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An emission pathway classification reflecting the Paris Agreement climate objectives

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The 2015 Paris Agreement sets the objectives of global climate ambition as expressed in its long-term temperature goal and mitigation goal. The scientific community has explored the characteristics of greenhouse gas emission reduction pathways in line with the Paris Agreement. However, when categorizing such pathways, the focus has been put on the temperature outcome and not on emission reduction objectives. Here we propose a pathway classification that aims to comprehensively reflect the climate criteria set out in the Paris Agreement. We show how such an approach allows for a fully consistent interpretation of the Agreement. For Paris Agreement compatible pathways, we report net zero CO_2 and greenhouse gas emissions around 2050 and 2065, respectively. We illustrate how pathway design criteria not rooted in the Paris Agreement, such as the 2100 temperature level, result in scenario outcomes wherein about 6 - 24% higher deployment (interquartile range) of carbon dioxide removal is observed.

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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 under the UNFCCC in the decisions accompanying the adoption of the Paris Agreement (see decision 10/CP.21)[5].

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"[5]. 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[6], and also points to 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. [7] 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[8]. Reaching and sustaining global net zero greenhouse gases with GWP100 will lead to long-term declining temperatures[9–11]. 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[12], countries have reaffirmed 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 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 upper limits for global temperature increase 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 (WG I) 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[9]. 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[13]. 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[14].

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 Working Group 3 (WGIII) contribution to the IPCC's 6th Assessment Report (AR6)[15]. The AR6 WGIII classified emission reduction pathways according to the probabilities of their temperature outcome. There is no objectively correct way to do such an assessment and categorization, and approaches have changed over time in the scientific community. While the AR6 WGIII classification is largely consistent with the approach taken in the Special Report on Global Warming of 1.5 °C (SR15), the authors of the IPCC's 5th Assessment Report, for example, chose to group scenarios according to their radiative forcing levels in 2100[16]. All attempts to provide such information involve value judgements. Implications of different approaches and interpretations therefore must be assessed critically and transparently communicated. Here, we assess such implications of the scenario categorization applied in the IPCC AR6 WGIII report 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. Low-emission scenarios in the categories C1-C3 in the IPCC AR6 WG III that form the basis for the statements in the Summary for Policymakers (SPM) are classified primarily by their likelihood of keeping global mean temperature increase above pre-industrial below a certain temperature level, either 1.5 °C or 2 °C[15,17] (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 AR6 WG III report, following the approach in the SR1.5, uses an exceedance probability metric, *P*, to make these classifications which maps to AR6 WGIII categories as follows (category names in *italics*): P(1.5 °C) ≤ 67%: C1 - *limit warming to 1.5 °C (>50%) with no or limited overshoot*; P(1.5 °C) > 67%: C2 - *return warming to 1.5 °C (>50%) after a high overshoot*. The next set of scenarios categories are defined according to their probability of not exceeding 2 °C. Scenarios are grouped according to their maximum likelihood of keeping warming below 2 °C, and either fall into the C3 - *limit warming to 2 °C (>67%)* category (P(2 °C) > 33%), or the C4- *limit warming to 2 °C (>50%)* category (34% <P(2 °C) < 50%). In addition to these categories from the SR1.5, the AR6 WG III also introduces additional categories C5 – C7 that limit warming to 2.5 °C, 3 °C, and 4 °C respectively with a greater than 50% chance, as well as category C8 that contains scenarios that exceed 4 °C of warming with a greater than 50% chance. However, categories C1 – C3 play a prominent role in the statements underlying the AR6 WG III SPM that describe low-emission system transformations and will hence form the basis for further exploration here.

While transparent and mirroring academic practice, the choice to categorize low-emission 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

Table 1 Characteristics of pathways categories following the emission pathway classification in the IPCC AR6 Working Group 3 report.

Pathway Category (AR6 WG III)	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
C1: limit warming to 1.5 °C (>50%) with no or limited overshoot	60 [57,63]	30 [21,38]	10 [8,11]	114	58	63
C1: no overshoot only	47 [46,48]	18 [14,30]	4 [3,6]	11	10	6
C1: limited overshoot only	61 [58,64]	31 [21,38]	10 [9,11]	103	48	57
C2: return warming to 1.5 °C (>50%) after a high overshoot	75 [72,80]	41 [31,45]	17 [14,20]	106	1	92
C3: limit warming to 2 °C (>67%)	79 [74,83]	63 [57,68]	23 [19,28]	343	0	109

Based on Table SPM1 and own calculations. Exceedance Probabilities are provided using an 11 year centered running mean of the reported values from AR6 WG III based on the MAGICC7 simple climate model (see Methods). Values shown: median (25th to 75th percentile) across the scenarios. 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 greenhouse gas emissions in AR6 GWP100, respectively.

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 being aligned with either 1.5 °C or 2 °C, but lack the understanding of how these levels are linked. Such a presentation is 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. This is acknowledged in the IPCC AR6 WGIII report in footnote 49 in the Summary for Policy Makers (SPM) that clarifies that scenarios in the C1 no or limited overshoot category: "*are found to have simultaneous likelihood to limit peak global warming to 2 °C throughout the 21st century of close to and more than 90%*"[11]. A probability of 90% or higher would translate into a very likely outcome in IPCC calibrated uncertainty language (see below)[18]. Furthermore, the pathway categories are mutually exclusive and do not overlap, which means that pathways that achieve the C1 criterion are not included in C3. While this of course makes sense from a categorization perspective, it does send a very different message in terms of how the results might be interpreted. By excluding C1 pathways (that all comply with the C3 criteria), the range for pathways presented as "limit warming to below 2 °C (>67%)" is narrower, and generally less ambitious in terms of its emission reduction benchmarks, than it in fact would be if only the probability criterion was applied– and policy makers aiming for that objective get a picture that is skewed.

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"[19]. 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)[5]. Under an emissions pathway following this interpretation, the risks of exceeding 2 °C remain significant at a 1-in-3 likelihood, and even the risk of exceeding 2.5 °C would be considerable[20]. The more stringent "well below *2 °C*" objective is a clear strengthening of the intent to avoid a temperature increase of 2 °C or more[4]. The calibrated uncertainty language applied by the IPCC in its assessments provides guidance on how to translate such a strengthening of language in quantifications. The next strongest IPCC qualification category above a likely (>66%) probability level is a very likely (> = 90%) outcome. Given that "below 2 °C" has been commonly translated into a likely chance in IPCC calibrated uncertainty language, we argue that following the same logic "well below 2 °C" would be best translated into a very likely outcome—so a 90% or higher chance of not exceeding 2 °C[18]. In the following, we will adopt an interpretation of "well below 2 °C" as a very likely probability and explore the implications for classifying emission pathways.

An unsupported end of century focus. Moving beyond peak temperature outcomes, AR6 WGIII takes forward scenario categories of so-called overshoot pathways that were introduced in SR1.5 and 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). Both SR15 and AR6 WGIII 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 net 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)[21]. 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 not be considered Paris Agreement compatible[21].

The AR6 WGIII SPM carries forward this perspective, by continuing to highlight only the C1 category of pathways as 1.5 °C pathways. Probably to avoid misinterpretations of the nature of high overshoot C2 pathways, the category name has been revised from "high overshoot 1.5 °C" in the SR1.5 to "return warming to 1.5 °C (>50%) after high overshoot" in the WGIII report. Still, the naming convention of the C2 pathways as "return warming to 1.5 °C" is 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 C2 pathways resemble closely the C3 pathways (limit warming to 2 °C (>67%)) 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 SPM1[11]). To achieve the temperature decline after peak, C2 pathways need to rely on CDR technologies at a very large scale that exceed identified sustainability limits for CDR deployment[22] and may thereby not be in line with the sustainable development and biodiversity provisions of the Paris Agreement and the UNFCCC[23]. We note, however, that the sustainability limits for CDR are technology dependent and some technologies such as Direct Air Capture with CCS would come with different sustainability trade-offs, requiring significantly more material and energy input while having a smaller land and water footprint[24,25].

In the AR6 WGIII report, the C1 category includes those scenarios that "limit warming to 1.5 °C (>50%) with no or limited overshoot". "No overshoot" pathways always keep warming below 1.5 °C with a 50% chance. "Low overshoot" pathways are those 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, with a greater than 50% chance. The median exceedance of 0.1 °C which is compensated by late-century deployment of CDR in most of these pathways is of the same order of magnitude as the potential contribution of non-CO_2 GHG mitigation[20]. The no and limited overshoot C1 category was previously disaggregated into two separate categories in SR1.5 ("Below 1.5 °C" and "1.5 °C low overshoot") and we provide this disaggregated data based on the composite category AR6 WGIII C1 in Table 1. The WGIII SPM includes two new subcategories for C1 separating out pathways that do or do not achieve net zero GHGs: C1a and C1b, respectively. Table SPM1 highlights the differences in pathway characteristics of those different subcategories, as does statement C2.4 in the IPCC WGIII SPM specifically on the long-term warming outcomes of achieving net zero GHGs.

The application of pathway categorization criteria to the temperature outcome in the year 2100, as part of the criteria for C1 and C2, is not rooted in the legal framework or text of the Paris Agreement nor of the UNFCCC more broadly. Instead, it appears to be the outcome of historic common practice by the scientific community of scenario modelers, setting technical modeling constraints in mitigation scenarios until the end of the century. 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[26]. 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 for several hundred gigatons of cumulative CO_2 removal by design. Yet, assuming such a strong after-peak cooling is not mandated by the Paris Agreement. 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 that such assumptions need to be made transparent.

A solution to this unsupported focus on temperature outcomes in 2100 has been presented in the literature[26], 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.

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

Criteria I to III 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 and assess key scenario features, including net zero timings and carbon dioxide removal deployment.

Results and discussion

We illustrate the effect of our scenario classification on the scenario database underlying the AR6 WG III report (see Methods). This scenario database 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). It is important to highlight that our method of categorizing pathways deviates slightly from the approach taken in

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[18]) 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[18].
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[8].

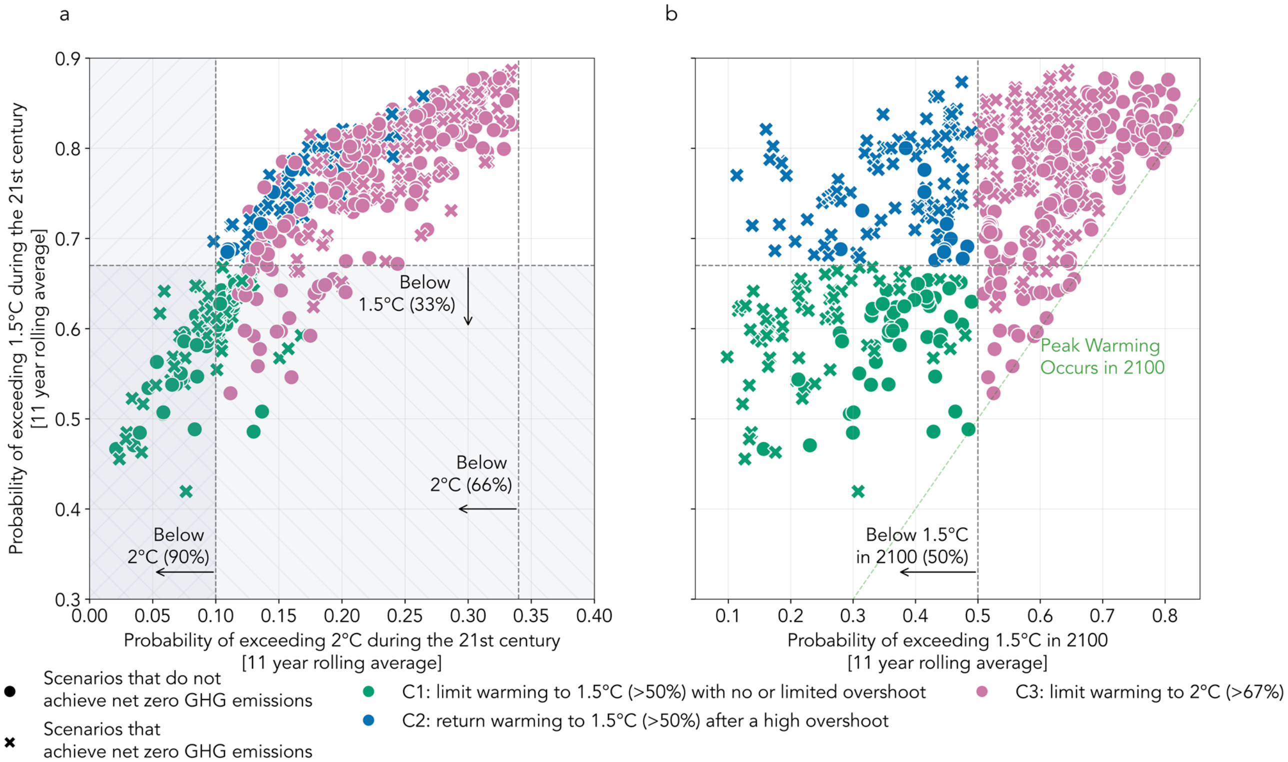

Fig. 1 Probabilities of exceeding 1.5 °C and 2 °C of global warming for different scenario categories. All values presented here use an 11-year running mean applied to the output from MAGICC7 included in the AR6 WGIII database (see Methods). **a** Probability of exceeding 2 °C against the probability of exceeding 1.5 °C over the 21st century. **b** Probability of exceeding 1.5 °C in 2100 against the probability of exceeding 1.5 °C at peak warming over the 21st century. The green dashed line indicates pathways for which peak warming occurs in 2100. The scenarios are colored according to their categorization in the AR6 WGIII (compare Table 1). Symbols indicate whether pathways achieve net zero greenhouse gas emissions in the 21st century.

the IPCC AR6 WGIII report. The scenarios as provided in the WGIII database include a component of natural variability, namely cyclically changing solar forcing over the 21st century with a 11 year periodicity[27]. The temperature goal of the Paris Agreement refers to anthropogenic warming only[28], which means that the anthropogenic warming component of the GMT signal would need to be approximated to apply a pathway classification that can be related to the temperature goal. A common method to do so is to apply a multi-decadal centered running mean, commonly of 20 years or more[9]. However, applying such a multi-decadal averaging would also smooth out other pathway features in the peak and decline temperature pathways studied here, where peak exceedance probabilities would be slightly lowered as a result. To address this trade-off, we apply an 11-yr centered running mean that filters out the specific solar forcing variability present in these scenarios, while having a minor effect of around −1% (median, with interquartile range of −2% to −1%) for 1.5 °C peak exceedance probabilities (see Supplementary Information for a sensitivity analysis).

Note that this approach is only viable for this specific application to filter out a solar forcing cycle from an otherwise anthropogenically forced warming time series, as 11 years would be too short to filter out other modes of natural variability present in the observed temperature record[9]. We find the effects of categorizing pathways according to the anthropogenic warming compared to the WGIII approach to be small in terms of the ensemble statistics, but for reasons of transparency we provide a version of relevant display items following the WGIII approach in the Supplementary Information.

Across the WGIII database we find that the criterion for temperature increase to very likely remain below 2 °C (Crit II) dominates the less than likely to exceed 1.5 °C criterion (Crit I), with the exception of one C2 pathway that complies with Criterion II, but not Criterion I. 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. Estimates of this uncertainty distribution are expected to change as science progresses (for a major recent update see e.g. ref. [29]). Because estimates based on a specific quantile of an uncertainty distribution are sensitive to changes in the assessed uncertainty distributions, it needs to be expected that the relevance of Criterion I and Criterion II for pathway classification will change between different assessments.

Peak temperature exceedance probabilities are largely independent from the Criterion III on achieving net zero GHG emissions (Fig. 2a). However, when comparing peak and 2100 exceedance probabilities, a clear dependency emerges (Fig. 2b, c). Post-peak temperature reductions in absence of achieving net zero GHGs are still apparent (compare Fig. 2b), potentially as a result of stringent and continued mitigation of short-lived non-CO_2 GHGs, substantial CDR without ever meeting the net zero GHG criterion because of high stable levels of short-lived GHGs, or as the result of a long-term cooling trend resulting from a negative zero emissions commitment[30]. But median post-peak temperature reduction (Fig. 2b) and decadal temperature trend (Fig. 2c) are almost three times higher in pathways achieve net zero GHGs. This illustrates that achieving net zero GHGs provides for a valuable pathway classification and design criterion.

The AR6 WGIII recognizes this to some extent, by breaking out the C1 category into two subcategories in Table SPM.1—subcategory C1a (all pathways achieve net zero GHG emissions) and subcategory C1b (no pathway achieves net zero GHG emissions). Pathways belonging to the C1a subcategory would meet Criterion I (less than likely to exceed 1.5 °C) and Criterion

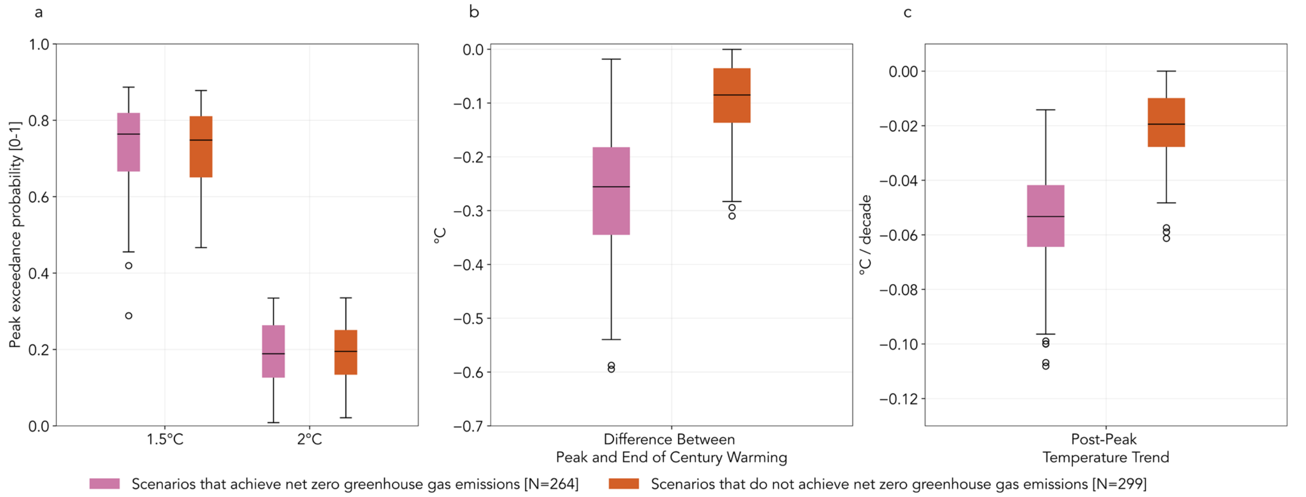

Fig. 2 Emission pathway characteristics and their relation to achieving net zero greenhouse gas emissions. a Peak exceedance probability for 1.5 °C, and 2.0 °C using an 11-year running mean, **b** Difference between peak and end of century warming, **c** Decadal temperature trend post peak warming. For **b** and **c**, we use the median of the temperature outcomes calculated using an 11-year running mean based on the output from MAGICC7 (see Methods). We include scenarios that fall into the following AR6 WGIII categories: C1 (limit warming to 1.5 °C (> 50%) with no or limited overshoot), C2 (return warming to 1.5 °C (> 50%) after a high overshoot), and C3 (limit warming to 2 °C (> 67%)) (compare Table 1), and group scenarios according to whether they do (pink) or do not achieve (orange) net zero greenhouse gas emissions during the 21st century. The box represents the interquartile range (25th–75th percentile) and the whiskers represent the range with outlier datapoints (defined as datapoints that lies beyond 1.5 times the interquartile range above the 25th or 75th percentiles) represented as individual datapoints.

III (achieving net zero GHGs). A smaller subset of these C1a pathways that also have a very likely chance not to exceed 2 °C (Crit II) can be considered Paris Agreement compatible according to Criterion I-III identified here.

Compared to the complete C1 category, pathways in the Paris Agreement compatible category exhibit a similar, yet slightly earlier, date of net zero CO_2 emissions (unrounded median estimate 2049 instead of 2052, with a significantly narrower range, Fig. 3c) and reach net zero GHGs about 15 years after net zero CO_2 (compared to about 35 years later or never). Also compatible 2030 emission levels are similar, which might be partly due to the fact that near-term warming is dominated by non-CO_2 forcing and there is limited variety in the rate of near-term methane reductions in WGIII pathways independent of the long-term warming outcome[15]. Interestingly, a significant time-lag can be observed between the peak exceedance probability for 1.5 °C (between 2040-2046, interquartile range, Fig. 3a) and 2 °C (between 2051-2059, interquartile range, or later, see also Figure S3) for the WGIII C1 scenarios. Understanding the origins of this time-lag and its dependence on the methodological setup used in the IPCC AR6 WGIII[15] (scenario infilling, harmonisation methods or emulator calibration) is beyond the scope of this analysis. It raises, however, some important questions with regards to our understanding of the relation between emission reductions, net zero timings, and peak warming under best estimate versus high warming outcomes.

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, non-CO_2 emissions and CDR it can be fulfilled can lead to different outcomes as shown for three illustrative scenarios in Fig. 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 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 CO_2 and non-CO_2 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 the AR6 WGIII database represents an ensemble of opportunity that has not been designed with a specific focus on net zero GHGs (Crit III) and therefore does not allow for a systematic analysis of these interdependencies. To the contrary, the net zero carbon budget design approach pursued in a large number of scenarios in the database from the ENGAGE project and others, may lead to less scenarios reaching net zero GHGs compared to an end-of-century budget approach[31]. Other scenarios may deploy large amounts of CDR beyond net zero GHGs by design[26].

Bearing these limitations in mind, we pursue an explorative analysis of these questions. 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. We analyse the implications across different IAM pathways that belong to the Paris Agreement consistent category (Fig. 5) as well as the broader suite of C1a pathways that meet Crit I and III, but not Crit II in the database. The absolute CDR deployed differs strongly between scenarios as does our estimation of the allocation to different objectives. Across the pathway ensemble 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 less than 300 to up around 1000 Gt CO_2

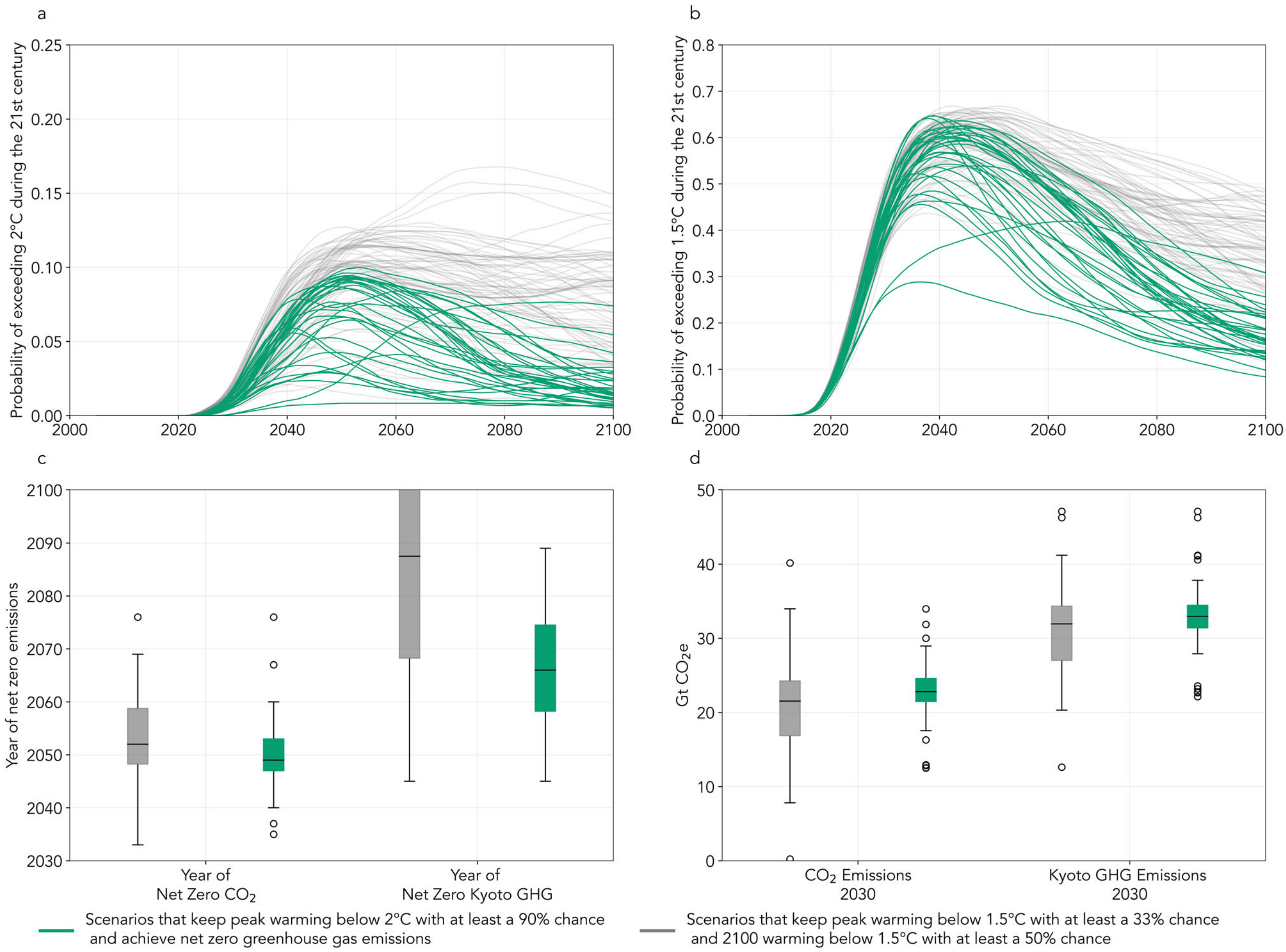

Fig. 3 Characteristics of pathways assessed as Paris Agreement compatible in comparison with the AR6 pathways that limit warming to 1.5 °C (>50%) with no or limited overshoot. **a** Probability of exceeding 2 °C over the 21st century. **b** Probability of exceeding 1.5 °C over the 21st century. **c** 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. The box represents the interquartile range (25th–75th percentile) and the whiskers represent the range with outlier datapoints (defined as datapoints that lie beyond 1.5 times the interquartile range above the 25^{th} or 75^{th} percentiles) represented as individual datapoints. Panel **a** and **b** use an 11-year centered running mean (see Method).

over the course of the 21st century depending on scenario and model assumptions (Fig. 5). Across the Paris Agreement consistent category about 14% (median, with interquartile range: 6–24%) of the total CDR is the result of additional assumptions included in the scenario design beyond net zero GHGs—in individual cases several hundred gigatonnes of CDR. Across the broader C1a subcategory, about 17% (median, with interquartile range: 10–26%) of the total CDR is the result of such additional assumptions.

Such additional assumptions may well be motivated by legitimate reasons. For example, arguments for the need of a more pronounced post-peak temperature reversal through more CDR deployment to reduce long-term impacts could be made as argued above. However, any such additional scenario assumptions, and their implications, need to be rigorously analysed and communicated transparently. This is of critical importance to avoid misinterpretations such as e.g., linking long-term large-scale CDR deployment to peak warming outcomes[32]. Our preliminary analysis suggests that understanding the differences in CDR needs to achieve the Paris Agreement's net zero GHG goal merits further attention—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.

Conclusion

The pathway classification suggested in our manuscript illustrates how designing and applying pathway criteria that are aligned with the Paris Agreement objectives can lead to further insights on Paris Agreement compatible mitigation benchmarks. We have identified two categories of pathways respecting the three criteria identified (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.

At the same time, our analysis reveals significant research gaps with regards to emission pathways designed to meet Paris Agreement compatible criteria. Pathways that meet these criteria in the ensemble of opportunity studied here still include additional design assumptions that go beyond the criteria set out in the Agreement itself (compare Fig. 5) and significantly affect long-term outcomes in such pathways. Our analysis also highlights research gaps in relation to achieving net zero targets and

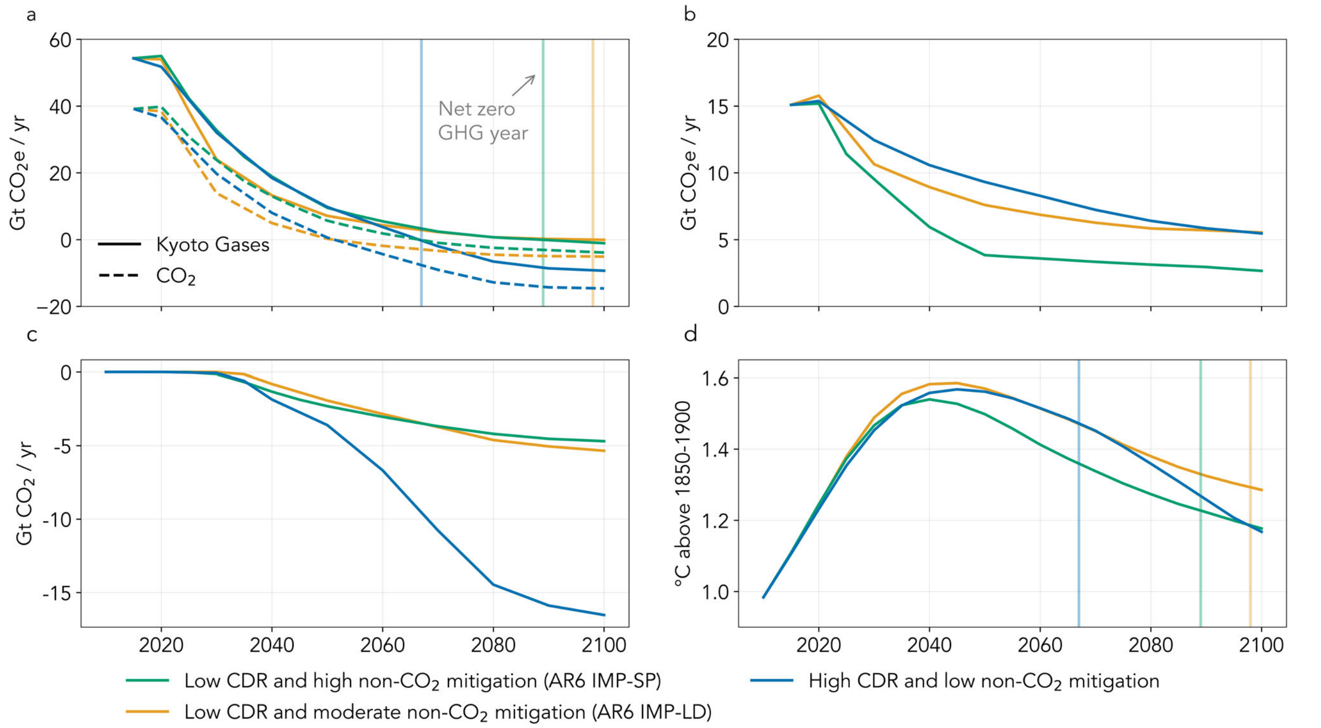

Fig. 4 Illustrative pathways that achieve the three criteria for Paris Agreement consistency. **a** Kyoto greenhouse gas and CO_2 emissions in Gt CO_2/yr and CO_2/yr respectively. The years when net zero greenhouse gas emissions are reached are indicated by vertical lines. **b** Non-CO_2 emissions aggregated using AR6 GWP100. **c** Total carbon dioxide removal deployed. **d** Median temperature rise assessed using MAGICC7. As in (**a**), colored vertical lines denote net-zero GHG timings for the different pathways. The AR6 IMP-SP and IMP-LD refers to two of three illustrative C1 pathways that were highlighted in the AR6 WG III SPM. The remaining illustrative pathway (IMP-Ren) does not meet Criterion III (net zero greenhouse gas emissions). While the IMP-LD does not meet Criterion II, it misses this criteria by just about 1% points and we include it for illustrative purposes given the prominence of this scenario[39].

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.

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[33]. 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"[10]. Our novel pathway classification scheme might help to further sharpen the understanding of key characteristics of emission pathways that comply with global, national or sub-national policy objectives.

Specifically, we identify a set of pathways from the IPCC AR6 WG III database that can be considered Paris Agreement compatible following criteria derived directly from the Paris Agreement goals that can help to support key policy processes including the 2nd Periodic Review of the long-term global goal[33] and the Global Stocktake under the Paris Agreement. We show how the conventionally perceived dichotomy in presenting 1.5 °C and 2 °C pathways is neither rooted in the Paris Agreement itself, nor scientifically motivated, and that moving beyond it by providing a more comprehensive perspective on Paris Agreement compatibility can provide clearer guidance to policy makers on mitigation benchmarks compatible with political objectives.

Methods

Removing natural variability from the IPCC scenarios and scenario categorisation. In this study, we assess scenarios from the IPCC's WG III 6th Assessment Report (AR6 WG III)[15,34]. The AR6 WGIII scenarios include natural variability, namely projections of solar forcing[27]. To average out natural variability and approximate the anthropogenic warming only, we deploy a centered 11-yr centered running mean assuming a constant trajectory after 2100. We apply this running mean to the exceedance probabilities and median temperature outcomes for the MAGICC7 simple climate model[35,36], as reported in the scenario database. Based on these time-averaged outcomes, we reclassify the AR6 WGIII scenarios according to the category criteria set out in the report[17]. Pathways belonging to the C1 category limit warming to 1.5 °C in 2100 with a greater than 50% chance and hold warming below 1.5 °C throughout the 21st century with at least a 34% chance. This category of pathways have been used to identify pathways that are consistent with the Paris Agreement temperature goal[26,37]. We further proceed to classify these low and no overshoot 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 6th Assessment Report[38]. We demonstrate that comparable results are obtained when the entire analysis is performed using the reported temperature and exceedance values in AR6 WGIII in the supplementary information that accompanies this paper.

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 CDR via direct air capture and enhanced weathering (ref. [31] discusses this in further detail). Not all scenarios report carbon sequestration from land use, so we follow the approach adopted by ref. [32], 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

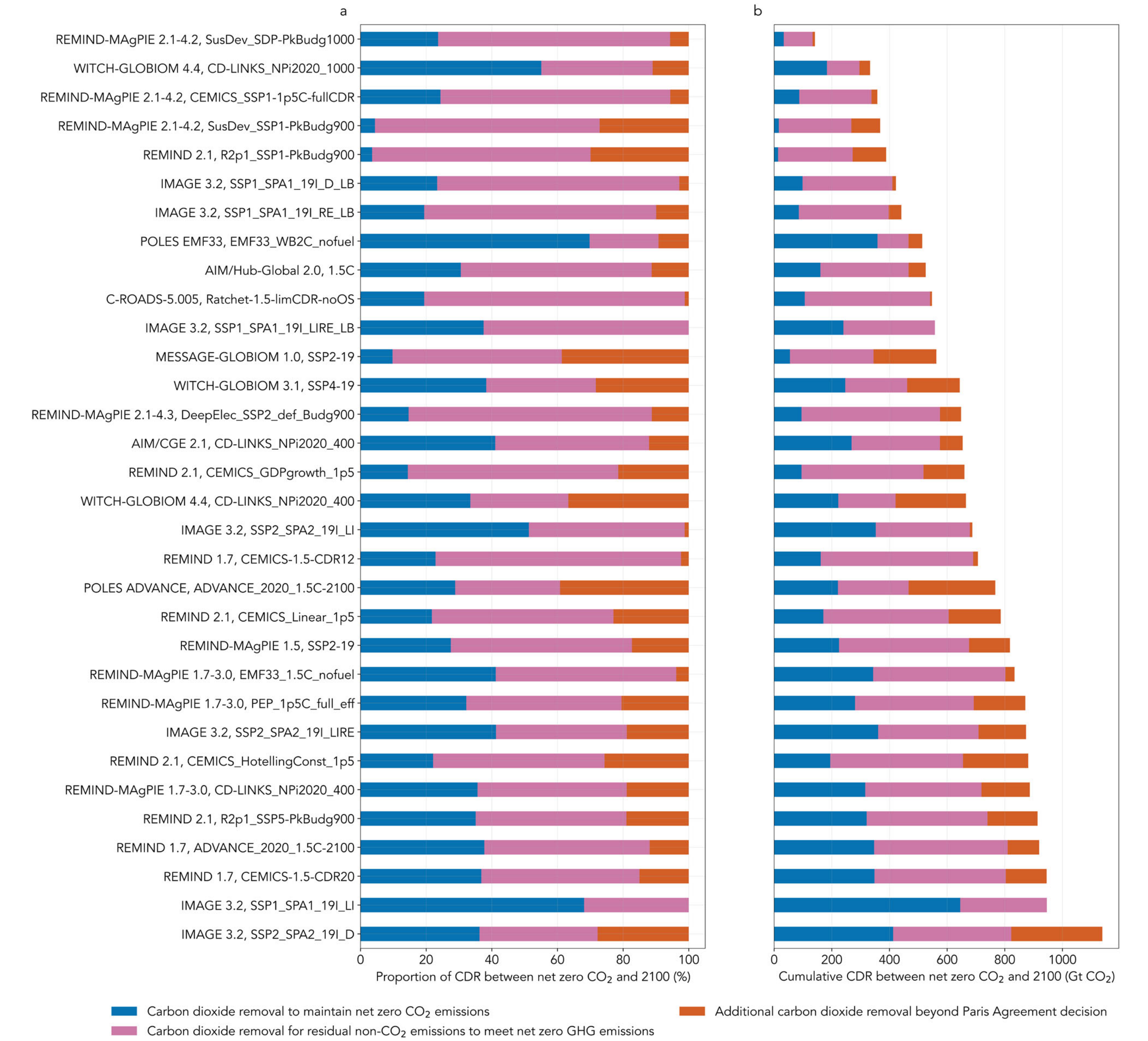

Fig. 5 Carbon dioxide removal deployment in very likely below 2 °C net zero GHG pathways. The carbon dioxide removal is colored according to the relative contributions towards balancing residual CO_2, non-CO2 emissions, as well as additional carbon dioxide removal. **a** Proportion of CDR between the year of net zero CO_2 and 2100. **b** Cumulative CDR between net zero CO2 and 2100.

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 (Eq. 1).

$$CCDR^{netzeroCO2-netzeroGHG}_{CO2,estimated} = CDR_{CO2,netzeroCO2} * (netzeroGHG - netzeroCO2) \tag{1}$$

Where $CCDR^{netzeroCO2-netzeroGHG}_{CO2,estimated}$ 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.

$$CCDR^{netzeroCO2-netzeroGHG}_{KyotoGHG} = \sum_{netzeroCO2}^{netzeroGHG} E_{kyotoGHG,t} \tag{2}$$

Where $CCDR^{netzeroCO2-netzeroGHG}_{KyotoGHG}$ 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 Eq. 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 Eq. 1 and 2 (Equation 3).

$$\triangle CCDR^{netzeroCO2-netzeroGHG} = \left(\sum_{netzeroCO2}^{netzeroGHG} E_{CDR,t}\right) - CCDR^{netzeroCO2-netzeroGHG}_{CO2,estimated} - CCDR^{netzeroCO2-netzeroGHG}_{KyotoGHG} \tag{3}$$

Table 3 Pathway characteristics of AR6 WG III pathways achieving the Paris Agreement criteria.

Pathway Category	Subcategory [Count]	2030 GHG emissions [Gt CO_2eq]	Year of net zero CO_2 emissions	Year of net zero GHG emissions	Peak warming [°C]	Warming in 2100 [°C]
Very likely below 2 °C	Below 1.5 °C [6]	23 [23]	2045 [2035,2060]	2070 [2055,2080]	1.48 [1.45,1.48]	1.14 [1.12,1.18]
	1.5 °C low overshoot [28]	33 [33,35]	2050 [2050,2055]	2065 [2060,2075]	1.56 [1.54,1.58]	1.2 [1.17,1.24]
	Joint Distribution [34]	33 [31,34]	2050 [2045,2055]	2065 [2060,2075]	1.56 [1.53,1.57]	1.19 [1.14,1.24]

In addition to the warming criteria, all pathways achieve net zero GHGs. We report the median and interquartile range across the pathways. 2030 emissions are rounded to the closest integer. Years of net zero emissions are rounded to the closest five-year timestep. Warming outcomes are rounded to two decimal places.

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

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

Where, $CCDR^{netzeroCO2-netzeroGHG}_{CO2,corrected}$ 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 (Eq. 5), and use this quantity for estimation in the next step.

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

Between net zero GHG and 2100. We effectively perform the same sequence of steps laid out in Eq. 1–3, with two key differences: we perform this calculation for a different time period (netzeroGHG – 2100), and the level applied in Eq. 1 is $CDR_{CO2,netzeroGHG}$. We now proceed to allocate the $\triangle CCDR^{netzeroGHG-2100}$ to the variable $CCDR^{netzeroGHG-2100}_{Additional}$, 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. Additionally, explicitly including scenario variables that address this lack of information would negate the need for the bespoke analysis we perform here.

Data availability

The AR6 WGIII scenario data (ref. [34]) underlying this study is accessible online at: https://data.ene.iiasa.ac.at/ar6/.

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.

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References

1. UNFCCC. Adoption of the Paris Agreement. FCCC/CP/2015/10/Add.1 (2015).
2. Rajamani, L. & Werksman, J. The legal character and operational relevance of the Paris Agreement's temperature goal. *Phil. Trans. R. Soc. A*. **376**, 20160458 (2018).
3. Mace, M. J. Mitigation commitments under the paris agreement and the way forward. *Clim. Law* **6**, 21–39 (2016).
4. Schleussner, C.-F. et al. Science and policy characteristics of the Paris agreement temperature goal. *Nat. Clim. Chang.* **6**, 827–835 (2016).
5. UNFCCC. *Adoption of the Paris Agreement*. (2015).
6. Fuglestvedt, J. et al. Implications of possible interpretations of 'greenhouse gas balance' in the Paris Agreement. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci* **376**, 20160445 (2018).
7. Rajamani, L. Ambition and differentiation in the 2015 Paris agreement: interpretive possibilites and underlying politics. *Int. Comp. Law Q.* **65**, 493–514 (2016).
8. UNFCCC. *FCCC/PA/CMA/2018/3/Add.2. Conference of the Parties serving as the meeting of the Parties to the Paris Agreement Report* (2018).
9. IPCC. Summary for Policy Makers. in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Masson-Delmotte, V. et al.) (IPCC, 2021).
10. Rogelj, J., Geden, O., Cowie, A. & Reisinger, A. Net-zero emissions targets are vague: three ways to fix. *Nature* **591**, 365–368 (2021).
11. IPCC. Summary for Policymakers. in *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Shukla, P. R. et al.) https://doi.org/10.1017/9781009157926.001 (Cambridge University Press, 2022).
12. UNFCCC. *CMA 3 Glasgow Climate Pact*. vol. 2 (2021).
13. UNFCCC. *United Nations Framework Convention on Climate Change*. (UNFCCC, 1992).
14. Mengel, M., Nauels, A., Rogelj, J. & Schleussner, C.-F. Committed sea-level rise under the Paris Agreement and the legacy of delayed mitigation action. *Nat. Commun.* **9**, 601 (2018).
15. Riahi, K. et al. Mitigation pathways compatible with long-term goals. in *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Shukla, P. R. et al.) https://doi.org/10.1017/9781009157926.005 (Cambridge University Press, 2022).
16. Clarke, L. et al. Assessing Transformation Pathways. in *Climate Change 2014: Mitigation of Climate Change*. (eds. Edenhofer, O. et al.) (Cambridge University Press, 2014).
17. IPCC. Annex III: Scenarios and modelling methods [Guivarch, C., E. Kriegler, J. Portugal-Pereira, V. Bosetti, J. Edmonds, M. Fischedick, P. Havlík, P. Jaramillo, V. Krey, F. Lecocq, A. Lucena, M. Meinshausen, S. Mirasgedis, B. O'Neill, G.P. Peters, J. Rogelj, S. in *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Shukla, P. R. et al.) https://doi.org/10.1017/9781009157926.022 (Cambridge University Press, 2022).
18. Mastrandrea, M. D. et al. Guidance note for lead authors of the IPCC fifth assessment report on consistent treatment of uncertainties. (2010).
19. UNFCCC. The Cancun Agreements. FCCC/CP/2010/7/Add.1 (2010).
20. Rogelj, J. et al. Chapter 2: Mitigation Pathways Compatible with 1.5 °C in the Context of Sustainable Development. in *Global Warming of 1.5 C:An IPCC special report on the impacts of global warming of 1.5 C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*, (IPCC, 2018).
21. IPCC. *IPCC WGI SR15 Final Government Draft Review Comments And Responses - Summary for Policymakers IPCC WGI SR15 Final Government Draft Review Comments And Responses*. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/09/SR15FGD_Summary_for_Policymakers_Comments_and_Responses.pdf (2018).
22. Fuss, S. et al. Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.* **13**, 063002 (2018).
23. Schleussner, C.-F., Nauels, A., Schaeffer, M., Hare, W. & Rogelj, J. Inconsistencies when applying novel metrics for emissions accounting to the Paris Agreement. *Environ. Res. Lett.* 0–22 https://doi.org/10.1088/1748-9326/ab56e7 (2019).
24. Realmonte, G. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nat. Commun.* **10**, 3277 (2019).
25. Chatterjee, S. & Huang, K. W. Unrealistic energy and materials requirement for direct air capture in deep mitigation pathways. *Nature Commun.* **11**, 1–3 (2020).
26. Rogelj, J. et al. A new scenario logic for the Paris Agreement long-term temperature goal. *Nature* **573**, 357–363 (2019).
27. Matthes, K. et al. Solar forcing for CMIP6 (v3.2). *Geosci. Model Dev* **10**, 2247–2302 (2017).

28. Rogelj, J., Schleussner, C. F. & Hare, W. Getting It Right Matters: Temperature Goal Interpretations in Geoscience Research. *Geophys. Res. Lett.* https://doi.org/10.1002/2017GL075612 (2017).
29. Sherwood, S. et al. An assessment of Earth's climate sensitivity using multiple lines of evidence. *Rev. Geophys.* vol. n/a (2020).
30. MacDougall, A. H. et al. Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO2. *Biogeosciences* **17**, 2987–3016 (2020).
31. Riahi, K. et al. Cost and attainability of meeting stringent climate targets without overshoot. *Nat. Clim. Chang.* **11**, 1063–1069 (2021).
32. Warszawski, L. et al. All options, not silver bullets, needed to limit global warming to 1.5 °C: a scenario appraisal. *Environ. Res. Lett.* **16**, 064037 (2021).
33. Schleussner, C.-F. & Fyson, C. L. Scenarios science needed in UNFCCC periodic review. *Nat. Clim. Chang.* **377**, 2019 (2020).
34. Byers, E. et al. AR6 Scenarios Database. https://doi.org/10.5281/zenodo.5886912 (2022).
35. Meinshausen, M. et al. The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geosci. Model Dev.* **13**, 3571–3605 (2020).
36. Nicholls, Z. et al. Reduced Complexity Model Intercomparison Project Phase 2: Synthesizing Earth System Knowledge for Probabilistic Climate Projections. *Earth's Futur* **9**, e2020EF001900 (2021).
37. Brecha, R. et al. Institutional 'Paris Agreement Compatible' Mitigation Scenarios Evaluated Against the Paris Agreement 1.5 °C Goal. *Prepr. Res. Sq.* https://doi.org/10.21203/rs.3.rs-599934/v1 (2021).
38. Forster, P. et al. The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Masson-Delmotte, V. et al.) (Cambridge University Press, 2021).
39. van Beek, L., Oomen, J., Hajer, M., Pelzer, P. & van Vuuren, D. Navigating the political: An analysis of political calibration of integrated assessment modelling in light of the 1.5 °C goal. *Environ. Sci. Policy* **133**, 193–202 (2022).

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Author contributions
C.-F.S. and G.G. initiated the study. G.G. performed the analysis and produced the figures with support by C.-F.S. and M.J.G. C.F.S., G.G., J.R. and M.J.G. wrote the manuscript.

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