A new scenario logic for the Paris Agreement long-term temperature goal

Authors

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Summary

To understand how global warming can be kept well-below 2°C and even 1.5°C, climate policy uses scenarios that describe how society could reduce its greenhouse gas emissions. However, current scenarios have a key weakness: they typically focus on reaching specific climate goals in 2100. This choice may encourage risky pathways that delay action, reach higher-than-acceptable mid-century warming, and rely on net carbon-dioxide removal thereafter to undo their initial shortfall in emissions reductions. Here we draw on physical science insights to propose a scenario framework that focusses on capping global warming at a specific maximum level with either temperature stabilisation or reversal thereafter. The ambition of climate action until carbon neutrality determines peak warming, and can be followed by a variety of long-term states with different sustainability implications. This new approach closely mirrors the intentions of the UN Paris Agreement, and makes questions of intergenerational equity explicit design choices.

Main text

International climate policy aims to prevent dangerous anthropogenic interference with the climate system[1]. Since about a decade ago, decision makers have begun translating this broad objective into more specific temperature limits[2]. Such temperature goals have limitations but can serve as a proxy for climate impacts, at both global and local scales[3-5]. In 2015, the Paris Agreement concluded many years of negotiation and reset the aim of international climate policy to holding global warming to levels well-below 2°C and pursuing efforts to limit it to 1.5°C[6] – an objective which in its entirety is referred to as the Paris Agreement's long-term temperature goal[6] (LTTG). The Paris Agreement LTTG hence defines an envelope of acceptable climate outcomes, which – it specifies – should be pursued in the broader context of sustainable development[7] (see Methods for more background on the LTTG).

Scenarios of the combined energy-economy-environment system provide key tools to explore how the future could evolve, and how today's decisions could affect longer-term outcomes[8]. Over the past decades, researchers have extensively used such scenarios to identify integrated solutions that can limit climate change, and to inform international climate policy[8,9]. This literature does not cover all possible interpretations of global climate goals with equal detail and depth. The vast majority of scenarios available in the literature either aim to stabilize greenhouse gas concentrations over the 21st century[10,11] or attempt to limit end-of-century radiative forcing to specific levels[8,12,13]. In a related approach, scenarios prescribe an overall limit on total cumulative CO_2 or greenhouse gas emissions over the 21st century, as a proxy for global-mean temperature rise in the year 2100[14,15]. Models are then optimized to achieve these objectives in a cost-effective manner.

Focussing on end-of-century outcomes, combined with discounting long-term compared to present-day mitigation, leads to a feature that is present in virtually all resulting scenarios: the assumed possibility of substantial net negative CO_2 emissions in the second half of the century allows for weaker emissions reductions in the nearer term and results in temporarily higher warming over the course of the century. Because of their end-of-century focus, many current scenarios hence contradictorily suggest that the best way of keeping warming to a specific level in 2100 is achieved by temporarily exceeding the set maximum level before 2100. Such interpretations seem to be inconsistent with the text of the UN Paris Agreement LTTG[6,7].

A focus on end-of-century outcomes also results in the perception that meeting temperature goals in line with the Paris Agreement requires substantial levels of net negative emissions[8,16-18] which continue to increase until 2100, and that putting an explicit cap on the gross deployment of carbon-dioxide removal (CDR) measures will also affect the maximum warming over the 21st century[19]. (For the sake of clarity, we here consistently use the term net negative emissions to refer to actual removal of CO_2 from the atmosphere. We refer to CDR when referring to specific technologies or measures, although these terms are currently used interchangeably in the literature[20,21].) The assumed rapid scale-up and potential land-use consequences of large-scale CDR in stringent mitigation scenarios[8,21,22] have increased the perception that meeting stringent climate goals is infeasible or, in some cases, socially undesirable due to sustainability and intergenerational equity concerns[17,23-25]. For these and other reasons, scholars have labelled these scenarios as particularly risky[26,27].

However, the perceived linkage between end-of-century outcomes and the amount of late-century net negative emissions is not robust; instead, it is to a large degree driven by the design characteristics underlying the scenario cohort currently available in the literature[8,26,28,29]. Specifically, net negative emissions correlate with temperature goals such as 1.5°C or 2°C in most of the currently available scenarios because these scenarios attempt to achieve temperature goals by optimizing costs and emissions over the entire century. Such an approach does not consider a limit to peak temperature rise which, for low temperature targets, typically occurs well before 2100. Under such an approach, changes in gross CDR deployment also change the maximum amount of warming over the course of the century[19], because peak warming is not one of the current design criteria for mitigation scenarios.

Here we present a new simple mitigation scenario logic that enables studies to explore climate action strategies that cap global warming at a specific level, and that makes intergenerational trade-offs regarding the timing and stringency of mitigation action an explicit design criterion. In addition, it provides a framework in which future CDR deployment can be explored independently from variations of desired climate outcomes, in the light of social, technological, or ethical concerns[16,17,21,23-27]. Earlier climate change mitigation scenarios were designed by putting a limit to greenhouse gas concentrations[30], the radiative impact of climate pollution[13] and in some cases also directly on temperature change[19]. In most cases, these scenarios aimed at reaching this limit at a specific time in the future after a period over which the target limit could be temporarily exceeded[30], at times referred to as an overshoot. In the context of on-going climate change and the Paris Agreement LTTG of keeping warming well-below 2°C or 1.5°C, these existing approaches do not adequately cap the maximum or peak warming over the next decades.

This new scenario logic is grafted onto an envelope of alternative interpretations of the Paris Agreement LTTG[7,31], and can be combined with the existing Shared Socio-economic Pathway (SSP) framework which explores different alternative socio-economic futures and their implications for the challenges of mitigation and adaptation[32]. The SSPs are typically combined with end-of-century radiative forcing targets[13] consistent with the representative concentration pathways (RCPs) that are used by the climate modelling community for climate change projections[13]. This approach by construction suffers from the weaknesses highlighted earlier, and the new mitigation scenario logic presented here can hence further improve the integrative work of the current SSP scenario framework in light of informing the implementation of the UN Paris Agreement.

Structural elements of the climate goal

Our proposed scenario logic builds on a three-part decomposition of the Paris Agreement LTTG. At the basis of this decomposition is a focus on peak warming rather than end-of-century warming. In the specific context of the Paris Agreement's LTTG, a focus on peak warming implies that global-mean temperature rise needs to be halted at a level well-below 2°C, potentially well before the end of the century, and that afterwards it should at least remain stable or decrease gradually (see Methods). Interpretations of other sections of the Paris Agreement even suggest that a temperature decline after having peaked would be an integral part of the Paris Agreement's intentions, because achieving the mandated net zero greenhouse gas emissions target of the Paris Agreement would result in a gradual reversal of temperature rise over time[33].

We identify three structural elements that together can describe possible temperature evolutions consistent with the Paris Agreement: (i) the time at which global-mean temperature reaches its peak level, (ii) the level of warming at that point in time, and (iii) the temperature trend after the peak, being either stable or declining. Each of these three elements can be prescribed directly or approximated with geophysical emission constraints based on the well-established concept of the near-linear temperature response to cumulative emissions of carbon[15,34,35], combined with considerations of limits to non-CO_2 emissions. Subsequently, these structural elements can be modelled and prescribed independently in scenarios (Table 1, Figure 1, and Methods).

The use of a limit on cumulative CO_2 emissions or of a net zero target as a way to make global climate mitigation goals more fathomable has been suggested by several scholars in the past. Firstly, it has been proposed as a geophysically appropriate way of responding to the climate change mitigation challenge[35-38], and subsequently also as a useful way to provide climate policy with an actionable and stable long-term emissions target[39-41]. Achieving net zero CO_2 emissions, however, is not yet sufficient to meet the emission reduction requirements spelled out in the Paris Agreement, which demand that a balance between sinks and sources of all greenhouse gases is achieved[33]. Our proposed scenario logic allows modellers to translate these geophysical and political science insights in a quantitative framework. Importantly, this new scenario logic defines how models that simulate the energy-economy-environment system can be used to compute climate change mitigation scenarios but does not change the fundamental rules on which these models are built to represent society.

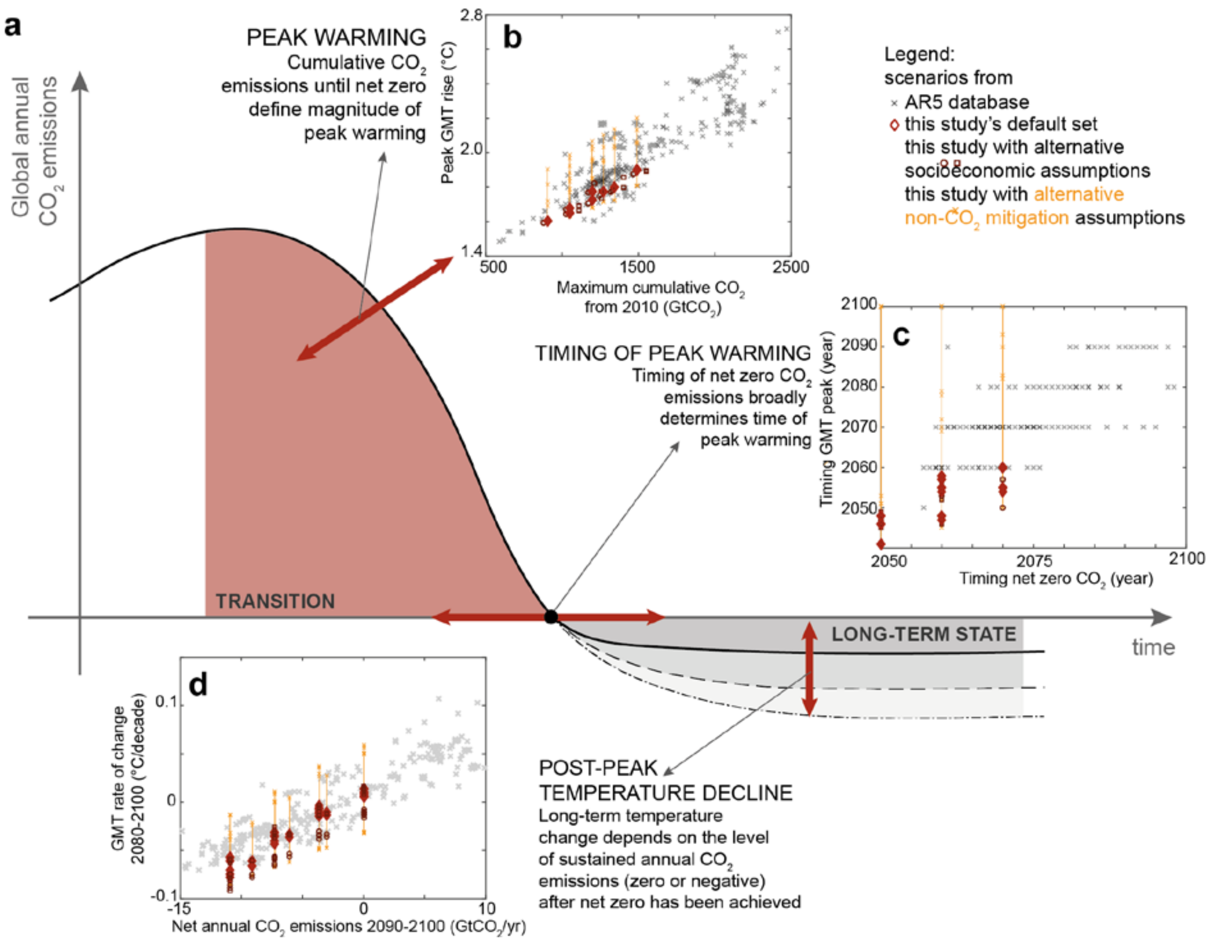

Figure 1 | Three structural elements defining the level of achievement of the Paris Agreement's long-term temperature goal (LTTG). a, schematic overview of structural pathway elements and relationship between pathway elements and global mean temperature (GMT) outcomes. Specifically, the schematic shows how a specific level of peak warming leaves open many post-peak options with different levels of net negative emissions. Subplots show quantitative outcomes, as found in scenarios from the literature (grey crosses, Methods, https://tntcat.iiasa.ac.at/AR5DB/) and scenarios used in this study (red markers). Orange features show sensitivity variations in the level of non-CO_2 mitigation in scenarios (see main text, Methods, and Extended Data Figure 1); **b**, relationship between maximum cumulative CO_2 emissions achieved at the time of net zero CO_2 and peak warming, highlighting the importance of also addressing non-CO_2 emissions in addition to reaching net zero CO_2 emissions; **c**, relationship between the timing of reaching net zero CO_2 emissions and peaking GMT. Additional mitigation of non-CO_2 emissions is required for temperatures to stabilize. GMT peaking values from literature scenarios (grey crosses) appear binned because they are reported at decadal time intervals, while timing of net zero CO_2 emissions from this study are binned by design; **d**, relationship between sustained net annual negative emissions and the rate of temperature change by the end of the century.

Table 1 | Translation of the Paris Agreement's long-term temperature goal (LTTG) into three structural scenario design elements. Fig. 1 illustrates these structural elements, while more detailed information is provided in the Methods section.

Key element of the Paris Agreement LTTG	**Range informed by the Paris Agreement**	**Related geophysical emission scenario characteristic**	**Translation into structural scenario design element**	**Values used in this study**
1) Time of peak global-mean temperature, or time of temperature stabilization	Broadly in the second half of the century based on mitigation target specified in Article 4 of Paris Agreement and a consistent range of non-CO_2 forcing[40]	Peak warming is reached around the time global CO_2 emissions reach net zero[38,42], and non-CO_2 emissions have to be limited so that their warming contribution stabilizes or declines.	The timing of reaching global net zero CO_2 emissions can be prescribed, as well as the stringency with which non-CO_2 emissions are targeted until the time of net zero CO_2 emissions.	Net zero CO_2 emissions are prescribed in scenarios for 2050, 2060, and 2070. Non-CO_2 emissions are limited at a level consistent with the concurrent CO_2 reductions.
2) Level of peak warming or level at which it is stabilised	Well below 2°C relative to preindustrial levels, pursuing to limit it to 1.5°C	There is an approximately linear relationship between peak global-mean temperature and the total cumulative amount of anthropogenic CO_2 emissions[15,34,35]. Maximum net cumulative CO_2 emissions are reached once global CO_2 emissions reach net zero.	The total amount of CO_2 emissions until the time of reaching net zero CO_2 (i.e. the maximum allowable carbon budget) can be prescribed.	A range of remaining carbon budgets and consistent non-CO_2 forcings is explored that would lead to peak warming below 2°C relative to preindustrial levels with at least a likely chance.
3) Post-peak rate of temperature change	Zero or negative (temperatures either to stay constant or to peak and decline at a given rate)	Maintaining net zero CO_2 emissions results in global-mean temperatures remaining approximately constant for centuries[34], provided non-CO_2 emissions are limited so as to not to result in continuous further warming. Net negative CO_2 emissions could enable gradually declining global-mean temperatures[43].	The sustained amount of annual net negative CO_2 emissions to be achieved after reaching net zero CO_2 emissions can be prescribed, as well as the stringency with which non-CO_2 emissions are targeted in the long term.	Net annual negative emissions levels by the end of the century are varied from 0 to about 11 $GtCO_2$/yr. Non-CO_2 emissions are limited at a level consistent with the effort of maintaining the CO_2 levels specified above.

Emissions and warming variations

We now apply this new scenario logic (Table 1) to a model of the energy-economy-environment system (see Methods) to illustrate how its implementation maps onto a range of global temperature outcomes and how it allows for a more direct representation of intergenerational and technological decisions or choices compared to the currently dominant end-of-century approach.

The three design elements proposed in Table 1 map usefully onto the three temperature evolution characteristics that define our new scenario logic: the timing and level of peak warming, as well as the rate of temperature decline thereafter (Figure 1). Different combinations of CO_2 and non-CO_2 mitigation span much of the variation that can be found across a wide set of scenarios available in the literature[8]; and reiterate the importance of paying attention to both CO_2 and non-CO_2 emissions reductions[44]. When non-CO_2 emissions are reduced consistently with the implied carbon price assumed for carbon-dioxide (red markers in Figure 1), the range of temperature outcomes is much narrower than the full range. For example, in the very unlikely case where non-CO_2 emission would not be penalized at all while CO_2 is reduced to zero and beyond (Extended Data Figure 1) peak warming could be markedly higher and warming would not fully stabilize during the 21st century (Figure 1, orange crosses). This case is anticipated to be an overestimate of the potential variation due to non-CO_2 mitigation choices, particularly in light of recent policy developments that emphasize action on short-lived climate forcers, including methane[45], and fluorinated gases under another international agreement, the Montreal Protocol[46].

Our scenario framework decouples the transition in the first half of the century from the stable emissions achieved in the longer term. Peak global warming is therefore disconnected from the total amount of net negative emissions over the 21st century. End-of-century warming is still determined by the difference between CO_2 emitted until net zero, and the net amount of CO_2 removed afterwards (Fig. 2, maximum cumulative CO_2 since 2010 and shaded grey background showing total net negative emissions until 2100). However, peak warming and its timing do not depend on the amount of post-peak net negative emissions. In addition, the main climate outcome characteristics over the 21st century would also be largely independent of the chosen discount rate, in contrast to scenarios designed with the current end-of-century focussed approach.

This scenario logic hence presents the amount of societally acceptable warming and net negative emissions as an explicit design choice and allows one to explicitly explore intertemporal mitigation questions. Considering these aspects explicitly at the scenario design stage allows to cover a much wider domain of potential low-carbon scenarios and more nuanced exploration of futures compared to focussing on an end-of-century target only (see variation in different red versus blue markers in Fig. 2, see also Methods).

If achieving net negative CO_2 emissions in the second half of the century is considered either inconceivable or undesirable, global-mean temperature will at best stabilize around peak warming. Under these assumptions, emissions over the next 3 to 4 decades determine the long-term temperature outcome (Fig. 2). On the other hand, annually removing a certain net amount of CO_2 would result in a gradual decline of global mean temperatures over time[43], provided that also non-CO_2 emissions are limited to a sufficient degree (Methods, Fig. 1c, Extended Data Table 1). Specific levels of either peak or end-of-century warming can be reached with a diverse range of net negative emissions, here ranging from 0 to more than 10 $GtCO_2$/yr (Fig. 2).

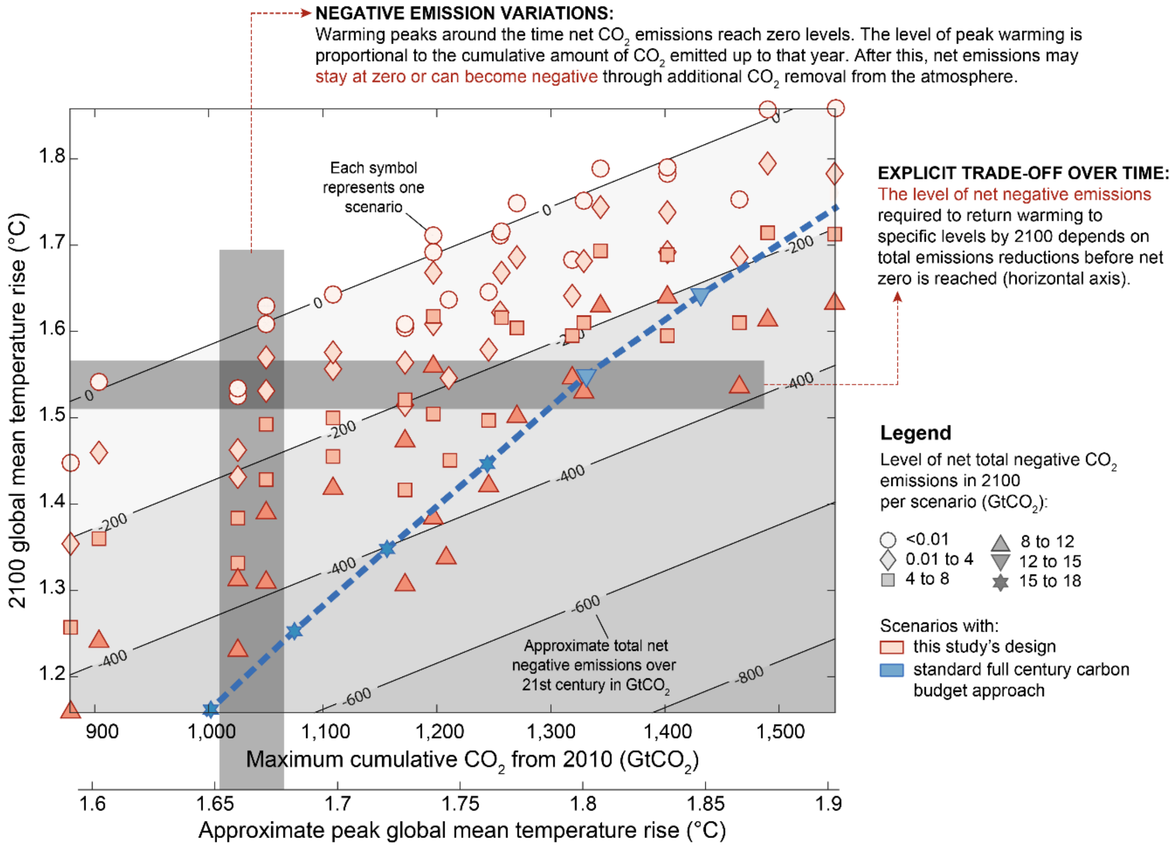

Figure 2 | Variations in the contribution of net negative emissions in reaching specific temperature outcomes over the course of the century. Relationship between maximum cumulative CO_2 emissions from 2010 onward (proportional to peak global mean temperature rise as shown on a second horizontal axis, see Fig. 1b) and year-2100 warming, as a function of total net negative emissions over the 21st century (grey shaded background). Single scenarios are depicted with symbols that show the net annual negative CO_2 emissions achieved in 2100. Red symbols depict scenarios that follow the design presented in this study, while blue symbols depict how a carbon budget is used when optimized over the entire century. Blue scenarios are linked with a dashed line to illustrate the limited solution space that would be covered when using a standard full century carbon budget approach only, compared to the wider space of independent climate outcomes that is achieved when the design presented in this study is followed (red markers).

Negative emissions alternatives

An important part of the on-going climate mitigation debate has focussed on the scale of negative emissions[16,21,23]. Ultimately, it is the gross deployment of CDR options and their key technological components that underpins sustainability and feasibility concerns. For example, the sustainability of large-scale bioenergy production has been questioned due to its pressure on water and food security[21,47,48]. Alternatively, the scale of carbon-dioxide capture, transportation and sequestration (CCS) infrastructure in scenarios could be hard to achieve[49,50]. Our scenario framework as presented in Table 1 does not eliminate these concerns directly, but it offers a way to explore choices and strategies in relation to these CDR options in the context of firmly achieving the Paris LTTG in a way which was not possible with approaches that focus on end-of-century outcomes only (Fig. 3, Extended Data Table 2). Specifically, our new framework provides a logic that enables studies to explore future CDR deployment as an independent variation under a desired temperature outcome.

For example, to a certain degree one can vary the acceptable deployment levels of both bioenergy and CCS (or its combined use BECCS) independently of the net level of negative emissions (Fig. 3, Extended Data Fig. 2) and hence the climate outcome. These constraints can affect the gross deployment of CDR measures and thus the sustainability and feasibility assessment of stringent mitigation goals. For example, annual net negative emissions of about 4 $GtCO_2$/yr could be achieved with different system configurations that see CCS deployment vary by a factor of 5, and bioenergy use either venturing into a domain for which increasing sustainability concerns have been identified[47] (>150 EJ/yr) or being kept at levels where sustainability concerns could be limited[47,48] (<100 EJ/yr) (Fig. 3). This illustrates also that the overall level of bioenergy deployment is not simply a function of BECCS deployment[51]. Also the total amount of CO_2 generated varies by a factor of 4 across alternative system configurations with net negative emissions of about 4 $GtCO_2$/yr, indicating markedly different challenges for achieving required levels of gross negative emissions.

The variations highlighted here are illustrative and further dimensions could easily be explored, like capping the extent of afforestation, the total amount of gross CDR, or limiting the overall amount of CO_2 that is generated annually by the entire economy. Furthermore, concerns do not only have to apply to the availability of certain technological options in the second half of the century, but can also apply to the pace and timing of their scale up over the next decades. Even to achieve global net zero CO_2 emissions, scenarios often use sizeable amounts of CDR that require technologies to be scaled up well before the point global net zero CO_2 emissions are achieved[29,52-54] (Extended Data Figs

2 and 3). An illustrative overview of these and other concerns is provided in Extended Data Table 2 together with a suggestion of how they could be explored as part of the scenario framework presented here. Hence, despite only covering a limited subset of potential sensitivity cases, the variations shown here already illustrate the interplay between mitigation action over the coming decades, the level of CDR technology deployment that given our current understanding can be considered acceptable[21,23], and the achievability of stringent temperature targets over the course of the 21st century.

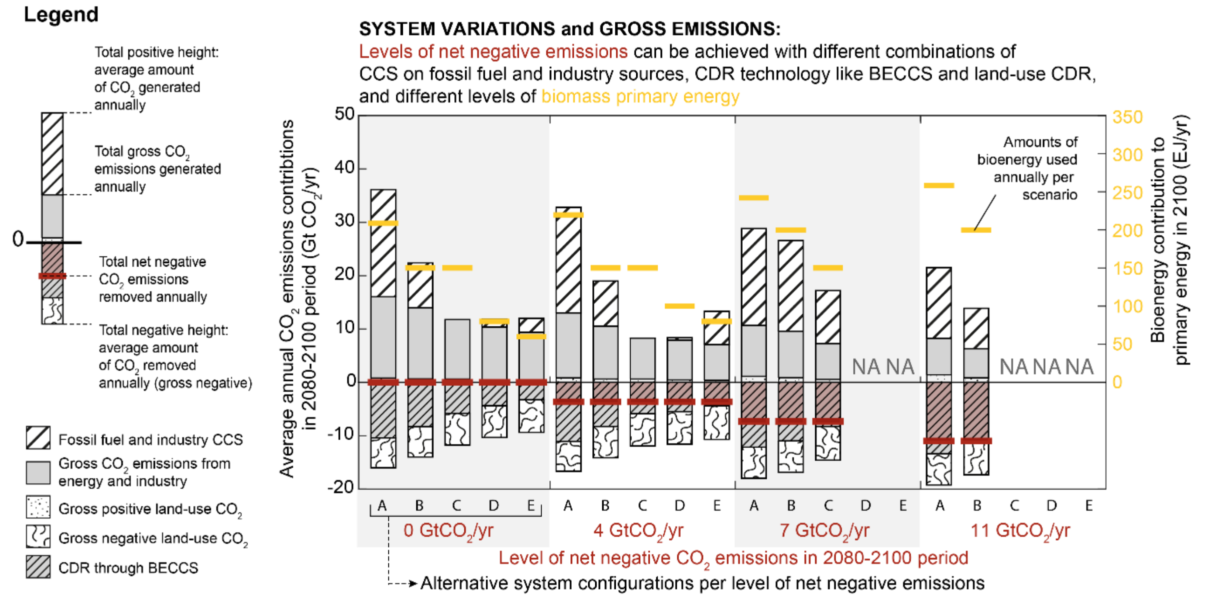

Figure 3 | Scenario variations of system configurations and of contributions of carbon-dioxide removal (CDR) technologies and bioenergy to achieve different levels of negative emissions. System variations to achieve four net negative emissions levels (0, 4, 7, and 11 $GtCO_2$/yr). Five illustrative system variations are shown per level labelled A to E, and defined in Extended Data Tables 3 and 4. CO_2-related values (black bars and red lines) are read on the left axis. Primary energy contributions from bioenergy (yellow features) are read on the right axis. Scenarios labelled with "NA" did not solve under the imposed CDR and bioenergy constraints (Extended Data Table 4). Fossil fuel and industry CCS contributions (white hatched areas) represent CO_2 that is generated but not emitted to the atmosphere. Net negative CO_2 emissions are the sum of gross positive CO_2 emissions from energy and industrial sources and gross positive land-use CO_2 emissions. Gross negative CO_2 emissions comprise gross land-use CO_2 emissions, and CDR through BECCS. The combined size of all bars per scenario gives an indication of the overall size of the remaining CO_2 producing system by the end of the century. The 2080-2100 period is chosen because the lowest net negative emission levels explored in these illustrative scenarios is reached only two decades after reaching net-zero CO_2 emissions.

Mitigation investment legacy

The staged design of our scenario framework also allows studies to explore intertemporal mitigation investment decisions (Fig. 4). Unsurprisingly, estimated mitigation investments until net zero CO_2 are strongly related to the desired level of peak warming (Fig. 4c). Similarly, mitigation investments in the 20 years after temperature has peaked increase robustly with the magnitude of desired long-term net negative CO_2 emissions (Fig. 4d). However, once a long-term level of net negative emissions is achieved, scenarios following the new design show little variation in mitigation investments estimated to sustain emissions at a specific level (Fig. 4e), and are also markedly smaller than those estimated under a standard end-of-century perspective.

The precise magnitude of these investment numbers is illustrative, because they are based on a single model, while technology and other socioeconomic assumptions are known to impact cost estimates to an important degree[55,56]. At the same time, relative changes are considered to be more robust[8] and highlight intertemporal policy choices. For example, the patterns in Figure 4 illustrate how the pace of emissions reductions over the coming decades and the corresponding peak warming affects projected mitigation costs in the longer term. These patterns reflect explicit policy choices about the timing and stringency of climate action, and contrast with limited choices that are suggested with a standard approach of aiming for end-of-century targets only (blue features). The latter show a similar evolution in the period until carbon neutrality (Fig. 4c). However, particularly in the period after carbon neutrality, the newly proposed approach highlights the diversity in choices available to decision makers, as well as the implications and legacy of decisions over the coming decades for future generations.

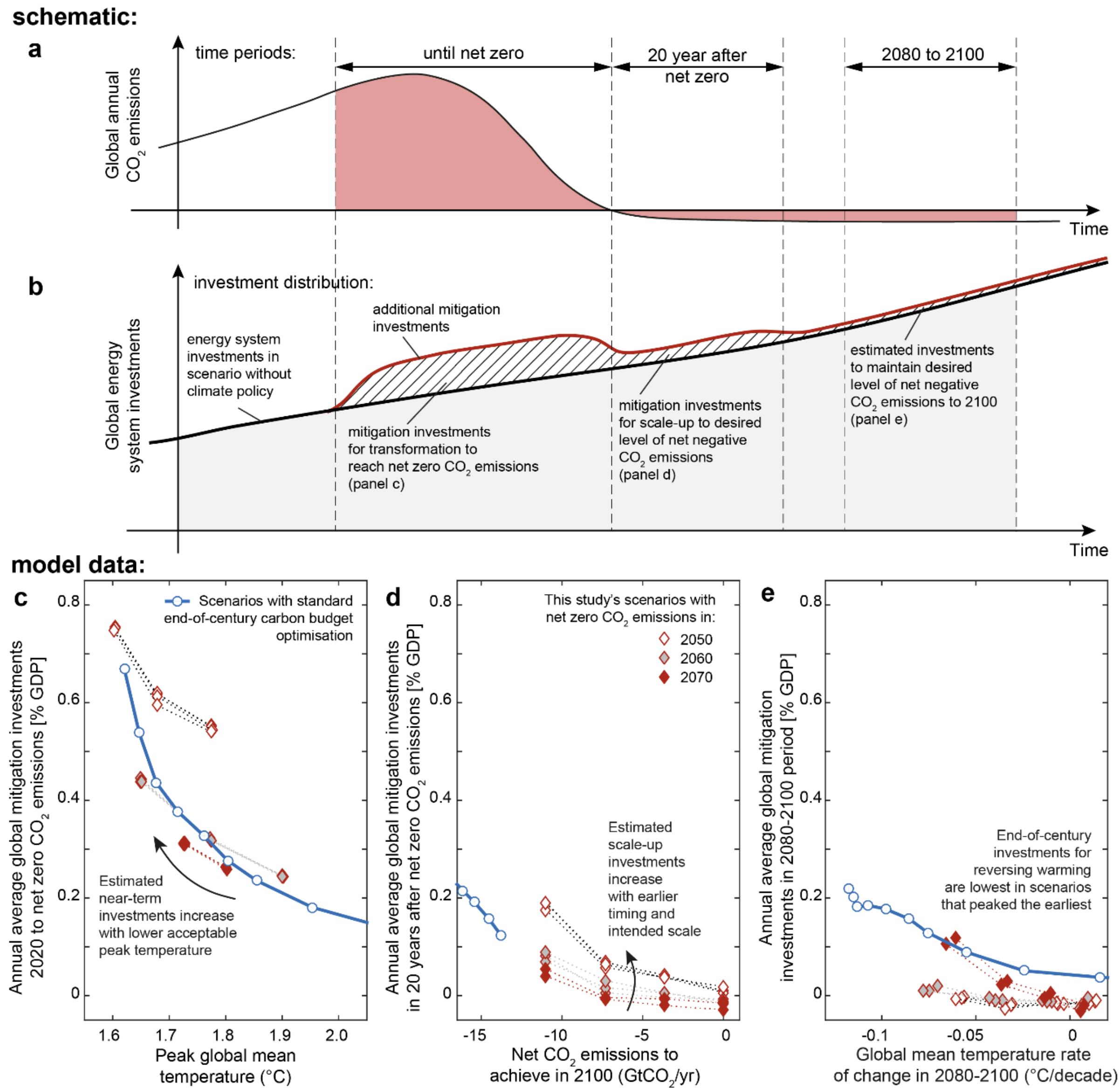

Figure 4 | Global mitigation investment evolutions and choices in scenarios. a, schematic of time periods explored in other panels; **b**, schematic of mitigation investments over time (hatched areas); **c–e**, estimated annual average global mitigation investments as a percentage of global gross domestic product (GDP) for different time periods; **c**, average annual investments from 2020 until the time net zero CO_2 emissions are reached as a function of peak global mean temperature rise. Dotted lines connect subsets of scenarios with similar key assumptions not visible on the graph. In panel **c** they connect scenarios with the same levels of net CDR by the end of the century; **d**, average annual investments in the 20 years after achieving net zero CO_2 emissions as a function of the level of net negative CO_2 emissions to be achieved. Dotted lines connect subsets of scenarios with the same levels of peak global mean temperature rise; **e**, average annual investments in the 2080-2100 period as a function of the rate of global mean temperature change in the same period. Dotted lines connect subsets of scenarios with the same levels of peak global mean temperature rise; **c–e**, red symbols are scenarios following this study's design, blue symbols follow a standard end-of-century carbon budget optimisation. Scenarios with different net zero CO_2 emission years are distinguished by different marker fill colours as defined in panel **d**.

Further exploration

The here proposed scenario framework provides a starting point to more explicitly address a variety of choices decision makers face in pursuit of the achievement of the Paris Agreement LTTG. The new framework's logic can be used to create scenarios that inform mitigation choices in the context of intergenerational societal concerns or technological limitations (Extended Data Table 2). Many of the conditions that affect scenario projections are highly uncertain in nature, and our understanding of these aspects is thus expected to evolve over time. This strongly suggests that methods to identify robust features of climate action should be incorporated in the scenario design approach described here, as well as adaptive strategies to reconsider these actions over time[57]. Doing so would enable better understanding of the implications of decisions made today and help align climate action and other societal objectives now and into the future.

Methods

Interpretations of the Paris Agreement Long-Term Temperature Goal (LTTG).

The Paris Agreement LTTG is defined in the agreement's text[6] as: "Holding the increase in the 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". This wording provides quantitative benchmarks within which all acceptable temperature outcomes are supposed to fall. However, some issues remain open[7].

A first issue is the level of warming that governments would consider consistent with a maximum level of "well below 2°C". In earlier UNFCCC texts[58], the global temperature goal was only expressed in terms of holding warming "below 2°C". This "below 2°C" goal has been interpreted in documents at the science-policy interface as avoiding 2°C of global warming with at least a 66% probability[59,60]. The precise implications of the strengthening of the legal language expressing the international temperature goal (from "below 2°C" to "well below 2°C") are not quantified or made explicit in current policy discussions. A second issue is the interpretation of the statement that the Paris Agreement is "pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels". This wording leaves open whether 1.5°C is applied to limiting peak or long-term warming, or both (that is, whether 1.5°C is never exceeded or is achieved after a slightly higher, yet still "well below 2°C", peak). Finally, the Paris Agreement as a whole "aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty". Whether this context of sustainable development is fully covered by the UN Sustainable Development Goals (SDGs, http://www.undp.org/content/undp/en/home/sustainable-development-goals.html) is not specified. This hence requires climate mitigation strategies to be considered and explored within a wider context of multiple societal objectives, many of which are not quantitatively defined at the moment. In conclusion, scientific studies of the Paris Agreement LTTG thus have to cover an adequate space of potential outcomes in line with the envelope defined by all aspects of the Paris Agreement. The framework presented in this study addresses many of these issues explicitly.

Model and data

We use the MESSAGE*ix*-GLOBIOM integrated assessment model[61] driven by middle-of-the-road (SSP2) assumptions of future socioeconomic baseline development[55,62] for the central scenario cases, and variations reflecting a more sustainable (SSP1) and a more fragmented (SSP3) world for some of the sensitivity cases in Figure 1. A detailed description of the SSP implementation is provided in an earlier publication[62], and the SSP model documentation[63] is available at http://data.ene.iiasa.ac.at/message-globiom/.

For the temperature assessment of the scenarios, we use the MAGICC reduced complexity carbon-cycle and carbon model[64] in the same setup as used for the SSP future greenhouse gas projections for the Coupled Model Intercomparison Project's Sixth Phase (CMIP6) with a 2.5K climate sensitivity, a carbon cycle calibrated to emulate the UVIC model and with the permafrost feedback module[65] enabled. Furthermore, we use updated CO_2, N_2O and CH_4 forcing algorithms to represent the higher methane forcing as suggested by the Oslo line-by-line model results[66]. Global mean temperature increase refers here to the change in globally averaged surface air temperatures. Alternative model calibrations might lead to slightly different levels of warming compared to those reported in Figure 1, yet would not affect the overall concept and framework presented here. Permafrost thawing feedbacks could release CO_2 on timescales beyond the 21st century and this would subsequently require some level of net CDR to keep global mean temperature stabilized after 2100[67,68]. The setup used here has an implied transient climate response to cumulative emissions of carbon (TCRE) of about 0.46°C per 1000 PgC, centrally located in the 0.2-0.7°C per 1000 $GtCO_2$ range assessed in the IPCC Working Group I contribution to the IPCC Fifth Assessment Report[34] (AR5). Given the assessed uncertainties in the Earth system response to CO_2 emissions[34,43], a sustained annual removal of CO_2 of 1 $GtCO_2$/yr is estimated to result in global temperatures declining by about 0.02–0.07°C per decade, particularly if peak warming is kept low[68], which can be translated into the number of years required to reduce global mean temperature rise by 0.1°C given a sustained level of annual net negative emissions (see Extended Data Table 1).

More generally in multi-gas scenarios, however, temperature change is further modulated by changes in the emissions of other climate forcers[45,69]. These are included in our scenarios and linked to their common sources of CO_2 emissions when appropriate[69-72]. A set of sensitivity cases explores their contribution further (see below).

Literature scenario data for Figure 1 is drawn from the IPCC AR5 Working Group III Scenario Database, which is hosted at the International Institute for Applied Systems Analysis (IIASA) and available online at https://tntcat.iiasa.ac.at/AR5DB/. Data is shown for a large range of scenarios, many of which are not necessarily consistent with the Paris Agreement (for example, see Fig. 1b). However, they are included to illustrate that the assumed relationships are valid over a wider range than that which is allowed for by the Paris Agreement.

Approach & protocol

Our proposed approach deconstructs the Paris Agreement's LTTG in three structural elements: the level of peak warming, the timing of peak warming, and the rate of temperature change after the peak. Each of these elements is modelled independently (see also Extended Data Table 3):

Timing of peak warming The timing of peak warming is modelled by setting the year in which global net CO_2 emissions are to become zero. The years 2050, 2060, and 2070 are explored here.

Level of peak warming The level of peak warming is modelled by setting a maximum limit to the total amount of CO_2 emissions until the time net CO_2 emissions have to become zero. This is implemented by setting a maximum to the average annual total CO_2 emission level from 2021 to the time of net zero CO_2. The various values that are explored here are: 3, 4, 5, 6, 8, and 10 PgC/yr (or about 11, 15, 18, 22, 29, and 37 in $GtCO_2$/yr). See Extended Data Table 3 for the implied cumulative CO_2 emissions until net zero for each modelled case. In addition, non-CO_2 greenhouse gas emissions are limited by imposing an equivalent carbon price consistent with the modelled CO_2 reductions, using AR4 100-year global warming potential for the conversion between non-CO_2 greenhouse gases and CO_2.

Post-peak rate of temperature change The rate of temperature change after peak warming is modelled by prescribing the level of net CO_2 emissions to be achieved two to three decades after global CO_2 emissions reached net zero. Levels corresponding to annual net negative CO_2 emissions of 0, 1, 2, and 3 PgC/yr (or 0, 3.7, 7.3, and 11 in $GtCO_2$/yr) have been explored. Also here continued attention to limit non-CO_2 emissions is necessary.

This modelling protocol can be utilized directly without any modifications in IAMs that rely on an intertemporal optimization method. To avoid end-point effects, all three constraints have been optimized simultaneously in the illustrative scenarios computed for this paper over a period that is at least one time step longer than the year of latest emissions constraint (in this case, the level of net negative emissions 20 years after reaching carbon neutrality). In recursive-dynamic IAMs, the CO_2 emissions budget until reaching net zero emissions, needs to be translated into an emissions trajectory, using a heuristic to distribute the budget over time (for example, the hoteling rule). The net CO_2 emissions after reaching net zero can again be implemented as an emissions constraint.

Furthermore, technology variations in two dimensions have been implemented to illustrate the possibility of exploring the achievement of net negative CO_2 emissions levels with different energy system and CDR technology configurations leading to varying contributions of gross negative CO_2 emissions:

Different deployment rates of total CCS Maximum yearly levels of total global CCS deployment have been specified. The following levels have been explored: no limit, 8, 5, 2, and 1 PgC/yr (or 29.3, 18.3, 7.3, and 3.7 in $GtCO_2$/yr). All no-CCS cases were found to be infeasible under the constraints and middle-of-the-road socioeconomic assumptions[62] used in this study.

Different levels of bioenergy Maximum yearly levels of the amount of primary energy from biomass are set, not to be exceeded at any year during the entire century. The following levels have been explored: no limit, 200, 150, 100, 80 and 60 EJ/yr, informed by the sustainability concerns identified in an earlier study[47]. An overview of explored sensitivity cases is provided in Extended Data Table 4, a selection of which is shown in Fig. 3 and Extended Data Figs 2 and 3.

Suite of core scenarios Extended Data Table 3 lists all scenarios following the new design presented in this paper, and their respective specifications. For each scenario, the MESSAGE*ix*-GLOBIOM model is run in three stages. First, it is solved in line with the three CO_2 constraints as specified in Table 1, and detailed in Extended Data Table 3. Then, in a second stage, consistent evolutions of other forcers are derived. The price of carbon obtained in stage 1 from the per-year shadow prices on the CO_2 constraint is applied as a tax to all non-CO_2 emissions as a proxy of equivalent mitigation efforts. This could be varied and would influence temperature projections for the scenarios, but would not affect the more general insights as presented in Figs 1 to 4 (see also the non-CO_2 sensitivity case description below). Because sources of CO_2 and non-CO_2 emissions are at times linked, applying these taxes to all greenhouse gas emissions influences the marginal abatement costs of carbon emissions. Therefore, in a third step, the model is iteratively solved updating these taxes, until the maximum deviation between the shadow price of carbon and the taxes imposed on non-carbon emissions in any year is below 5%.

Sensitivity scenarios Extended Data Table 4 lists the specifications for a suite of scenarios that illustrate the possibility of exploring the sensitivity of mitigation efforts with regard to maximum CCS deployment and the use of bioenergy in the energy system. Many additional sensitivity cases can be used to explore further dimensions, as illustrated in Extended Data Table 2.

Two additional sensitivity sets that vary non-CO_2 mitigation have been developed to explore the influence non-CO_2 mitigation can have on the climate performance of our scenario logic. A first non-CO_2 sensitivity set assumes no penalty on non-CO_2 greenhouse gas emissions at all, and only sees non-CO_2 emissions reductions that are dictated by the phase-out of emissions sources that are shared with CO_2. A second non-CO_2 sensitivity set explores the most stringent end of non-CO_2 mitigation by assuming an exponentially increasing emissions price on non-CO_2 emissions, starting at

200 USD/tCO_2e and increasing exponentially with 5% per year until 2100. These sensitivity cases are further illustrated in Extended Data Figure 1.

Comparison scenarios Additionally, a set of traditional mitigation scenarios that aim at optimizing a carbon budget over the entire century is created, as a point of comparison (blue features in Figs 2 and 4, and Extended Data Figure 4).

Under the assumptions used by the scenario ensemble for this study (see above), the lowest peak warming achieved in our scenarios is about 1.6°C relative to preindustrial levels. In this study we do not explore whether achieving lower levels of peak warming is categorically excluded. Maximum values of about 1.5°C have been reported by studies exploring strong mitigation futures using more favourable socioeconomic assumptions (including reduced global inequalities and efficiency improvements beyond the historical experience)[73].

Data availability

Online data documentation[63] for the SSP implementation is available at http://data.ene.iiasa.ac.at/message-globiom/. The scenario data analysed during the current study are available online at https://data.ene.iiasa.ac.at/postparis-explorer (DOI: 10.22022/ene/06-2019.48).

Code availability

The MESSAGE*ix* modelling framework[61], including its macroeconomic module MACRO, is available under an APACHE 2.0 open-source license at http://github.com/iiasa/message_ix. Data can be analysed online via a dedicated scenario explorer instance at https://data.ene.iiasa.ac.at/postparis-explorer, although analytical codes for producing the manuscript figures are not available.

References

1. United Nations Framework Convention on Climate Change. 1-25 (United Nations, Rio de Janeiro, Brazil, 1992).
2. Randalls, S. History of the 2°C climate target. *Wiley Interdisciplinary Reviews: Climate Change* **1**, 598-605, doi:10.1002/wcc.62 (2010).
3. Knutti, R., Rogelj, J., Sedlacek, J. & Fischer, E. M. A scientific critique of the two-degree climate change target. *Nature Geosci* **9**, 13-18, doi:10.1038/ngeo2595 (2016).
4. O'Neill, B. C. *et al.* IPCC reasons for concern regarding climate change risks. *Nature Climate Change* **7**, 28-37, doi:10.1038/nclimate3179 (2017).
5. Seneviratne, S. I., Donat, M. G., Pitman, A. J., Knutti, R. & Wilby, R. L. Allowable CO2 emissions based on regional and impact-related climate targets. *Nature* **529**, 477-483, doi:10.1038/nature16542 (2016).
6. UNFCCC. Paris Agreement. 1-25 (UNFCCC, Paris, France, 2015).
7. Schleussner, C.-F. *et al.* Science and policy characteristics of the Paris Agreement temperature goal. *Nature Climate Change* **6**, 827-835, doi:10.1038/nclimate3096 (2016).
8. Clarke, L. *et al.* in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds O. Edenhofer *et al.*) Ch. 6, 413-510 (Cambridge University Press, 2014).
9. Fisher, B. *et al.* in *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change* (eds B. Metz *et al.*) Ch. 3, 169-250 (Cambridge University Press, 2007).
10. Clarke, L. *et al.* International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Econ.* **31**, S64-S81, doi:10.1016/j.eneco.2009.10.013 (2009).
11. Kriegler, E. *et al.* The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change* **123**, 353-367, doi:10.1007/s10584-013-0953-7 (2014).
12. IEA. *World Energy Outlook 2015*. (International Energy Agency, 2015).
13. van Vuuren, D. P. *et al.* A new scenario framework for Climate Change Research: scenario matrix architecture. *Climatic Change* **122**, 373-386, doi:10.1007/s10584-013-0906-1 (2014).
14. Meinshausen, M. *et al.* Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature* **458**, 1158-1162, doi:10.1038/nature08017 (2009).
15. Matthews, H. D., Gillett, N. P., Stott, P. A. & Zickfeld, K. The proportionality of global warming to cumulative carbon emissions. *Nature* **459**, 829-832, doi:10.1038/nature08047 (2009).
16. Fuss, S. *et al.* Betting on negative emissions. *Nature Clim. Change* **4**, 850-853, doi:10.1038/nclimate2392 (2014).
17. Shue, H. Climate dreaming: negative emissions, risk transfer, and irreversibility. *Journal of Human Rights and the Environment*, 203–216, doi:10.4337/jhre.2017.02.02 (2017).
18. Williamson, P. Emissions reduction: Scrutinize CO2 removal methods. *Nature* **530**, 153–155, doi:10.1038/530153a (2016).
19. Azar, C., Johansson, D. J. A. & Mattsson, N. Meeting global temperature targets—the role of bioenergy with carbon capture and storage. *Environmental Research Letters* **8**, 034004 (2013).
20. Minx, J. C., Lamb, W. F., Callaghan, M. W., Bornmann, L. & Fuss, S. Fast growing research on negative emissions. *Environmental Research Letters* **12**, 035007 (2017).
21. Smith, P. *et al.* Biophysical and economic limits to negative CO2 emissions. *Nature Clim. Change* **6**, 42-50, doi:10.1038/nclimate2870 (2016).
22. Popp, A. *et al.* Land-use futures in the shared socio-economic pathways. *Global Environmental Change* **42**, 331-345, doi:10.1016/j.gloenvcha.2016.10.002 (2017).
23. Field, C. B. & Mach, K. J. Rightsizing carbon dioxide removal. *Science* **356**, 706-707, doi:10.1126/science.aam9726 (2017).

24 Boysen, L. R. *et al.* The limits to global-warming mitigation by terrestrial carbon removal. *Earth's Future* **5**, 463-474, doi:10.1002/2016ef000469 (2017).

25 Morrow, D. R. & Svoboda, T. Geoengineering and Non-Ideal Theory. *Public Affairs Quarterly* **30**, 85-104 (2016).

26 Obersteiner, M. *et al.* How to spend a dwindling greenhouse gas budget. *Nature Climate Change* **8**, 7-10, doi:10.1038/s41558-017-0045-1 (2018).

27 Anderson, K. & Peters, G. The trouble with negative emissions. *Science* **354**, 182-183, doi:10.1126/science.aah4567 (2016).

28 Huppmann, D., Rogelj, J., Kriegler, E., Krey, V. & Riahi, K. A new scenario resource for integrated 1.5 °C research. *Nature Climate Change* **8**, 1027-1030, doi:10.1038/s41558-018-0317-4 (2018).

29 Rogelj, J. *et al.* 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, sustainable development, and efforts to eradicate poverty* (eds Greg Flato, Jan Fuglestvedt, Rachid Mrabet, & Roberto Schaeffer) Ch. 2, 93-174 (IPCC/WMO, 2018).

30 Wigley, T. M. L., Richels, R. & Edmonds, J. A. Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. *Nature* **379**, 240-243 (1996).

31 Rogelj, J., Schleussner, C.-F. & Hare, W. Getting It Right Matters: Temperature Goal Interpretations in Geoscience Research. *Geophysical Research Letters* **44**, 10,662-610,665, doi:10.1002/2017gl075612 (2017).

32 O'Neill, B. C. *et al.* A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change* **122**, 387-400, doi:10.1007/s10584-013-0905-2 (2014).

33 Fuglestvedt, J. *et al.* Implications of possible interpretations of 'greenhouse gas balance' in the Paris Agreement. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **376**, doi:10.1098/rsta.2016.0445 (2018).

34 Collins, M. *et al.* in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley) Ch. 12, 1029-1136 (Cambridge University Press, 2013).

35 Knutti, R. & Rogelj, J. The legacy of our CO2 emissions: a clash of scientific facts, politics and ethics. *Climatic Change* **133**, 361-373, doi:10.1007/s10584-015-1340-3 (2015).

36 Matthews, H. D., Solomon, S. & Pierrehumbert, R. Cumulative carbon as a policy framework for achieving climate stabilization. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* **370**, 4365-4379 (2012).

37 Matthews, H. D. & Solomon, S. Atmosphere. Irreversible does not mean unavoidable. *Science* **340**, 438-439, doi:10.1126/science.1236372 (2013).

38 Matthews, H. D. & Caldeira, K. Stabilizing climate requires near-zero emissions. *Geophysical Research Letters* **35**, doi:10.1029/2007gl032388 (2008).

39 Haites, E., Yamin, F. & Höhne, N. Possible Elements of a 2015 Legal Agreement on Climate Change. *IDDRI SciencesPo Working Paper*, 1-24 (2013).

40 Rogelj, J. *et al.* Zero emission targets as long-term global goals for climate protection. *Environmental Research Letters* **10**, 105007, doi:10.1088/1748-9326/10/10/105007 (2015).

41 Geden, O. An actionable climate target. *Nature Geoscience* **9**, 340, doi:10.1038/ngeo2699 (2016).

42 Ricke, K. L. & Caldeira, K. Maximum warming occurs about one decade after a carbon dioxide emission. *Environmental Research Letters* **9**, 124002 (2014).

43 Tokarska, K. B. & Zickfeld, K. The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change. *Environmental Research Letters* **10**, 094013 (2015).

44 Weyant, J. P., de la Chesnaye, F. C. & Blanford, G. J. Overview of EMF-21: Multigas Mitigation and Climate Policy. *The Energy Journal* **27**, 1-32 (2006).

45 Shindell, D. *et al.* Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. *Science* **335**, 183-189, doi:10.1126/science.1210026 (2012).
46 Höglund-Isaksson, L. *et al.* Cost estimates of the Kigali Amendment to phase-down hydrofluorocarbons. *Environmental Science & Policy* **75**, 138-147, doi:https://doi.org/10.1016/j.envsci.2017.05.006 (2017).
47 Creutzig, F. *et al.* Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy* **7**, 916-944, doi:10.1111/gcbb.12205 (2015).
48 de Coninck, H. *et al.* 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, sustainable development, and efforts to eradicate poverty* (eds Amjad Abdulla, Rizaldi Boer, Mark Howden, & Diana Ürge-Vorsatz) Ch. 4, (World Meteorological Organisation, 2018).
49 Sanchez, D. L. & Kammen, D. M. A commercialization strategy for carbon-negative energy. *Nature Energy* **1**, 15002, doi:10.1038/nenergy.2015.2 (2016).
50 Reiner, D. M. Learning through a portfolio of carbon capture and storage demonstration projects. *Nature Energy* **1**, 15011, doi:10.1038/nenergy.2015.11 (2016).
51 Krey, V., Luderer, G., Clarke, L. & Kriegler, E. Getting from here to there – energy technology transformation pathways in the EMF27 scenarios. *Climatic Change* **123**, 369-382, doi:10.1007/s10584-013-0947-5 (2014).
52 Luderer, G. *et al.* Residual fossil CO2 emissions in 1.5–2 °C pathways. *Nature Climate Change* **8**, 626-633, doi:10.1038/s41558-018-0198-6 (2018).
53 Geden, O., Peters, G. P. & Scott, V. Targeting carbon dioxide removal in the European Union. *Climate Policy* **19**, 487-494, doi:10.1080/14693062.2018.1536600 (2019).
54 Davis, S. J. *et al.* Net-zero emissions energy systems. *Science* **360**, eaas9793, doi:10.1126/science.aas9793 (2018).
55 Riahi, K. *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* **42**, 153-168, doi:10.1016/j.gloenvcha.2016.05.009 (2017).
56 Rogelj, J., McCollum, D. L., Reisinger, A., Meinshausen, M. & Riahi, K. Probabilistic cost estimates for climate change mitigation. *Nature* **493**, 79-83, doi:10.1038/nature11787 (2013).
57 Maier, H. R. *et al.* An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together? *Environmental Modelling & Software* **81**, 154-164, doi:https://doi.org/10.1016/j.envsoft.2016.03.014 (2016).
58 UNFCCC. FCCC/CP/2010/7/Add.1 Decision 1/CP.16 - The Cancun Agreements: Outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention. 31 (2010).
59 UNEP. The Emissions Gap Report 2013. 64 (UNEP, Nairobi, Kenya, 2013).
60 UNFCCC. FCCC/CP/2015/7: Synthesis report on the aggregate effect of the intended nationally determined contributions. 66 (UNFCCC, Bonn, Germany, 2015).
61 Huppmann, D. *et al.* The MESSAGEix Integrated Assessment Model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development. *Environmental Modelling & Software* **112**, 143-156, doi:https://doi.org/10.1016/j.envsoft.2018.11.012 (2019).
62 Fricko, O. *et al.* The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change* **42**, 251-267, doi:http://dx.doi.org/10.1016/j.gloenvcha.2016.06.004 (2017).
63 Krey, V. *et al.* MESSAGE-GLOBIOM 1.0 Documentation. (International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, 2016).

64 Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmos. Chem. Phys.* **11**, 1417-1456, doi:10.5194/acp-11-1417-2011 (2011).

65 Schneider von Deimling, T. *et al.* Estimating the near-surface permafrost-carbon feedback on global warming. *Biogeosciences* **9**, 649-665, doi:10.5194/bg-9-649-2012 (2012).

66 Etminan, M., Myhre, G., Highwood, E. J. & Shine, K. P. Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters* **43**, 12,614-612,623, doi:doi:10.1002/2016GL071930 (2016).

67 Schädel, C. *et al.* Circumpolar assessment of permafrost C quality and its vulnerability over time using long-term incubation data. *Global Change Biology* **20**, 641-652, doi:10.1111/gcb.12417 (2014).

68 Burke, E. J. *et al.* Quantifying uncertainties of permafrost carbon–climate feedbacks. *Biogeosciences* **14**, 3051-3066, doi:10.5194/bg-14-3051-2017 (2017).

69 Rogelj, J. *et al.* Disentangling the effects of CO2 and short-lived climate forcer mitigation. *Proc Natl Acad Sci U S A* **111**, 16325-16330, doi:10.1073/pnas.1415631111 (2014).

70 Bond, T. C. *et al.* Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres* **118**, 5380-5552, doi:10.1002/jgrd.50171 (2013).

71 Rogelj, J. *et al.* Air-pollution emission ranges consistent with the representative concentration pathways. *Nature Clim. Change* **4**, 446-450, doi:10.1038/nclimate2178 (2014).

72 Rao, S. *et al.* Future air pollution in the Shared Socio-economic Pathways. *Global Environmental Change* **42**, 346-358, doi:http://dx.doi.org/10.1016/j.gloenvcha.2016.05.012 (2017).

73 Rogelj, J. *et al.* Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, doi:10.1038/s41558-018-0091-3 (2018).

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Author Contributions

JR initiated and led the research. JR designed the research, with contributions from MM, DH, KR, and VK. DH led the translation of the scenario concept of this study in the MESSAGE*ix* framework, with contributions from VK, KR, and JR. DH created all scenario data and coordinated its archival, MG and ZN translated scenario data into input files for the MAGICC model, MM carried out climate projection runs with the MAGICC model. JR carried out the analysis, created the figures and wrote the paper. All authors provided feedback and contributed to improving and finalising the paper.

Conflict of interest

The authors declare no conflict of interest.

Extended Data:

A new scenario logic for the Paris Agreement long-term temperature goal

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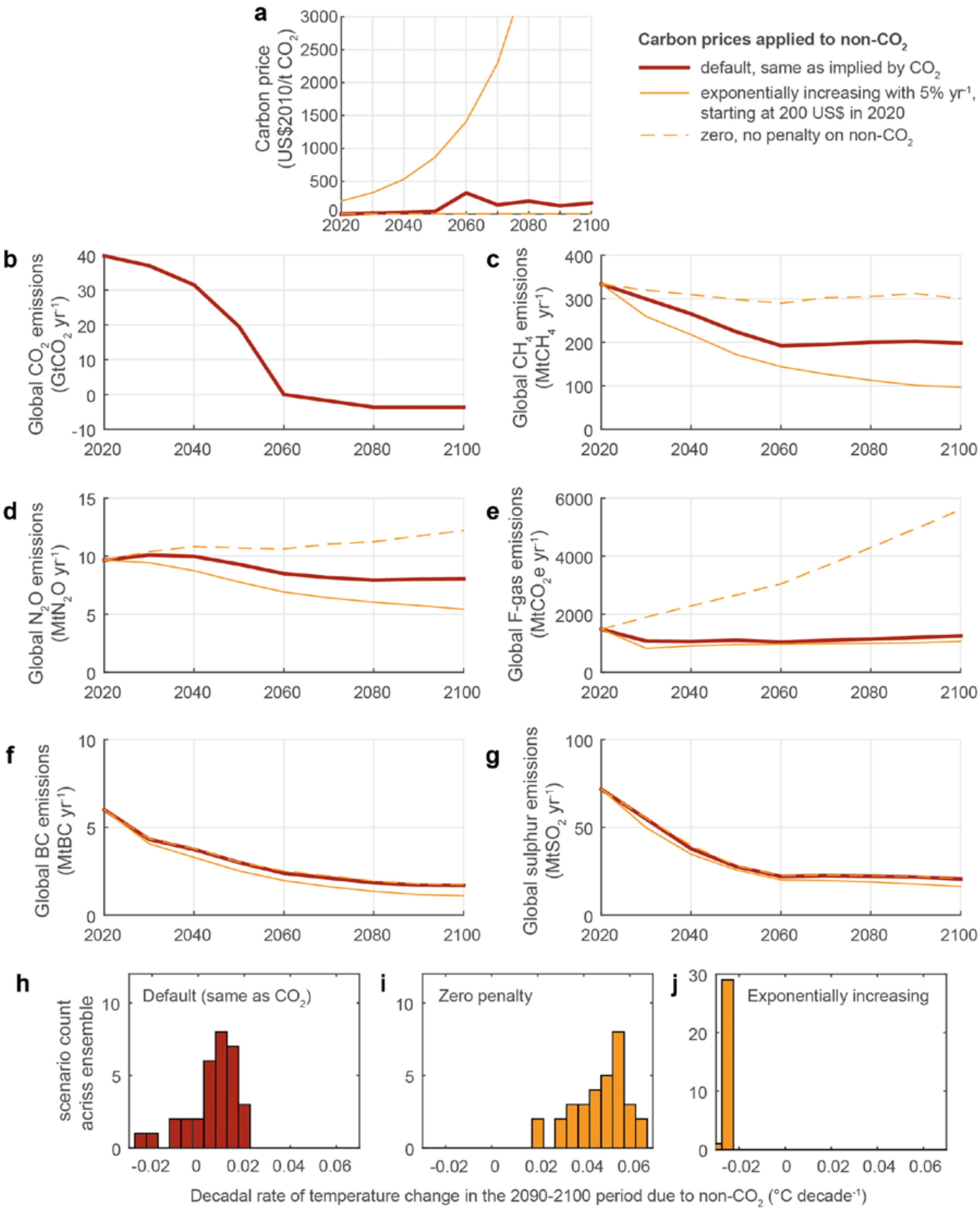
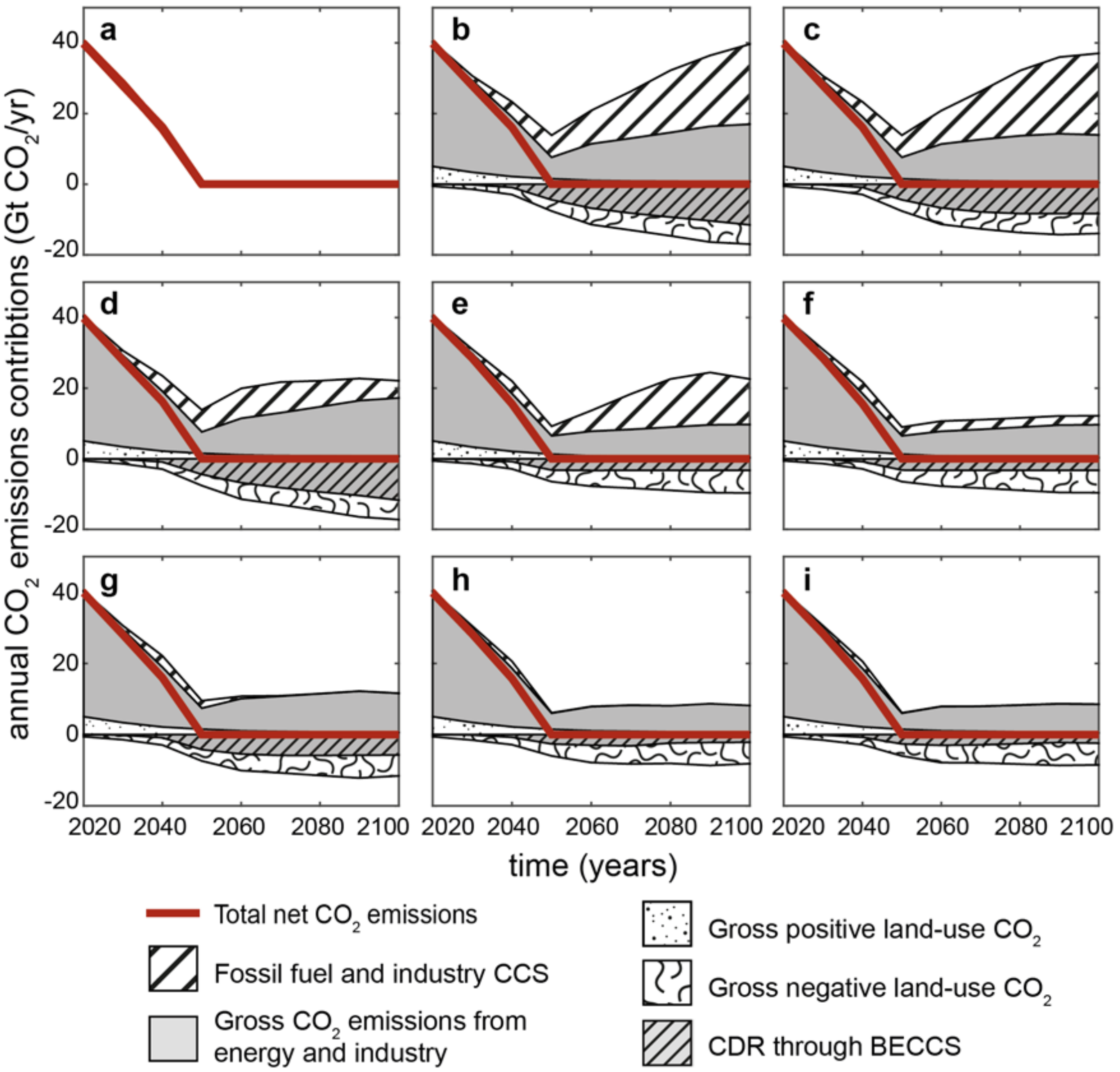
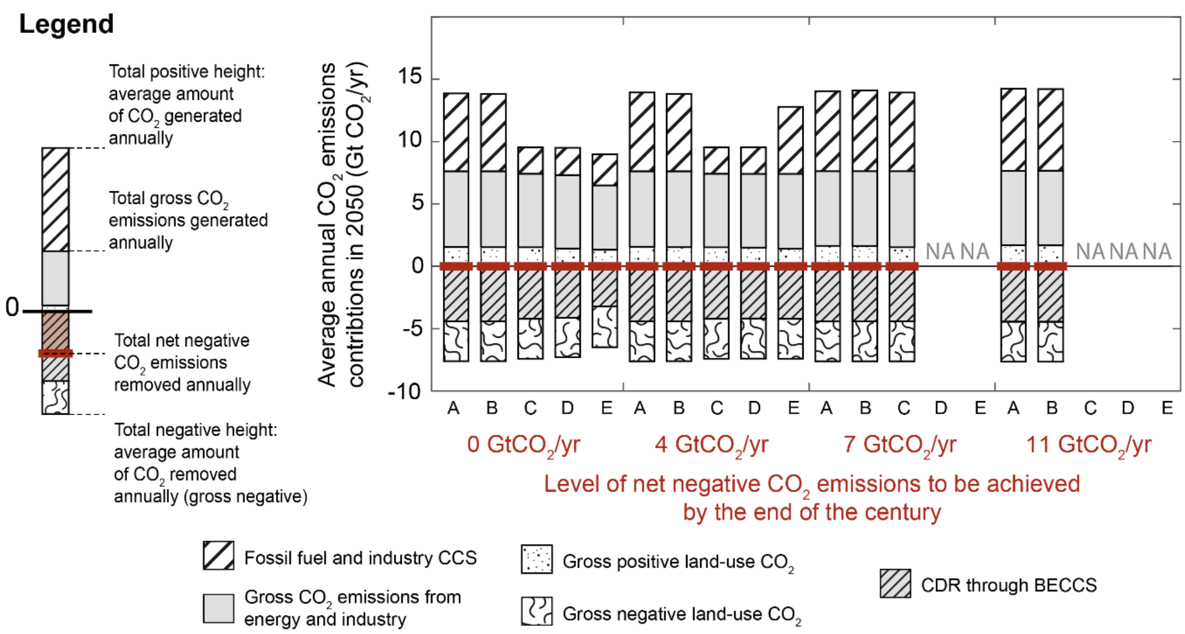
Extended Data: Figures



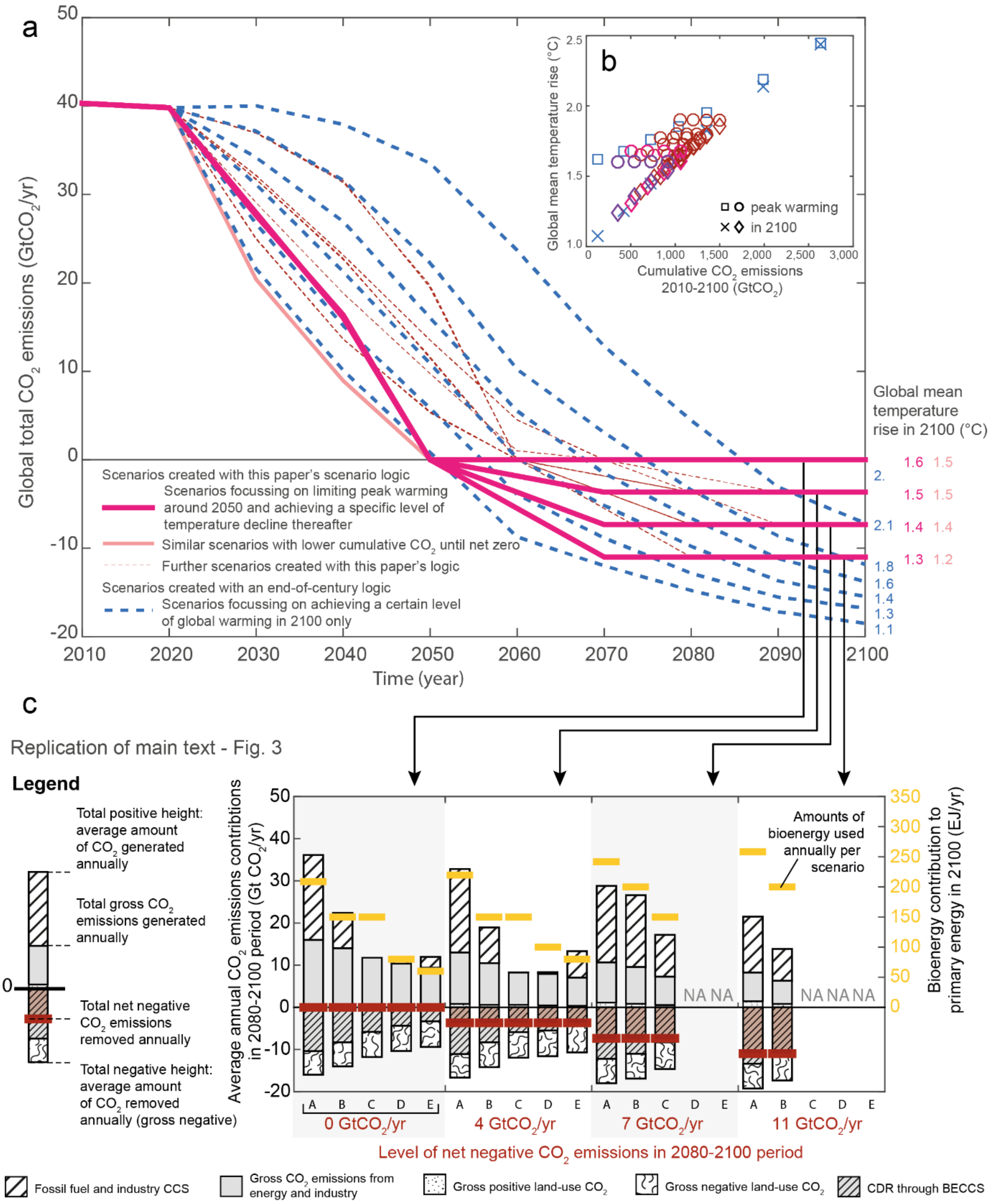
Extended Data Figure 1 | Illustration of non-CO_2 mitigation sensitivity cases. **a**, emission price trajectories applied to non-CO_2 greenhouse gas emissions in the default and the two sensitivity cases. In line with the scope of emissions covered under the UNFCCC, emissions from aerosol or aerosol precursor species like black carbon (BC) or sulphur-dioxide are not explicitly subjected to a carbon price; **b-g**, resulting emissions of CO_2 and internally consistent evolutions of a selection of non-CO_2 emissions; **h-j**, impact of non-CO_2 sensitivity cases on decadal rate of temperature change in the 2090-2100 period. Note that the sensitivity case assuming zero penalty on non-CO_2 emissions is extremely unlikely in light of recent efforts that specifically target reductions of methane and fluorinated gas emissions. Emissions of non-CO_2 gases are translated into CO_2 equivalence using global warming potentials over a 100-year time horizon as reported in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.



Extended Data Figure 2| Illustration of variation of CO_2 contributions in scenarios with identical temperature outcomes. Scenario variations in panels **b** to **i** are identified by their panel labels in Extended Data Table 3 and 4.



Extended Data Figure 3| Illustration of system configurations and of contributions of carbon-dioxide removal (CDR) technologies to achieve net zero CO_2 emissions. Corresponding system configurations are shown for all cases shown in main text Figure 3. The four levels of net negative CO_2 emissions to be achieved by the end of the century are for identification purposes only and are not visible on this figure, as they will only be achieved after the point of reaching net-zero CO_2 emissions. Five illustrative system variations are shown per level labelled A to E, and defined in Extended Data Tables 3 and 4. Scenarios labelled with "NA" did not solve under the imposed CDR and bioenergy constraints (Extended Data Table 4). Fossil fuel and industry CCS contributions (white hatched areas) represent CO_2 that is generated but not emitted to the atmosphere. Net negative CO_2 emissions are the sum of gross positive CO_2 emissions from energy and industrial sources and gross positive land-use CO_2 emissions, and are zero by design in this time step. Gross negative CO_2 emissions comprise gross land-use CO_2 emissions, and CDR through BECCS. The combined size of all bars per scenario gives an indication of the overall size of the remaining CO_2 producing system by the end of the century. Because the timing of CDR upscaling and amount of CDR at the time of reaching global net zero CO_2 emissions was not explicitly varied in the set of illustrative scenarios developed for this study, it would be wrong to interpret the narrow degree of variation and general agreement across scenarios as a robust feature. Variations could be explored through additional dedicated studies as highlighted in Extended Data Table 2.



Extended Data Figure 4| Illustration of scenario variation and differences between the scenario logic presented in this study and an end-of-century scenario approach. Pink to red scenarios in panel **a** show scenarios created with the scenario logic presented in this paper, while blue dashed scenarios show scenarios created with an end-of-century scenario approach (see labelling). Panel **b** shows that for a given amount of cumulative CO_2 emissions all scenarios result in a similar amount of temperature increase by 2100, but different levels of maximum (peak) warming. Panel **c** is a replication of Figure 3 in the main text showing how stable emissions levels in the second half of the century can be achieved by a variety of system configurations with different amounts of CDR. Note that to achieve a scenario that limits global mean temperature rise in 2100 to 1.5°C, the standard end-of-century scenario approach would suggest net negative CO_2 emissions of about 15 $GtCO_2$/yr in 2100, while the scenario logic presented in this paper allows to construct scenarios that achieve that temperature in 2100 with zero to about 5 $GtCO_2$/yr of net negative CO_2 emissions, and a variety of gross CDR contributions.

Extended Data: Tables

Extended Data Table 1 | Years required to reduce global mean temperature rise by 0.1°C given varying levels of sustained net negative emissions. These values are based on a TCRE of 0.46°C per 1000 $GtCO_2$. The range between brackets gives the range for the IPCC AR5 TCRE range of 0.2–0.7°C per 1000 $GtCO_2$.

Level of sustained net annual net negative emissions deemed achievable in the 2nd half of the century [$GtCO_2$/yr]	0.5	1	2	5	10
Years required to reduce global-mean temperature rise by 0.1°C [years]	43 (29-92)	22 (15-46)	11 (7-23)	4 (3-9)	2 (1-5)

Extended Data Table 2 | Illustrative overview of potential extensions of the scenario framework. Selection of concerns related to carbon-dioxide removal (CDR), pace and timing of technology deployment, water requirement, regional differentiation, and non-CO_2 emissions, as well as potential extensions of the here suggested scenario design that would allow studies to explore each of these concerns. This list is purely illustrative and non-exhaustive.

Concern to be addressed	**Scenario design allowing to explore concern**
Scale of carbon-dioxide removal (CDR)	
Bioenergy combined with carbon capture and storage (BECCS)	Limits can be prescribed to: - BECCS as a whole - Particular types of BECCS, like biomass power generation with CCS - BECCS subcomponents like the amount of bioenergy from different sources (first generation, second generation, residues only, …), or the scale of CCS
Afforestation	Limits can be prescribed to the overall scale in units of CO_2 removed by afforestation
Other CDR methods	Other CDR methods like direct air capture and sequestration (DACS), biochar, or enhanced weathering, can be included in scenarios, potentially accompanied by limits to their maximum scale
Land requirements of CDR	
Bioenergy	Limits can be set to where and how much land is used for bioenergy production, and in which areas it can expand
Afforestation	Limits can be set to where and how much land is used for afforestation, and in which areas it can expand
Timing and pace of deployment	
BECCS	The year in which BECCS is thought to become available can be varied (e.g. 2040 or 2050 only) as can its cost assumptions and maximum pace by which it could scale up
Other CDR methods	The year in which CDR methods are thought to become available can be varied (e.g. 2040, 2050, or later) as can their cost assumptions and the maximum pace at which they could scale up
Potential land conversion	The maximum pace of land conversion (e.g. in million hectares per decade) from one type to another in a given region or globally can be capped
Renewable energy technologies	The maximum annual expansion rate and cost assumptions of renewable energies can be varied
Nuclear technology	The maximum annual expansion rate, and cost assumptions of nuclear energy can be varied
General societal acceptability	For any mitigation measure or technology, its use and expansion can be capped or modified as a function of assumed future societal acceptability of given technology or measure
Water requirements	
Bioenergy	The total amount of water available for irrigation of bioenergy crops can be capped either globally or per region
Afforestation	The total amount of water available for drinking water can be mandated per region
Regional differentiation	
Regional distribution of mitigation potentials	Although generally already varied per region, deployment of specific technologies and availability of resources could be varied per region
Institutional barriers to implementation	Cost of capital and investment discount rates can be varied per region depending on institutional circumstances
Non-CO_2 mitigation	
Differential mitigation of different greenhouse gases	Emissions of non-CO_2 greenhouse gases with different lifetimes can be penalized to a different degree (e.g. long-lived vs short-lived greenhouse gases)
Alternative mitigation timing	Mitigation of emissions of non-CO_2 greenhouse gases can be delayed or brought forward by penalizing their emissions following a specific cost trajectory over time

Extended Data Table 3 | Overview of core set of scenarios available in this study and their design specifications. Each triplet of peak warming year, average annual emissions until net zero, and average annual net negative emissions levels defines one scenario and is represented by one red diamond in Figure 1. All scenarios have been modelled under SSP1 and SSP2 assumptions. Scenarios marked with # have additionally been modelled under SSP3 assumptions. Further CCS and bioenergy variations are available for a subset of scenarios with peak warming in 2050 and achieving 0, 1, 2, or 3 PgC/yr of net negative emissions by the end of the century. Grey shaded scenario specifications are scenarios for which further sensitivity cases have been developed, as indicated in Extended Data Table 4. Sensitivity cases are illustrated in Fig. 3. The cases highlighted here are labelled with "A" in Fig. 3. One unit of PgC equals 3.664 units of $GtCO_2$. Values in $GtCO_2$/yr are provided between brackets, rounded to the nearest unit. The scenario shown in panel b of Extended Data Figure 2 is indicated below with curly brackets.

Peak warming year	**Average annual emissions until net zero CO_2 emissions**	**Cumulative emissions from 2021 until net zero CO_2 emissions**	**Average annual net negative emissions towards the end of the century**
[year]	[PgC/yr] ($GtCO_2$/yr)	[PgC] ($GtCO_2$)	[PgC/yr] ($GtCO_2$/yr)
2050#	10 (37)	290 (1063)	0 (0)# 1 (4)# 2 (7)# 3 (11)
2050	8 (29)	232 (850)	0 (0)# 1 (4)# 2 (7)# 3 (11)
2050	6 (22)	174 (638)	0 (0)# {b} 1 (4)# 2 (7)# 3 (11)
2050	4 (15)	116 (425)	0 (0) 1 (4) 2 (7) 3 (11)
2070	3 (11)	147 (539)	0 (0)# 1 (4)# 2 (7)# 3 (11)#

Peak warming year	**Average annual emissions until net zero CO_2 emissions**	**Cumulative emissions from 2021 until net zero CO_2 emissions**	**Average annual net negative emissions towards the end of the century**
[year]	[PgC/yr] ($GtCO_2$/yr)	[PgC] ($GtCO_2$)	[PgC/yr] ($GtCO_2$/yr)
2060	8 (29)	312 (1143)	0 (0)# 1 (4)# 2 (7)# 3 (11)#
	6 (22)	234 (857)	0 (0)# 1 (4)# 2 (7)# 3 (11)#
	4 (15)	156 (572)	0 (0)# 1 (4)# 2 (7)# 3 (11)#
2070	4 (15)	196 (718)	0 (0)# 1 (4)# 2 (7)# 3 (11)#
	5 (18)	245 (898)	0 (0)# 1 (4)# 2 (7)# 3 (11)#

Extended Data Table 4 | Overview of sensitivity cases for CCS and bioenergy use. Sensitivity cases are variations of the grey shaded core scenarios in Extended Data Table 3. Scenarios for which the model solved successfully are indicated with "1": scenarios that did not solve are indicated with "N/A". Orange shaded scenario are shown in Figure 3, in addition to the scenarios highlighted in Extended Data Table 3. One unit of PgC equals 3.664 units of $GtCO_2$ and values in $GtCO_2$/yr are provided between brackets, rounded to the nearest unit. Bold italicized characters B, C, D, and E indicate the labels used in Figure 3. Characters between curly brackets identify the scenarios shown in Extended Data Figure 2.

		Net amount of annual negative emissions at end of 21st century [PgC/yr] ($GtCO_2$/yr)			
Maximum level of annual bioenergy use during 21st century (primary energy) [EJ/yr]	**Maximum level of annual CCS deployment during 21st century [PgC/yr] ($GtCO_2$/yr)**	0 (0)	1 (3.7)	2 (7.3)	3 (11.0)
60	No limit	**1 {e}**	*N/A*	*N/A*	*N/A*
	0 (0)	*N/A*	*N/A*	*N/A*	*N/A*
	2 (7.3)	**1 *E* {f}**	*N/A*	*N/A*	*N/A*
	5 (18.3)	**1**	*N/A*	*N/A*	*N/A*
80	No limit	**1**	**1 *E***	*N/A*	*N/A*
	0 (0)	*N/A*	*N/A*	*N/A*	*N/A*
	2 (7.3)	**1 *D***	*N/A*	*N/A*	*N/A*
	5 (18.3)	**1**	*N/A*	*N/A*	*N/A*
100	No limit	**1**	**1**	*N/A*	*N/A*
	0 (0)	*N/A*	*N/A*	*N/A*	*N/A*
	2 (7.3)	**1**	**1 *D***	*N/A*	*N/A*
	5 (18.3)	**1**	**1**	*N/A*	*N/A*
150	No limit	**1 {c}**	**1**	**1 *C***	*N/A*
	0 (0)	*N/A*	*N/A*	*N/A*	*N/A*
	1 (3.7)	**1 {i}**	*N/A*	*N/A*	*N/A*
	2 (7.3)	**1 *C***	**1 *C***	*N/A*	*N/A*
	5 (18.3)	**1 *B***	**1 *B***	*N/A*	*N/A*
200	No limit	**1**	**1**	**1 *B***	**1 *B***
	0 (0)	*N/A*	*N/A*	*N/A*	*N/A*
	1 (3.7)	**1**	*N/A*	*N/A*	*N/A*
	2 (7.3)	**1**	*N/A*	*N/A*	*N/A*
	5 (18.3)	**1**	**1**	*N/A*	*N/A*
No limit	No limit	**1**			
	0 (0)	*N/A*			
	1 (3.7)	**1 {h}**			
	2 (7.3)	**1 {g}**			
	5 (18.3)	**1 {d}**			