determine CO 2 removal needs in 1.5°C pathways

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**Abstract**

Since its adoption, the Paris Agreement sets and defines the global climate ambition. The overall scope of this ambition is expressed in its long-term temperature goal in Article 2 as well as the 'net zero' mitigation goal in Article 4. To provide guidance to climate policy, the scientific community has explored the characteristics of greenhouse gas (GHG) emission reduction pathways that can meet the Paris Agreement goals. However, when categorizing and presenting such pathways including in reports of the Intergovernmental Panel on Climate Change (IPCC), the focus has been put on the temperature outcome and not on the emission reduction criteria set out in Article 4.1. Here we propose a pathway classification approach that aims to comprehensively reflect all climate criteria set out in the Paris Agreement. We show how such an approach allows for an internally consistent interpretation of the Paris Agreement in terms of emission reduction pathways. For pathways that simultaneously are very likely to hold warming to below 2°C, pursue efforts to limit warming to 1.5°C and achieve the provisions outlined in Article 4.1, we report 2030 global Kyoto-GHG emissions of between 20-26 Gt CO2eq (interquartile range), net zero CO2 emissions around 2050 and net zero GHG emissions around 2060. We further illustrate how prevalent pathway classifications focusing, for example, on the temperature outcome in 2100 result in additional criteria being applied that are not rooted in the Paris Agreement. We outline the consequences of such approaches including for the deployment of carbon dioxide removal (CDR) in such pathways. We find that across pathways classified as 'no or low overshoot' pathways in previous IPCC reports, such non-Paris related, additional criteria for end-of-century outcomes may lead to about 20% higher CDR deployment compared to purely achieving the Paris Agreement objectives in mitigation pathways.

# An emission pathway classification reflecting the Paris Agreement climate objectives

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**ABSTRACT**

*Since its adoption, the Paris Agreement sets and defines the global climate ambition. The overall scope of this ambition is expressed in its long-term temperature goal in Article 2 as well as the 'net zero' mitigation goal in Article 4. To provide guidance to climate policy, the scientific community has explored the characteristics of greenhouse gas (GHG) emission reduction pathways that can meet the Paris Agreement goals. However, when categorizing and presenting such pathways including in reports of the Intergovernmental Panel on Climate Change (IPCC), the focus has been put on the temperature outcome and not on the emission reduction criteria set out in Article 4.1. Here we propose a pathway classification approach that aims to comprehensively reflect all climate criteria set out in the Paris Agreement. We show how such an approach allows for an internally consistent interpretation of the Paris Agreement in terms of emission reduction pathways. For pathways that simultaneously are very likely to hold warming to below 2°C, pursue efforts to limit warming to 1.5°C and achieve the provisions outlined in Article 4.1, we report 2030 global Kyoto-GHG emissions of between 20-26 Gt $CO_2$eq (interquartile range), net zero $CO_2$ emissions around 2050 and net zero GHG emissions around 2060. We further illustrate how prevalent pathway classifications focusing, for example, on the temperature outcome in 2100 result in additional criteria being applied that are not rooted in the Paris Agreement. We outline the consequences of such approaches including for the deployment of carbon dioxide removal (CDR) in such pathways. We find that across pathways classified as 'no or low overshoot' pathways in previous IPCC reports, such non-Paris related, additional criteria for end-of-century outcomes may lead to about 20% higher CDR deployment compared to purely achieving the Paris Agreement objectives in mitigation pathways.*

The 2015 Paris Agreement is the guiding framework for global action to tackle climate change. The mitigation objectives of the Agreement are set out in its Articles 2.1 and 4.1. Article 2.1(a) establishes the 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, recognizing that this would significantly reduce the risks and impacts of climate change"*[1]. The long-term temperature goal of the Paris Agreement is to be understood as a single goal[2], that may allow for two interpretations: limiting the maximum temperature increase to less than 1.5°C, or allowing for a temporary overshoot above 1.5°C while always holding temperature increase to 'well below 2°C'[3,4]. The temperature goal is directly linked to the climate impact assessment that was conducted as part of the 2013-2015 Periodic Review under the UNFCCC and has been adopted as the current interpretation of the temperature goal of the UNFCCC alongside the Paris Agreement (see decision 10/CP.21)[1].

Article 4.1 establishes the mitigation goal of the Paris Agreement "*in order to achieve the long-term temperature goal set out in Article 2"*[1]. It sets out the objective to "*reach global peaking of greenhouse gas emissions as soon as possible […] and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty."* The goal is understood as setting out to achieve net zero greenhouse gas (GHG) emissions[5], and also highlights the importance and policy relevance of scientific assessments of emission reduction pathways to achieve the Paris Agreement goals. Further, the Paris Agreement climate objectives are framed in the context of equity and the principle of common but differentiated responsibilities and respective capabilities (see ref [6] for a detailed discussion).

The metric to establish a common accounting across GHGs adopted under the UNFCCC is the Global Warming Potential with a 100 year time horizon (GWP100) including under the Kyoto Protocol and the Paris Agreement rulebook[7]. Reaching and sustaining global net zero greenhouse gases with GWP100 will lead to long-term declining temperatures[8,9]. This is in line with the ongoing objective to "*pursue efforts to limit the temperature increase to 1.5°C"* in the case of a potential temperature overshoot above the 1.5°C level, establishing 1.5°C as the long-term temperature limit of the Paris Agreement temperature goal[2,4]. In the "Glasgow Climate Pact" adopted in 2021[10], countries have re-affirmed the Paris Agreement temperature goal and further strengthened their commitment to the 1.5°C limit by *"Recogniz[ing] that the impacts of climate change will be much lower at the temperature increase of 1.5 °C compared with 2 °C and resolv[ing] to pursue efforts to limit the temperature increase to 1.5 °C".*

It is important to emphasize that declining long-term temperatures as would be implied by achieving and sustaining net zero GHGs are fully in line with different interpretations of the Paris Agreement temperature goal. The temperature levels referred to in the Paris Agreement temperature goal reflect upper limits and the idea of stabilizing temperatures at any given level is not part of the Paris Agreement text. This understanding of how temperature limits are set and viewed under the Paris Agreement is in accordance with the scientific understanding that long-term climate impacts on time-lagged systems, such as sea level rise, are projected to be very significant even at low levels of warming. For example, the IPCC highlighted in its recent Working Group 1 Assessment Report that a global sea level rise of 2-3 meters can be expected if a temperature increase of around 1.5°C above pre-industrial levels is maintained over the timescale of 2000 years[8]. Such a global sea level rise would have far-reaching impacts and might itself represent a "dangerous anthropogenic interference" with the climate system, as by the ultimate objective of the UNFCCC[11]. A long-term temperature decline implied by achieving and sustaining net zero greenhouse gases compared to temperature stabilization may reduce the 2300 median sea level rise commitment by about half a meter[12].

The most detailed assessment of emission pathways and associated mitigation requirements that could be considered to align with the Paris Agreement temperature goal is provided in the Special Report on Global warming of 1.5°C (SR15) of the IPCC[13]. The SR15 classified emission reduction pathways according to the probabilities of their temperature outcome. The purpose of such a classification is to facilitate comparability across scenarios. There is no "correct" way to do such an assessment and categorization, and approaches have changed over time in the scientific community. For example, the authors of the IPCC's 5th Assessment Report chose to group scenarios according to their radiative forcing levels in 2100[14]. All attempts to provide such information involve value judgements. Implications of different approaches and interpretations therefore must be assessed critically and transparently communicated. In the following, we assess such implications of the scenario categorization applied in the IPCC SR15 and suggest an alternative classification scheme that more closely resembles the provisions of the Paris Agreement.

**A critical view on a temperature-based pathway classification**

Scenarios in the SR15 are classified primarily by their temperature outcome in relation to one temperature level, either 1.5°C or 2°C, and further by their likelihood of keeping below these temperature outcomes (compare Table 1). They are first classified according to whether they provide an at least 50% chance of keeping warming below 1.5°C in 2100, and then according to their maximum likelihood of keeping warming below 1.5°C throughout the 21st century. The SR15 uses an exceedance probability metric, *P*, to make these classifications which maps as follows:

(P(1.5°C) ≤ 50%: Below 1.5°C, P(1.5°C) < 67%: 1.5°C low overshoot, P(1.5°C) ≥ 67%: 1.5°C high overshoot). Any remaining scenarios are then grouped according to their maximum likelihood of keeping warming below 2°C, and either fall into the "Lower 2°C" category (P(2°C) ≤ 34%), or the "Higher 2°C" category (34% < P(2°C) ≤ 50%).

While transparent and mirroring academic practice, the choice to categorize pathways in terms of their probabilities to either keep warming below 1.5°C or 2°C does not reflect the understanding that Article 2.1 contains one single temperature goal that combines levels of 1.5°C and 2°C of warming. Applying a scenario classification based on a dichotomy between 1.5°C and 2°C pathways invites misinterpretation of the policy choices available for achieving the Paris Agreement, because they are presented as reaching either 1.5°C or 2°C but lack the understanding of how these levels are linked. Such a presentation is also at odds with the simple fact that each pathway simultaneously implies a probability of exceeding both 1.5°C and 2°C, and that the overlap is considerable as we show below.

The Paris Agreement language of holding warming "well below 2°C" is a clear strengthening of earlier UNFCCC decisions from 2010 that set a temperature goal to hold warming "below 2°C"[15]. A common interpretation of the previous "below 2°C" goal has been in terms of a *likely* (greater than 66%) chance (compare e.g. decision 1/CP.21 paragraph 17)[1]. Under such pathways a very significant chance of exceeding 2°C of about 1-in-3 remains, and even the risk of exceeding 2.5°C would be considerable[13]. The more stringent "*well below 2°C*" objective is a clear strengthening of the intent to avoid a temperature increase of 2°C that is in a straightforward way interpreted as an increased likelihood of not exceeding that level[4]. The calibrated uncertainty language applied by the IPCC in its assessments provides potential guidance on how to translate such a strengthening of language in quantifications. The next strongest IPCC qualification category following on from a *likely* probability level is a *very likely* outcome and corresponds to a 90% or greater likelihood.

The SR15 introduces scenario categories of so-called overshoot pathways that allow for a higher likelihood of temporary exceedance of 1.5°C during the 21st century before returning to below 1.5°C again in 2100 with a greater than 50% or 66% (*likely*) chance (see categories introduced above). The SR15 differentiates those further. So-called 'high overshoot' pathways are *unlikely* (33% chance or less) to keep peak warming to below 1.5°C, and hence have to deploy substantial amounts of Carbon Dioxide Removal (CDR) to bring temperatures down after peak warming to below 1.5°C in 2100 with a 50% or even 66% chance. During the review and approval process of the SR15 government delegates communicated that such 'high overshoot' pathways were not considered to be 1.5°C compatible (see e.g. IPCC SR15 Government comments No. 2226 among others)[16]. Because peak warming in such pathways is *unlikely* to be limited to 1.5°C, this pathway category might not be in line with the objective to "*pursue efforts to limit the temperature increase to 1.5°C*", and consequently it has been suggested that this pathway category should be not be considered Paris Agreement compatible after all[16]. High overshoot pathways need CDR technologies at a very large scale that exceed identified sustainability limits for CDR deployment[17] and may thereby not be in line with the sustainable development and biodiversity provisions of the Paris Agreement and the UNFCCC[18]. Due to those concerns, information on 'high overshoot' pathways is covered separately in the text of the Summary for Policy Makers of the SR15[19]. The naming convention of these 'high overshoot' pathways also provide for an illustration of the issues introduced by the artificial dichotomy in the pathway nomenclature in relation to 1.5°C in 2°C. In fact, the emission reduction characteristics of 'high overshoot' pathways resemble closely those of the likely 2°C pathways until net zero (i.e., the peak exceedance probability for 1.5°C is broadly similar for the two pathway classes, as shown in Table 1).

***Table 1| The emission pathway classification in the IPCC SR15****. Based on Table 2.SM.11 and 2.SM.12 and own analysis of additional scenarios not included in the SR15 database (see Methods). Exceedance Probabilities are provided as in the SR15 based on the MAGICC6 simple climate model[20]. Values shown: median (25th to 75th percentile) across scenarios, and rounded to two decimal places. The total number of scenarios in each category is provided as well as the number of scenarios in each category that are very likely to keep warming below 2°C, and/or achieve net zero GHGs, respectively.*

| Pathway Category (SR1.5) | MAGICC Peak Exceedance Probability 1.5°C [%] | MAGICC 2100 Exceedance Probability 1.5°C [%] | MAGICC Peak Exceedance Probability 2°C [%] | Number of Scenarios | Out of which very likely below 2°C | Out of which net zero GHGs |
|---|---|---|---|---|---|---|
| Below 1.5°C | 46 [42, 47] | 19 [12, 34] | 6 [6, 9] | 13 | 11 | 9 |
| 1.5°C low overshoot | 60 [56, 64] | 33 [27, 44] | 13 [11, 13] | 69 | 15 | 39 |
| 1.5°C high overshoot | 75 [72, 80] | 44 [34, 47] | 19 [17, 22] | 76 | 0 | 69 |
| Lower 2°C | 79 [74, 83] | 66 [59, 71] | 26 [21, 30] | 261 | 0 | 75 |

The SR15 also include a second category of 'low overshoot' pathways that are not *likely* (P(1.5°C) < 67%) to exceed 1.5°C. This translates into a median temperature exceedance of at maximum around 0.1°C. Also in these pathways, CDR is deployed to bring temperatures below 1.5°C in 2100 again, either with a 50% or greater than 66% (*likely*) chance. The median exceedance of 0.1°C which is compensated by late-century deployment of CDR in these pathways is of the same order of magnitude as the potential contribution of non-$CO_2$ GHG mitigation[13].

Important for the interpretation of these SR15 scenario categories is to explicitly acknowledge that the criteria of the SR15 pathway categorization that apply to the temperature outcome in the year 2100 are not rooted in the legal framework or text of the Paris Agreement, or of the UNFCCC more broadly. Much more, they appear to be the outcome of technical constraints and common practice of the past decades about how far into the future to run model simulations in the scientific community. This scenario logic focusing on 2100 outcomes has been criticized for missing the mark and being policy prescriptive in the context of the Paris Agreement[21]. For example, assumptions for a post-peak temperature decline implied by achieving a 66% or higher chance of limiting warming to 1.5°C in 2100 after an earlier overshoot (note, this is equivalent to a median warming outcome of around 1.3°C in 2100), would impose the need of several hundreds of gigatons of cumulative $CO_2$ removal by design. Yet, assuming such a strong after-peak cooling has no basis in the Paris Agreement policy context. Our critique does not invalidate such scenarios per se, and good arguments might exist why very high, yet sustainable, $CO_2$ removal and subsequent temperature decline might potentially be desirable (see the example on long-term sea level rise given above). However, it is important to acknowledge that these characteristics are the result of additional assumptions beyond those set by the Paris Agreement and which need to be made transparent.

A solution to this ill-supported focus on 2100 has been presented in the literature[21], involving a different pathway logic that defines key scenario parameters along two policy-relevant dimensions: the amount of allowable warming until peak temperature is reached (around the time of net zero $CO_2$ emissions) and the longer-term evolution of temperature after the peak (which may remain constant or can be slowly declining), implying different amounts of needed $CO_2$ removal. However, this proposed new logic stops short of providing a new classification scheme that is more closely oriented towards the provisions of the Paris Agreement.

In the following, we will explore such an alternative classification scheme designed to match more closely to the provisions of the Paris Agreement, considering joint exceedance probabilities of 1.5°C and 2°C as well as explicitly introducing achieving net zero greenhouse gases as an evaluation criterion.

## RESULTS

### A pathway classification designed to reflect the Paris Agreement provisions

Based on our assessment of the Paris Agreement presented above, we develop and suggest a pathway classification that closely reflects the provisions of the Paris Agreement. Specifically, we postulate the three criteria as shown in Table 2.

***Table 2| Criteria for Paris Agreement compatible pathways***

| Criterion | Specification |
|---|---|
| Criterion I (Crit I): "*pursuing efforts to limit warming to 1.5°C*" | Emission pathways need to reflect, at any point in time, the explicit ambition of the Paris Agreement of "*pursuing efforts to limit warming to 1.5°C*" and the Glasgow Climate Pact decision that "*resolve to pursue efforts to limit the temperature increase to 1.5°C*". In line with the SR15 we interpret this to imply a direct criterion for pathways to not ever have a greater than 66% probability to overshoot 1.5°C (so they are less than *likely* to exceed 1.5°C in calibrated IPCC uncertainty language[22]) and to bring global mean temperature increase down below 1.5°C again in case of a temporary overshoot. |
| Criterion II (Crit II): hold warming to "*well below 2°C*" | The exceedance probabilities of 2°C implied by pathways need to be considered in conjunction and we introduce the pathway criterion of *very likely* (90% chance or more) of not ever exceeding 2°C, which we argue is a plausible interpretation of how to translate the "well below 2°C" concept of Article 2.1 of the Paris Agreement into calibrated IPCC uncertainty language[22]. |
| Criterion III (Crit III): Achieving net zero greenhouse gases | Net zero greenhouse gases assessed in GWP100 must be achieved in the second half of the 21st century as set out by Article 4 of the Paris Agreement and informed by subsequent decisions on the greenhouse gas metrics for emissions reporting under the Paris Agreement[7]. |

Out criteria established are not an exclusive list and other criteria or interpretations may well be argued for. However, we find that these criteria provide for a consistent set that can be directly linked to the Paris Agreement provisions and subsequent UNFCCC decisions. In the following, we classify pathways that meet all three criteria as Paris Agreement compatible.

We illustrate the effect of our scenario classification on a scenario set combining the IPCC SR15 scenario database as well as the ENGAGE project database (see Methods). This set covers scenarios with a wide range of probabilities of limiting peak warming to 1.5°C and 2°C (Fig 1a), and peak versus end-of-century exceedance of 1.5°C (Fig 1b). The criterion for temperature increase to *very likely* remain below 2°C (Crit II) strictly dominates the less than *likely* to exceed 1.5°C criterion (Crit I) across the scenario set used here. However, for reasons of transparency and logic, we argue that the 1.5°C criterion (Crit I) needs to be retained as part of the classification. The interdependence between probabilities of exceeding 1.5°C and 2°C results from the uncertainty distribution of the climate response assumed in the underlying temperature assessment. The latter is expected to change as science progresses (for a major recent update see e.g. ref [23]). Because estimates based on a specific quantile of an uncertainty distribution are sensitive to changes in the assessed uncertainty distributions, keeping all criterions hedges against future changes in scientific understanding. At the same time, we find that pathways that do not overshoot 1.5°C simultaneously also achieve a *very likely* chance of holding warming to "well below 2°C".

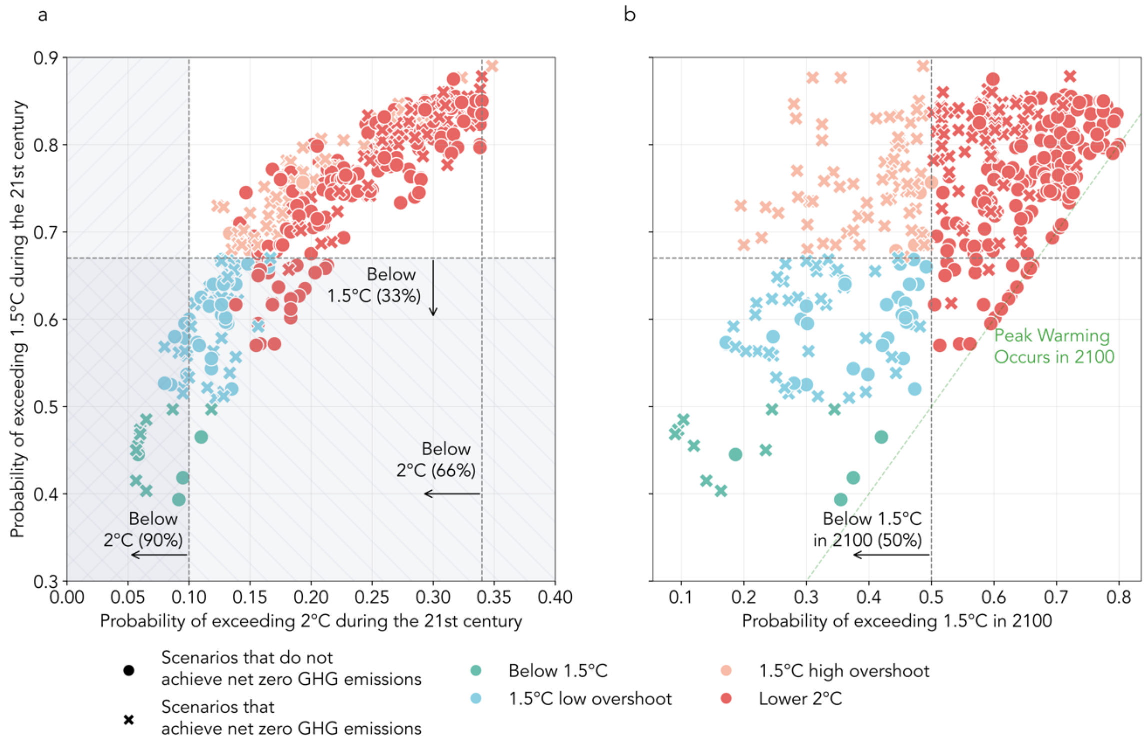


**Figure 1| Exceedance Probabilities for the 1.5°C and 2°C warming level for different scenario categories. a,** Probability of exceeding 2°C plotted against probability of exceeding 1.5°C over the 21st century. **b,** Probability of exceeding 1.5°C in 2100 plotted against probability of exceeding 1.5°C over the 21st century. The scenarios are coloured according to their categorization in the SR15 (compare Table 1). Symbols indicate whether pathways achieve net zero greenhouse gas emissions in the 21$^{st}$ century.

Peak temperature exceedance probabilities are largely independent from the Criterion III on achieving net zero GHG emissions (Crit III, Fig. 2a). However, when comparing peak and 2100 exceedance probabilities, a clear dependency emerges (Fig. 2b,c). Only a small number of pathways achieve significant post-peak temperature reductions in absence of achieving net zero GHGs, potentially through stringent and continued mitigation of short-lived non-$CO_2$ GHGs, or by substantial CDR without ever meeting the net zero GHG criterion because of high stable levels of short-lived GHGs (compare Fig. 2b). The majority of pathways achieving significant improvements in end-of-century exceedance probability (which equates to reduction in the projections of median temperature) achieve net zero GHGs. This illustrates how achieving net zero GHGs defines a pathway characteristic in its own right and thus provides a valuable pathway classification criterion. Introducing the peak probability criterion for 1.5°C (Crit I, less than *likely* to exceed 1.5°C) and achieving net zero GHGs (Crit III) appears to be sufficient to describe a ‘low or no overshoot pathway’ as used in SR15 in our database. We identify two categories of pathways that meet Crit I-II and can be considered Paris Agreement compatible: 1.5°C no overshoot pathways, and pathways allowing for a temporary overshoot while being *very likely* to not exceed 2°C.

Compared to the SR15 ‘low or no overshoot pathways’ category applied to our database, we find that Paris Agreement compatible pathways in our database have a generally lower probability of

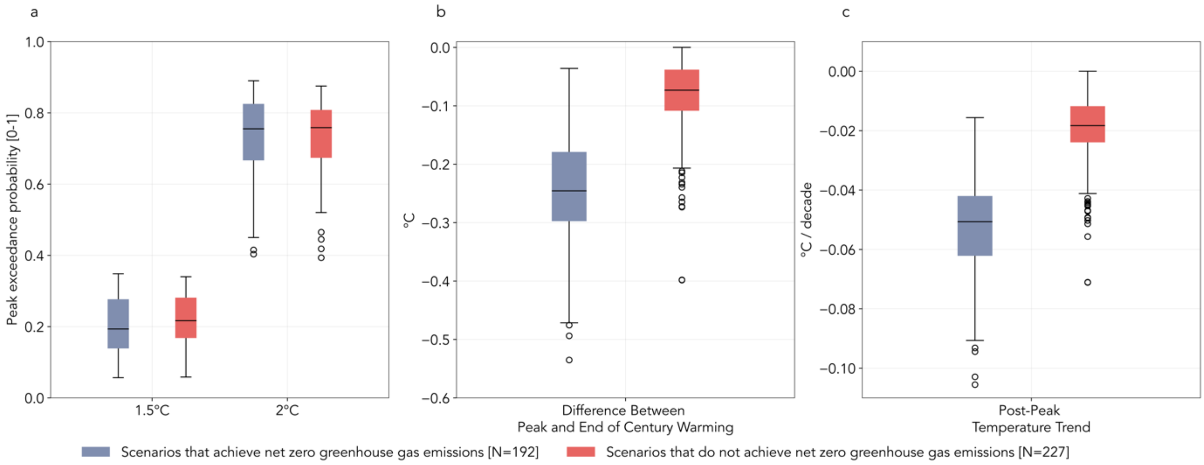


**Figure 2: Emission pathway characteristics and their relation to achieving net zero greenhouse gas emissions. a** Peak exceedance probability for 1.5°C, and 2.0°C, **b** Difference between peak and end of century warming, **d** Decadal temperature trend post peak warming. For **b** and **c**, we use the median of the temperature outcomes calculated using MAGICC6. We include scenarios that fall into the following SR15 categories: Below 1.5°C, 1.5°C low overshoot, 1.5°C high overshoot, and Lower 2°C (compare Table 1), and group scenarios according to whether they do (blue) or do not achieve (red) net zero greenhouse gas emissions during the 21st century.

exceeding 1.5°C (Fig 3b) and are characterised by significantly more stringent near-term emission reductions of 20-26 Gt $CO_2$eq (interquartile range) in 2030 (compared to 24-31 Gt $CO_2$eq interquartile range for the no or low overshoot pathways, see Fig 3d), an earlier date of net zero $CO_2$ emissions (median estimate 2050 instead of 2055, with a significantly narrower range, Fig 3c) and net zero GHGs about 10 years after net zero $CO_2$ (compared to about 25 years later or never). Note that the benchmarks identified for characteristics of low and no overshoot 1.5°C pathways in our database differs from those reported in the SR15, due to a new set of emissions scenarios included in the analysis presented here. Based on scenarios available at the time, the SR15 identified of 2030 emission levels of 25–30 Gt$CO_2$eq (interquartile range) for no or low overshoot pathways and net zero $CO_2$ emissions around 2050, and net zero GHGs between 2060 and 2080[13].

**Implications of scenario assumptions for carbon dioxide removal**

Our Paris Agreement classification scheme allows us to provide an assessment of pathway characteristics in line with the Agreement's provisions. While the temperature-based criteria are well defined, the criterion of net zero GHGs (Crit III) allows for some ambiguity. How, and with what combination of residual $CO_2$ and non-$CO_2$ emissions, as well as CDR, it can be fulfilled can lead to different outcomes as shown for three illustrative scenarios in Figure 4. Depending on the socio-economic pathway considered as well as model assumptions about mitigation potentials of different GHG emission sources, the remaining $CO_2$ and non-$CO_2$ emissions at the time of net zero

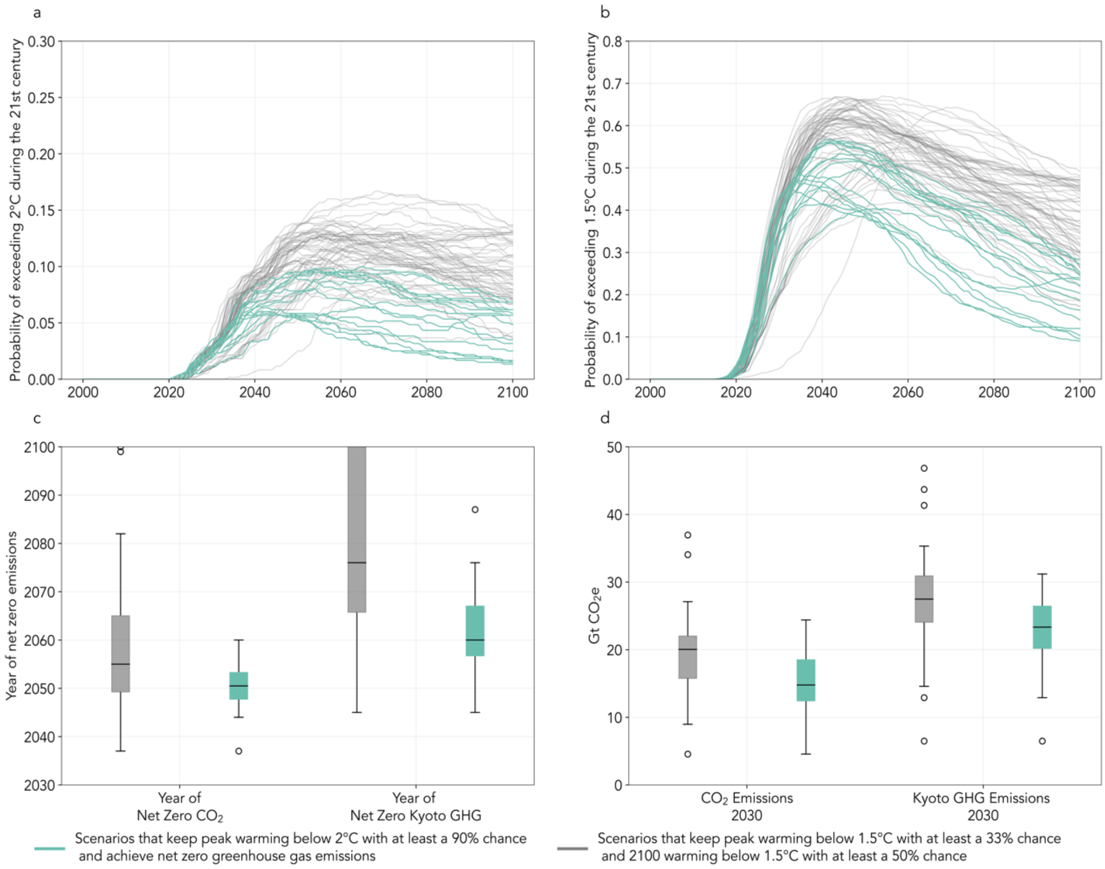


**Figure 3: Characteristics of pathways assessed as Paris Agreement compatible in comparison with the IPCC SR15 no or low overshoot pathways category. a,** Probability of exceeding 2°C over the 21st century. **b,** Probability of exceeding 1.5°C over the 21st century. **c,** Timing of global emissions reaching net zero for $CO_2$ and Kyoto GHG emissions. d, 2030 emission levels for $CO_2$ and total Kyoto-GHG emissions.

$CO_2$ and net zero GHGs, and additional assumptions beyond net zero GHGs, very different requirements for CDR deployment in these pathways are apparent. From minimal CDR needs for pathways with very small remaining GHG emissions, to pathways with high remaining non-$CO_2$ emissions that need to be balanced – and the resulting more pronounced temperature decline – to going strongly negative beyond net zero GHGs, a range of different long-term outcomes could be implied. The set of emission pathways in our database represents an ensemble of opportunity that has not been designed with this classification in mind which does not allow for a systematic analysis of these interdependencies. To the contrary, the net zero carbon budget design approach pursued in the ENGAGE scenarios may lead to less scenarios reaching net zero GHGs (Crit III) compared to an end-of-century budget approach[24]. Other scenarios may deploy large amounts of CDR beyond net zero GHGs by design[21].

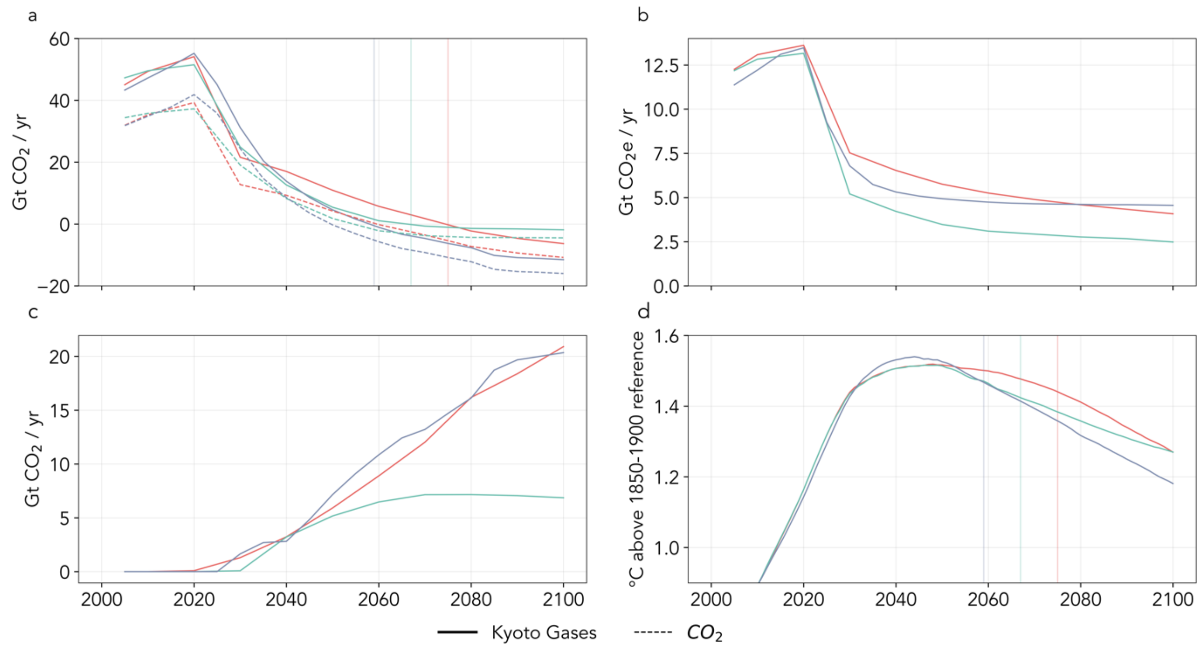


**Figure 4: Illustrative pathways that achieve the three criteria for Paris Agreement consistency** (a) Kyoto greenhouse gas, and $CO_2$ emissions, The years of net zero greenhouse gas emissions are indicated by vertical lines. (b) Non-$CO_2$ emissions aggregated using AR5 GWP100, (c) Carbon dioxide removal deployed, (d) Median temperature rise assessed using MAGICC6.

Bearing these limitations in mind, we nevertheless provide an explorative analysis of these questions based on our ensemble of opportunity. We have estimated the allocation of CDR deployment  beyond achieving net zero $CO_2$ emissions to different characteristics (see Methods): 1) Maintaining net zero $CO_2$ until 2100 – the CDR required to balance out remaining $CO_2$ emissions in the system after the achievement of net-zero $CO_2$. 2) Achieving and maintaining net zero GHGs – the additional CDR required to balance out remaining non-$CO_2$ emissions. 3) Additional CDR deployment beyond achieving, and maintaining net zero GHG. Figure 5 provides an overview across different IAM Paris Agreement compatible pathways in our database. The absolute CDR required differs strongly between different scenarios as does our estimation of the allocation to different objectives. Across pathways, the CDR required for achieving net zero GHG emissions is comparable to the amount needed to balance out remaining $CO_2$ emissions. In terms of cumulative removal, the range spans from around 300 to up to 700 Gt $CO_2$ over the course of the 21st century depending on scenario and model assumptions. Across the ensemble about 20% (interquartile range: 7 – 34%) of the total CDR is the result of additional assumptions included in the scenario design beyond net zero GHGs – in individual cases several hundred Gt of CDR. As outlined above, arguments for the need of a more pronounced a faster potential temperature reversal through more CDR can be made but need to be communicated transparently. Our preliminary analysis suggests that understanding the differences in CDR needs to achieve the Paris Agreement's net zero GHG goal – and identifies a systematic analysis of different configurations of remaining $CO_2$ and non-$CO_2$ emissions, and CDR, as a relevant area for future research.

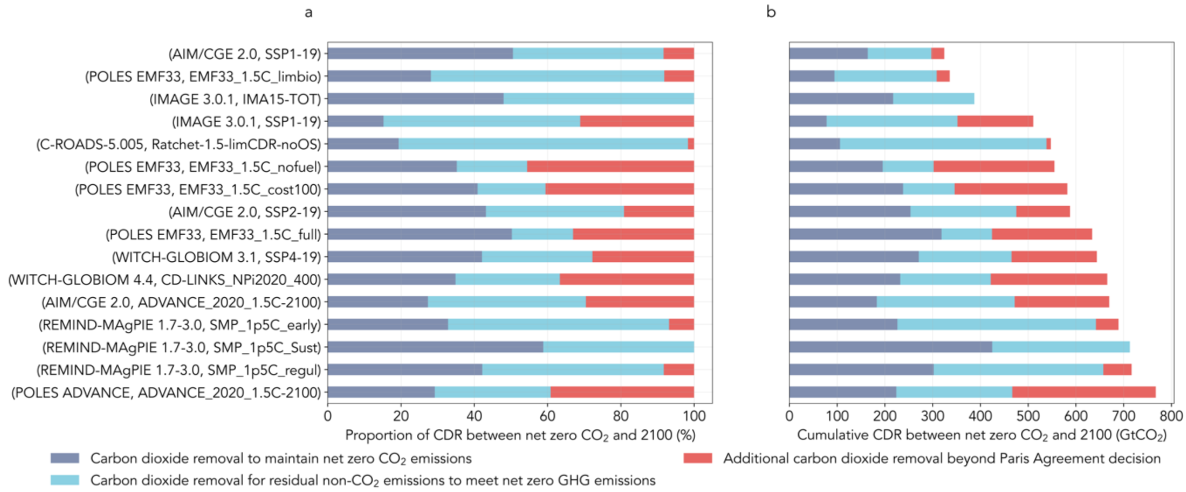


**Figure 5: Carbon dioxide removal deployment in very likely below 2°C net zero GHG pathways.** The carbon dioxide removal is coloured according to the relative contributions towards balancing residual CO2, non-CO2 emissions, as well as additional carbon dioxide removal. **a**, Proportion of CDR between the year of net zero CO2 and 2100. **b**, Cumulative CDR between net zero CO2 and 2100.

## DISCUSSION

The presented pathway classification has illustrated how designing and applying criteria that are aligned with the Paris Agreement objectives lead to new insights into how the goals of the Paris Agreement can be achieved. We have identified two categories of pathways (Table 3): the below 1.5°C category that provides for a 50% or more chance of not exceeding 1.5°C and the very likely below 2°C category. The first category reflects an interpretation of the Paris Agreement temperature goal in which the aim is not to overshoot 1.5°C of global warming, while the second category is in line with the interpretation of potentially temporarily exceeding 1.5°C while always holding warming to ‘well below 2°C’. Both categories reflect the Paris Agreement goal to reach net zero GHG emissions and therewith set global temperatures on a gradually declining trajectory.

With Parties’ renewed commitment to the Paris Agreement we argue that a Paris-aligned categorization as presented here could increase the policy relevance of pathway analysis as the policy debate has now progressed from the question on which global mitigation targets to set, to pursuing ways towards achieving them[25]. With more than 90% of global emissions under (announced) net zero targets, questions surrounding the achievement of net zero emissions have moved on now from “if” to “how”[9]. Our novel pathway classification scheme presented here might help to further sharpen the understanding of key characteristics of emission pathways that comply with global, national or sub-national policy objectives. Also, it highlights research gaps in relation to achieving net zero targets and the implications of different combinations of remaining $CO_2$ and non-$CO_2$ emissions and the required $CO_2$ removal to achieve net zero targets.

***Table 3| Pathway characteristics of pathways achieving the Paris Agreement criteria.*** In addition to the warming criteria, all pathways achieve net zero GHGs. We report the median and interquartile range across the pathways.

| Pathway Category | Subcategory [Count] | 2030 GHG emissions [Gt $CO_2$eq) | Year of net zero $CO_2$ emissions | Year of net zero GHG emissions | Peak warming | Warming in 2100 |
|---|---|---|---|---|---|---|
| Very likely below 2°C | Below 1.5°C [8] | 19 [14, 23] | 2051 [2048,2053] | 2057 [2056, 2066] | 1.48 [1.47, 1.49] | 1.11 [1.04, 1.17] |
| | 1.5°C low overshoot [8] | 26 [26, 27] | 2051 [2048, 2054] | 2063 [2060, 2069] | 1.53 [1.52, 1.54] | 1.25 [1.23, 1.27] |
| | Joint Distribution [16] | 23 [20, 26] | 2050 [2048, 2053] | 2060 [2057, 2067] | 1.51 [1.48, 1.53] | 1.22 [1.12, 1.26] |

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# Methods

**Data collection and scenario categorisation**

In this study, we assess scenarios from the IPCC's Special Report on 1.5°C (SR1.5) [13], as well as the ENGAGE model intercomparison project [24]. We first group the ENGAGE scenarios into the climate categories used in SR1.5. The climate assessment in both studies is performed using the reduced-complexity carbon-cycle and climate model MAGICC [28]. Pathways classified as "Below 1.5°" keep warming below 1.5°C with at least a 50% chance over the 21st century. Pathways classified as "1.5°C low overshoot" have at least 33% of chance of keeping warming below 1.5°C over the 21st century, as well as at least a 50% chance of keeping warming below 1.5°C in 2100. These two categories of pathways have been used to identify pathways that are consistent with the Paris Agreement temperature goal [21,29]. We further proceed to classify the pathways according to their consistency with an alternative, plausible interpretation of Article 2.1, and Article 4 of the Paris Agreement, that we lay out in this paper. These scenarios keep warming below 2°C with at least a 90% chance (interpretation of Article 2.1), and achieve net zero Kyoto greenhouse gas emissions before 2100 (interpretation of Article 4). Kyoto greenhouse gas emissions refer to the following emission species: $CO_2$, $CH_4$, $N_2O$, $SF_6$, HFC, and PFC emissions. The emissions are aggregated using global warming potential (GWP) over a 100-year horizon (GWP100) from the IPCC's 5th Assessment Report[30].

**Estimating total carbon dioxide removal**

The most common options for carbon dioxide removal (CDR) represented in the pathways are carbon sequestration via biomass with carbon capture and storage (BECCS) and carbon sequestration via land sinks. In addition, some models also represent via direct air capture (ref[24] discusses this in further detail). Not all scenarios report carbon sequestration from land use, so we follow the approach adopted by [31], and use the net-negative emissions from CO2 emissions from agriculture, forestry, and land use (AFOLU) as a measure of the carbon sequestration from land use emissions. We aggregate the three options into an overall CDR estimate.

**Disaggregating carbon dioxide removal into components**

We estimate the proportion of CDR after the achievement of net zero $CO_2$ emissions that is necessary to balance out the remaining $CO_2$ emissions, non-$CO_2$ greenhouse gas emissions, and any additional scenario constraints (for instance, achieving the 1.5°C goal in 2100 with a 66% chance). A key challenge that we face in this estimation, is that the scenarios do not report gross $CO_2$ emissions, requiring an assumption to be made to avoid double-counting CDR to balance $CO_2$ emissions. We follow a two-step procedure, with different assumptions for the period between net zero $CO_2$ emissions and net zero GHG emissions, and the period between net zero GHG emissions and 2100.

Between net zero CO2 and GHG emissions:

We first assume that the level of CDR necessary in the year of net zero $CO_2$ emissions, kept constant until the year of net zero GHG emissions, provides a first order approximation of the amount of CDR necessary to balance the remaining CO2 emissions (*Equation 1*).

$$CCDR_{CO2,estimated}^{netzeroCO2-netzeroGHG} = CDR_{CO2,netzeroCO2} * (netzeroGHG - netzeroCO2) \quad (1)$$

Where $CCDR_{CO2,estimated}^{netzeroCO2-netzeroGHG}$ is the cumulative CDR to balance $CO_2$, estimated between net zero $CO_2$ ($netzeroCO2$) and net zero GHG ($netzeroGHG$), and $CDR_{CO2,netzeroCO2}$ is the CDR level in the year of net zero $CO_2$. We sum up the non-$CO_2$ Kyoto GHG emissions over the same time period (*Equation 2*). This gives us a direct measure of the amount of CDR necessary to balance the non-$CO_2$ Kyoto GHG emissions.

$$CCDR_{KyotoGHG}^{netzeroCO2-netzeroGHG} = \sum_{netzeroCO2}^{netzeroGHG} E_{kyotoGHG,t} \quad (2)$$

Where $CCDR_{KyotoGHG}^{netzeroCO2-netzeroGHG}$ is the cumulative CDR to balance Kyoto GHGs, estimated between net zero $CO_2$ and net zero GHG emissions, and $E_{kyotoGHG,t}$ are the Kyoto GHG emissions, in each timestep *t*. The estimate from *Equation 1* can either overestimate the amount of CDR necessary to balance $CO_2$ emissions (if gross $CO_2$ emissions are actually reducing in this time period), or underestimate the amount of CDR necessary for this purpose (if gross $CO_2$ emissions are increasing in this time period). We measure this over-/under-estimation by calculating the difference between the cumulative CDR deployed in this period, and the quantities assessed in *Equation 1* and *2* (*Equation 3*).

$$\Delta CCDR^{netzeroCO2-netzeroGHG} = \left(\sum_{netzeroCO2}^{netzeroGHG} E_{CDR,t}\right) - CCDR_{CO2,estimated}^{netzeroCO2-netzeroGHG} - CCDR_{KyotoGHG}^{netzeroCO2-netzeroGHG} \quad (3)$$

We proceed to add this difference to the estimated CDR for $CO_2$ emissions, to correct for this imbalance (*Equation 4*).

$$CCDR_{CO2,corrected}^{netzeroCO2-netzeroGHG} = CCDR_{CO2,estimated}^{netzeroCO2-netzeroGHG} + \Delta CCDR^{netzeroCO2-netzeroGHG} \quad (4)$$

Where, $CCDR_{CO2,corrected}^{netzeroCO2-netzeroGHG}$ is the corrected estimate of the cumulative CDR to balance out the remaining $CO_2$ emissions. Finally, we recalculate the average CDR level to balance the CO2 emissions (*Equation 5*), and use this quantity for estimation in the next step.

$$CDR_{CO2,netzeroGHG} = \frac{CCDR_{CO2,corrected}^{netzeroCO2-netzeroGHG}}{(netzeroGHG - netzeroCO2)} \quad (5)$$

Between net zero GHG and 2100:
We effectively perform the same sequence of steps laid out in Equations 1-3, with two key differences: we perform this calculation for a different time period (netzeroGHG – 2100), and the level applied in *Equation 1* is $CDR_{CO2,netzeroGHG}$. We now proceed to allocate the $\Delta CCDR^{netzeroGHG-2100}$ to the variable $CCDR_{Additional}^{netzeroGHG-2100}$, which represents the additional CDR due to scenario assumptions. The limitations of this method are that it likely overestimates the amount of CDR necessary to balance out residual $CO_2$ emissions over the period between net zero GHG and 2100, since we assume there is no further reduction of $CO_2$ emissions in this period. This implies that it is likely that we underestimate the CDR deployed to meet additional criteria beyond the Paris Agreement climate objectives. Further research is necessary to reduce uncertainty in this regard.

# Data Availability

The Special Report on 1.5°C underlying this study is accessible online at: https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/. The ENGAGE data underlying this study is accessible online via the ENGAGE scenario portal: https://data.ece.iiasa.ac.at/engage

# Code Availability

The code used to perform the analysis, and generate the figures in this paper are openly available at: https://gitlab.com/gaurav-ganti/commsenv_temp21 under an Apache License, Version 2.0.

# Author Contributions

CFS

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