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Article

Keywords: global emissions scenarios, net negative CO2 emissions (NNCE)

Posted Date: January 15th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-127847/v1>

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Version of Record: A version of this preprint was published at Nature Climate Change on November 29th, 2021. See the published version at <https://doi.org/10.1038/s41558-021-01215-2>.

Long-term economic benefits of stabilizing warming without overshoot – the ENGAGE model intercomparison

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Global emissions scenarios play a critical role in the assessment of strategies to mitigate climate change and their related societal transformations. The current generation of scenarios, however, are criticized because they rely heavily on net negative CO₂ emissions (NNCE) that result from allowing temperature limits to be temporarily exceeded. In this study we present a new set of emissions scenarios that exclude NNCE. We show that such scenarios require a more rapid near-term transformation with significant long-term gains for the economy (even without considering the benefits of avoided climate impacts). Scenarios that avoid temperature overshoot and NNCE are thus not only economically more attractive over the long term, they also involve lower climate risks. Our study further identifies possible alternative configurations of net-zero CO₂ emissions systems and the distinct roles of different sectors and regions in order to balance emissions sources and sinks.

The UN Paris Agreement sets the framework for international climate action. Within that context, countries are aiming to hold warming well below 2°C and pursue limiting it to 1.5°C. How such global temperature outcomes can be achieved has been explored widely in the scientific literature¹⁻⁴ and assessed by the Intergovernmental Panel on Climate Change (IPCC), for example, in its Fifth Assessment Report⁵ and its Special Report on Global Warming of 1.5°C⁶. Studies explore aspects of the timing of emissions reductions, of energy and land use system transformations consistent with these reductions and of associated mitigation costs^{3,7,8}. However, this literature has been criticized, in particular because its scenarios rely heavily on net negative CO₂ emissions (NNCE) that result from allowing temperature limits to be exceeded in the hope to recover from this overshoot later⁹⁻¹². Recently, a solution to this issue was presented¹². This solution applies a precautionary principle to the design logic of mitigation scenarios and was earlier illustrated in one

modelling framework¹². The broader implications of this new logic for emissions, energy and land-use systems transformations and related mitigation costs, however, remain unexplored to date.

Here we present the first modelling inter-comparison project (MIP) to address this knowledge gap. Bringing together nine international modelling teams, we explore mitigation pathways for limiting temperature change without global reliance on net negative CO₂ emissions. We adopt the new scenario design from ref. ¹² and contrast a set of scenarios with a fixed remaining carbon budget until the time when net zero CO₂ emissions are reached with scenarios based on the traditional end-of-century logic, that permits the use of net negative CO₂ emissions and thus results in the overshoot of the carbon budget and the temperature target. The former ‘net-zero budget’ scenarios are explicitly designed to avoid net negative CO₂ emissions and thus explore specific strategies that keep global warming below a certain threshold with temperature stabilization thereafter.

These new pathways fill two important knowledge gaps. First, they cover the range of carbon budgets consistent with low stabilization targets in a systematic way. They thus help to explore important uncertainties, including the scenario space that is attainable by the IAM models¹³. Secondly, by comparing pathways that either allow or prevent net negative CO₂ emissions throughout the 21st century, we explore the system implications and economics of avoiding the overshoot of temperature limits. The main narratives of the pathways and assumptions are provided in Table 1.

Scenario name	Narrative	Near-term policy assumptions to 2020-2030	Long-term climate policy assumptions	2030 GHG emissions range (GtCO ₂ e)	Range of attainable cumulative CO ₂ emissions (2020-2100, GtCO ₂)*
NPI	GHG emissions follow currently implemented national policies. No additional new policies assumed in the future.	No additional policies compared to today	No additional policies compared to those implemented today	54.2-62.1	3552-4972
NDC	Development to 2030 guided by nationally determined contributions (NDCs). No additional policies relative to NDCs are assumed after 2030.	Achievement of NDCs by 2030	No additional policies after 2030 beyond the NDCs (including emission (intensity) targets, but also sectoral targets mentioned in NDCs)	48.9-56.4	2144-3920
End-of-century budget	The “ end-of-century budget ” scenarios assume long-term climate policies that limit cumulative CO ₂ emissions over the full course of the century. The scenarios may comprise high amounts of global net negative CO ₂ emissions in the second half of the century.	Two variants are explored with either (a) immediate introduction of climate policies as of 2020 or (b) near-term policies follow the NDC to 2030, and more stringent policies are introduced only thereafter.	Long-term CO ₂ pathway constrained by cumulative CO ₂ emissions over the entire century, allowing temperature overshoot and net negative CO ₂ emissions. - Non-CO ₂ emissions are priced at the same level as CO ₂ except non-CO ₂ emissions in the agricultural sector, where GHG prices are capped at <200\$/tCO ₂ e (limiting negative impacts on food security due to high GHG prices).	(a) NPI: 23.9-59.2 (b) Near-term emissions depend on NDC implementation (see above)	Depends on near term policy assumptions: (a) NPI: 200-3000 GtCO ₂ (b) NDC: 300-3000 GtCO ₂
Net-zero budget	The “ net-zero budget ” scenarios assume climate policies that limit the remaining cumulative CO ₂ emissions until carbon neutrality (net zero CO ₂ emissions) is reached. These scenarios do not rely on global net-negative CO ₂ emissions and thus limit temperature overshoot.	Two variants are explored with either (a) immediate introduction of climate policies as of 2020 or (b) near-term policies follow the NDC to 2030, and more stringent policies are introduced only thereafter.	Long-term CO ₂ pathway constrained by maximum cumulative CO ₂ emissions. CO ₂ emissions approach net zero without reliance on net negative CO ₂ emissions. Non-CO ₂ emissions assumptions are the same as in the end-of-century budget scenarios (see above).	(a) NPI: 21-59.3 (b) Near-term emissions depend on NDC implementation (see above)	Depends on near term policy assumptions: (a) NPI: 300-3000 GtCO ₂ (b) NDC: 500-3000 GtCO ₂

Table 1 | Scenario narratives and assumptions.

*Ranges of cumulative CO₂ emissions over the 2018-2100 period are reported for the scenario experiments for which models provided a solution (see supplementary information Table SI.2).

Implications for emissions pathways

Reaching stringent temperature targets while avoiding global net negative CO₂ emissions and thus limiting overshoot, requires a pronounced acceleration of the near-term transformation towards net-zero CO₂ emissions. To stay within a stringent carbon budget of 500 GtCO₂ (broadly consistent with a median temperature goal of 1.44-1.65°C), for example, CO₂ emissions reach net-zero between 2045 and 2065 (range across all models). However, when net negative CO₂ emissions are allowed and only the 'end-of-century' carbon budget is capped, the time of reaching net zero CO₂ emissions is delayed between 5 to 10 years (to 2055-2075). This delay, combined with the higher emissions over that period, results in 0.08-0.23°C higher peak temperatures compared to scenarios that are identical in all but their allowance of net negative CO₂ emissions.

A broad set of behavioral, biophysical, economic, geophysical, legal, political and technological factors render transformations to net-zero easier, more challenging, or in some cases impossible¹⁴. These factors are reflected in considerations of whether pathways can be feasible or not. The modelling exercise presented here informs primarily aspects of economic, geophysical and technological feasibility. The lowest attainable cumulative CO₂ emissions until net zero range from 300 to 1000 GtCO₂ across models in the case of no NNCE and assuming immediate implementation of ambitious policies and a middle-of-the road socioeconomic development¹⁵. These budgets correspond to a maximum projected median global warming during the 21st century between 1.44 and 1.71°C. Weak near-term policies that result in higher GHG emissions over the next decade, such as those implied by the current NDCs, will affect the lowest attainable carbon budget. We estimate that the NDCs will lead to GHG emissions of 48.9-56.4 GtCO₂e by 2030, which is significantly higher

than the range of cost-effective emissions pathways consistent with 2°C (21.0-46.3 GtCO₂e), let alone 1.5°C, by 2030 (21.0-32.7 GtCO₂e). Assuming NDCs are not improved and comprehensive climate policies are thus delayed until after 2030, the lowest attainable cumulative CO₂ emissions until net zero increase to 500–1000 GtCO₂ across models. The corresponding lowest attainable temperature change starting from the NDCs is 1.62 and 1.82°C. Current NDCs thus put limiting warming to 1.5°C out of reach based on the biophysical, economic, geophysical, technological and economic feasibility dimensions reflected by the models applied here. Other feasibility dimensions, such as behavioral, legal, political or social aspects, can affect these ranges further, although this study does not explore their impact.

The overall cumulative deployment of net negative CO₂ emissions over the 21st century ranges from a few megatons to about 600 GtCO₂ across models in the scenarios that only cap the end-of-century budget, and our scenarios show a techno-economic potential for declining warming after its peak by 0.12 to 0.37°C until 2100 across models (Figure 1b). This temperature reversal is not only driven by net negative CO₂ emissions but can also be partially the result of reductions in non-CO₂ forcings after the point when net zero CO₂ emissions is reached (known as the Zero Emissions Commitment) ¹⁶. The drawdown due to Non-CO₂ emissions in the net-zero budget scenarios is between 0°C–0.14°C by 2100 (see blue dots in Figure 1b). In contrast to steady NNCE deployment, the latter contributions are thus limited in scope. The uncertainty in mitigation potential of non-CO₂ emissions is also a major determinant of the spread in temperature response of net negative CO₂ emissions across the scenarios (see red dots in Figure 1b).

1 The net-zero budget scenarios allow for the systematic quantification of the residual non-
2 CO₂ emissions consistent with different peak temperature levels (Figure 1c). A large share of
3 these residual non-CO₂ emissions is caused by the Agriculture, Forestry and Other Land-Use
4 (AFOLU) sector, most prominently by enteric fermentation (CH₄) and fertilizer use (N₂O). The
5 residual non-CO₂ emissions in the second half of the century range from slightly above 3 to
6 more than 10 GtCO₂e highlighting once more the dual importance of CO₂ and non-CO₂
7 mitigation measures (Figure 1c). We emphasize that while our net-zero budget scenarios
8 exclude NNCE, for many policy goals, including those of the Paris Agreement¹⁷ or the climate
9 neutrality target of the EU¹⁸, NNCE are needed in order to balance residual non-CO₂
10 emissions and reach net-zero greenhouse gas emissions.

Figure 1 | Emissions and temperature characteristics. Panel a (left-hand): GHG emissions in NDC scenarios (grey) compared to stringent mitigation scenarios that reach peak temperatures below 2°C while avoiding NNCE (net-zero budget scenarios, blue), and mitigation scenarios with the same long-term carbon budget allowing for NNCE (end-of-century budget scenarios, red). Panel b: Residual non-CO₂ emissions after the point of reaching net zero CO₂ emissions for specified temperature stabilization levels. Panel c: Relationship between cumulative net negative CO₂ emissions and resulting temperature drawdown after peak temperature (i.e., overshoot). Panel d: Timing of when net-zero CO₂ emissions are reached. Net-zero budget scenarios consistent with 1.5°C (low overshoot) and 2°C respectively (blue bars) are compared to scenarios with the same end-of-century carbon budget with net negative emissions (red bars).

Long-term economic benefits of rapid transformations

The IPCC Fifth Assessment Report and most of the IAM literature emphasize that mitigation costs would raise over time as a result from efforts to limit climate change⁵. These mitigation costs traditionally reflect the lowering of GDP while ignoring the benefits of

mitigation due to avoided impacts⁵. Typically, relatively smaller mitigation costs are reported in the near term through to 2030 compared to the medium term (2050) or the very long term by 2100^{4,5,12,19}. This evolution is primarily a result of most IAM studies emphasizing cumulative emissions and forcing by the end of the century, which, by design, favors postponement of mitigation action until later in the century²⁰.

Scenarios that avoid net negative CO₂ emissions, by contrast, entail the need for more rapid near-term transitions towards net zero CO₂ emissions (Figure 1 and Figure SI-1.8 in the supplementary information). Once net zero CO₂ emissions are reached, mitigation costs and associated carbon prices peak and start to fall again since the stringent and binding required structural changes for reaching zero CO₂ emissions are completed and maintaining a constant level of net zero CO₂ emissions is less challenging.

Accelerating the transformation, avoiding temperature overshoot, and avoiding reliance on net negative CO₂ emissions comes with a near-term price tag, particularly for tight carbon budgets consistent with the Paris Agreement. Mid-term GDP losses by 2050 are thus higher in scenarios that avoid NNCE compared to scenarios that achieve the same carbon budget with NNCE by the end of the century (Figure 2b).

However, in contrast to the reported costs in earlier studies⁵, we find that the long-term savings in mitigation costs are by far larger than the upfront near-term investments to avoid reliance on NNCE. In other words, the near-term GDP growth impact of net-zero budget scenarios is fully compensated by higher GDP growth in the second half of the century (when compared to end-of-century budget scenarios, see Figure 2b). The absolute GDP levels in the long term (2100) are thus higher across all models and mitigation scenarios that avoid net negative CO₂ emissions, compared to those that do (Figure 2b). For a 2°C target,

1 the long-term (2100) GDP losses are 5-70% lower in scenarios that avoid NNCE and
2 overshoot. Similarly, the peak carbon prices over the course of the century – a relevant
3 indicator measuring policy stringency and disruptiveness^{21,22} – is significantly lower in most
4 scenarios without reliance on NNCE (see Figure SI.7 in the supplementary information).

5 Across all IAMs we find large-scale benefits of rapid transformations towards net zero CO₂
6 emissions, even without considering the benefits of avoided impacts that are traditionally
7 not included in the type of scenario analysis presented here. With many countries coming
8 forward with net zero targets, these insights are of high relevance to policy. From a
9 methodological perspective, it illustrates the importance of assumed underlying discount
10 rates. Confirming findings based on a different scenario design²⁰, we conclude that discount
11 rates of less than about 2% would make the corresponding IAM scenarios without NNCE
12 cheaper and thus cost-optimal overall (Figure 2c).

1

2

3 **Figure 2 | Economic implications of scenarios with increased near-term stringency and avoided**
 4 **reliance on net negative CO₂ emissions.** Panel a: Development of GDP in baseline scenarios
 5 following current national policies (NPI). GDP projections measured in power purchasing parity
 6 (straight lines) and in market exchange rates (dashed lines). Panel b: Development of GDP in
 7 mitigation scenarios without NNCE relative to scenarios with NNCE. In the near-term the GDP of net-
 8 zero budget scenarios is relatively smaller, but this is fully compensated in the second half of the
 9 century where GDP in net-zero budget scenarios grows bigger. Panel c: The ratio of the average price
 10 of carbon (net present value, 2020-2100) assuming different discount rates (1-5%). The price in net-
 11 zero budget scenarios without NNCE are compared to scenarios with the same end-of-century
 12 carbon budget with NNCE (ratio <100 means that scenarios without NNCE are overall less costly)

13

14 Net Zero CO₂ Emissions Systems

15 A final novel dimension that can be explored through this study is the diversity in net zero
 16 CO₂ emission systems. Achieving a net zero emissions system globally requires deep
 17 emissions cuts across all economic sectors and regions. The distribution of the emissions
 18 reductions across space and time depends critically on a number of factors, including
 19 relative abatement costs, the inertia of sectors against fundamental structural changes, and

the ability to reduce emissions in different sectors to zero or even further to net negative CO₂ emissions. In a zero CO₂ emissions system, some sectors and regions continue thus to act as sources of residual emissions, which are balanced by an equal amount of sinks in other sectors and regions that remove CO₂ from the atmosphere in order to achieve overall net zero emissions (Figure 3).

The magnitude of the sinks differs across the assessed models, ranging globally from about 5 GtCO₂ per year (REMIND-MAgPIE and GEM-E3 models) to more than 10 GtCO₂ per year (POLES and WITCH, Figure 3). Afforestation and reforestation, as well as bioenergy with carbon capture and storage (BECCS), are responsible for the bulk of the gross negative emissions in the scenarios. They contribute to a very varying degree though. AFOLU and energy supply sectors act as sinks, while the demand-side sectors (transport, buildings, and industry) are primarily responsible for any of the remaining residual emissions sources. These results emphasize the importance of demand-side measures to reduce the residual emissions in these sectors, which in turn would permit lower reliance on carbon-dioxide removal (CDR) from the atmosphere. In some models (e.g., REMIND-MAgPIE and GEM-E3), industrial processes, feedstocks, and/or the buildings sector reach zero emissions or contribute smaller amounts of net negative CO₂ emissions. Electrification, efficiency, and demand reductions play a critical role in these sectors.

The sectors differ significantly with respect to the timing of when they may achieve net zero CO₂ emissions. Globally CO₂ emissions reach net zero around 2050-2075 and 2050-2100 in 1.5°C pathways with low overshoot and 2°C pathways, respectively (Figure 1d). However, in most scenarios, the AFOLU sector is fully decarbonized more than 20-40 years earlier, and the energy supply sector more than 10-20 years earlier (Figure 3c). The demand-side sectors

on the other hand (buildings, industry and transport), with many small dispersed and difficult-to-abate emissions sources, do in many instances not reduce emissions to zero throughout the century when considered in this overarching, integrated net zero strategy (Figure 3c).

Also, the timing of when different regions reach net zero CO₂ emissions varies significantly (Figure 3c). Regions with more low-cost CDR potential and large-scale availability of land resources, such as Latin America and the Reforming Economies including Russia, tend to decarbonize first and much earlier than the world average. This sequence in the timing of decarbonization is because the pathways describe a cost-effective response across regions, implicitly assuming that there is some degree of coordination and financial collaboration that allows regions to tap into mitigation options that stretch across regions (when needed). Regions with high projected economic catch-up and continued population growth in the future and/or lower CDR potentials, such as Africa, parts of Asia, and the Middle East thus tend to reach net zero CO₂ emissions relatively later. In some scenarios these regions even maintain some residual emissions throughout the century. Generally, today's rich economies of the OECD reach net zero CO₂ emissions domestically about the same time as the global average if climate change mitigation is to be achieved cost-effectively. In a world in which rich OECD economies aim at taking up a climate leadership position, or in order to reflect higher historic responsibility, their net zero CO₂ timing could well be set earlier.

Figure 3 | Net zero CO₂ emissions systems, and the contribution of different sectors (upper panels) and different regions (lower panels). Left panels (a,d): Development of sectoral/regional sinks and sources over time in an illustrative pathway (MESSAGE_{ix}-Globiom model and a net-zero budget of 1000 GtCO₂). Middle panels (b,e): Results from different models, showing the contribution of sectors/regions at the time when net zero CO₂ emissions is reached. Right panels (c,f): The timing of net-zero for different sectors and regions relative to the timing of net-zero global total CO₂ (blue line at zero). The histogram includes all pathways that limit temperature to <2°C.

Discussion

We have shown that scenarios without a reliance on net negative CO₂ emissions avoid a systematic bias in favor of temperature overshoot, but at the same time require a much more pronounced near-term transition. Furthermore, the intercomparison identified possible front-runner sectors and regions that may provide an entry point for rapid and deep cuts towards zero CO₂ emissions, and illustrates that rapid-transition scenarios are not only associated with major economic gains in the long-term (even without considering benefits of avoided climate impacts), they also involve lower climate risks.

Net-zero CO₂ emissions systems can imply the deployment of a portfolio of CDR measures with very different implications for the sustainability of the overall mitigation portfolio. BECCS in particular has been criticized for possible trade-offs with sustainable development,

strongly depending on the scale of deployment, implementation practice, and local context^{14,23,24}. Successful implementation will hinge upon appropriate policy designs that avoid competition over land for food or other basic ecosystem services, water resources and/or biodiversity²⁵⁻²⁸. To account for such possible trade-offs, the models in this study limit land-based mitigation and cap the GHG price effect on the agricultural sector to <200\$/tCO₂e. Some models include, in addition, explicit biodiversity protection constraints (MESSAGE_{ix}-GLOBIOM). An important insight from our study is that the portfolio of CDR measures may vary significantly across models, providing policy flexibility with respect to technology choices. In some of the pathways (e.g., REMIND-MAgPIE) CDR is primarily relying on BECCS, while other pathways rely more heavily on nature-based solutions and re-/afforestation or more balanced approach across these options (WITCH, POLES, MESSAGE_{ix}-GLOBIOM). The IAMs do not include all possible CDR options that are identified in the literature²⁹. Considering more CDR options will likely affect the results.

The importance of demand-side measures cannot be overemphasized. It is the demand in service sectors which ‘sizes’ the overall mitigation challenge³⁰⁻³² and comprises hard-to-abate processes and activities. More research is needed for a better understanding of residual emissions and possible mitigation options in these sectors. Bottlenecks include particularly the industry sector’s demand for carbonaceous fuels and the transport sector, as well as the materials and consumption goods sectors. From a methodological perspective, we find that material substitution and options for demand-side electrification need to be represented in a more bottom-up and granular fashion in the models.

Last but not least, we emphasize that our regional results indicate opportunities for mitigation, and do not imply political feasibility, which would need to consider a diverse set

of ethical and other considerations³³. In fact, we find large differences across regions to reach net zero CO₂ emissions, and the pathways suggest that from an economic perspective, it will be most attractive if some regions act as sources while others act as sinks. Achieving such an effective solution, however, poses a major challenge for the international policy process, because it requires stronger international collaboration and markets for cross-regional trade and support across different world regions. In this context, it is encouraging to observe that net zero emissions targets in a number of key countries, like China³⁴, EU³⁵ Japan³⁶, and South Korea³⁷ are broadly consistent with the pace of the transformation as depicted by our study.

Methodology

The nine integrated assessment model (IAM) frameworks, drawn upon in this study include AIM-Hub^{38,39}, COFFEE⁴⁰, GEM-E3^{41,42}, IMAGE⁴³, MESSAGEix-GLOBIOM⁴⁴, TIAM-ECN⁴⁵, POLES^{46,47}, REMIND-MAGPIE^{48,49} and WITCH-GLOBIOM^{50,51}. The models span a wide range from least-cost optimization to computable general equilibrium models, and from game-theoretic to recursive-dynamic simulation models. Such diversity is beneficial for shedding light on those model findings that are robust to diverging assumptions and model structures. Of particular importance for the current study is that all models have a detailed coverage of the energy sector, and seven out of the nine models in addition represent land-use changes and related mitigation measures in detail.

A common scenario design and modelling protocol was implemented by all models (see Supplementary information). For the mitigation scenarios, the models explored the full scenario space of cumulative CO₂ emissions limits of <3000 GtCO₂ (2018-2100) in 100 GtCO₂

1 increments (see supplementary information, Table SI-2.1 and SI-2.2). Mitigation of non-CO₂
 2 GHGs follow the same equivalent carbon price as for CO₂ (driven by the cumulative CO₂
 3 emissions budget constraint). For land use, a carbon price ceiling of \$200/tCO₂ was applied.

4 The NPi (baseline) scenario broadly incorporates middle of the road socio-economic
 5 conditions based on the second marker baseline scenario from the Shared Socioeconomic
 6 Pathways (SSP2)⁴. It also assumes that climate, energy and land use policies that are
 7 currently ratified are implemented (cut-off date 1 July 2019). The NDC scenario builds upon
 8 the NPi and assumes that the NDCs (both unconditional and conditional NDC actions) as
 9 submitted by April 2020 are implemented by 2030. For the NPi and NDC scenarios, a
 10 continuation of effort in the long-term was assumed. This was implemented by
 11 extrapolating the “equivalent” emissions reductions or carbon price in 2020/2030 (see
 12 supplementary information). We have not considered the impact of the COVID-19 pandemic
 13 quantitatively, effectively assuming a full recovery without significant effect on long-term,
 14 global emissions⁵². The scenarios explored here, however, can inform governments that aim
 15 for ‘green’ recovery packages⁵³, by illustrating the required pace and contribution of key
 16 mitigation sectors to reach net-zero CO₂ emissions.

17 GHG emissions here always refer to the gases of the Kyoto basket (that is, CO₂, CH₄, N₂O,
 18 HFCs, PFC and SF₆, aggregated with 100-year Global Warming Potentials from the IPCC AR5.

19 Global mean temperature projections were estimated with the probabilistic reduced-
 20 complexity carbon-cycle and climate model MAGICC^{54,55} in a setup that captures the IPCC
 21 AR5 climate sensitivity uncertainty assessment^{54,56,57}, as used in the IPCC Special Report on
 22 Global Warming of 1.5°C⁶ (IPCC SR1.5). If not otherwise specified, the definition of the

temperature goals follow the IPCC SR1.5, i.e., limiting the exceedance probability to <0.34 for 2°C, and limiting the exceedance probability for 1.5°C (*with low overshoot*) to <0.67 for the peak temperature, and <0.34 for the year 2100.

Data Availability

The data for all scenarios is made accessible online via the ENGAGE Scenario Portal: <https://data.ene.iiasa.ac.at/engage/#/login> (For the moment access is restricted to the reviewers only though the following username and password. After review the database will be fully accessible for the public. *Username: EOPreview - Password: EOPpassword*)

Code Availability

The models are documented on the common integrated assessment model documentation website (https://www.iamcdocumentation.eu/index.php/IAMC_wiki), and several have published open source code (e.g. REMIND: <https://github.com/remindmodel/remind>; MESSAGE: https://github.com/iiasa/message_ix). The code that was used to generate the figures is made available before publication at GitHub. For a brief documentation of the models and main concepts see also the Supplementary Information.

References:

- 1 McCollum, D. L. *et al.* Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy* **3**, 589-599, doi:10.1038/s41560-018-0179-z (2018).
- 2 Bauer, N. *et al.* Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. *Climatic Change*, doi:10.1007/s10584-018-2226-y (2018).
- 3 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).
- 4 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:<https://doi.org/10.1016/j.gloenvcha.2016.05.009> (2017).
- 5 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* (ed Edenhofer O. *et al.*) 413-510 (Cambridge University Press, 2014).
- 6 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* (ed G. Flato, Fuglestad, J., Mrabet, R. & Schaeffer, R.) 93-174 (IPCC/WMO, 2018).
- 7 Riahi, K. *et al.* Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change* **90**, 8-23, doi:<https://doi.org/10.1016/j.techfore.2013.09.016> (2015).

- 8 Tavoni, M. *et al.* Post-2020 climate agreements in the major economies assessed in the light of global models. *Nature Climate Change* **5**, 119-126 (2015).
- 9 Anderson, K. & Peters, G. The trouble with negative emissions. *Science* **354**, 182-183 (2016).
- 10 Geden, O. Policy: Climate advisers must maintain integrity. *Nature* **521**, 27-28 (2015).
- 11 Peters, G. P. & Geden, O. Catalysing a political shift from low to negative carbon. *Nature Climate Change* **7**, 619-621 (2017).
- 12 Rogelj, J. *et al.* A new scenario logic for the Paris Agreement long-term temperature goal. *Nature* **573**, 357-363 (2019).
- 13 Fujimori, S., Rogelj, J., Krey, V. & Riahi, K. A new generation of emissions scenarios should cover blind spots in the carbon budget space. *Nature Climate Change* **9**, 798-800 (2019).
- 14 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* (ed A. Abdulla, Boer, R., Howden, M. & Ürge-Vorsatz, D.) (World Meteorological Organisation, 2018).
- 15 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 (2017).
- 16 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).
- 17 Fuglestad, 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**, 20160445 (2018).
- 18 EC. A clean planet for all: Long-term low greenhouse gas emission development strategy of the European Union and its Member States. . (European Commission, Brussels, 2018).

1 19 Van Vuuren, D. P. *et al.* The representative concentration pathways: an overview. *Climatic*
2 *change* **109**, 5 (2011).

3 20 Emmerling, J. *et al.* The role of the discount rate for emission pathways and negative
4 emissions. *Environmental Research Letters* **14**, 104008 (2019).

5 21 Rogelj, J., McCollum, D. L., O'Neill, B. C. & Riahi, K. 2020 emissions levels required to limit
6 warming to below 2° C. *Nature Climate Change* **3**, 405-412 (2013).

7 22 Kriegler, E. *et al.* Short term policies to keep the door open for Paris climate goals.
8 *Environmental Research Letters* **13**, 074022 (2018).

9 23 Fuss, S. *et al.* Negative emissions—Part 2: Costs, potentials and side effects. *Environmental*
10 *Research Letters* **13**, 063002 (2018).

11 24 Shukla, P., Skea, J. & Calvo Buendia, E. Summary for policymakers. *Climate Change and Land:*
12 *an IPCC special report on climate change, desertification, land degradation, sustainable land*
13 *management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (2019).

14 25 Hasegawa, T. *et al.* Risk of increased food insecurity under stringent global climate change
15 mitigation policy. *Nature Climate Change* **8**, 699-703 (2018).

16 26 Fujimori, S. *et al.* Inclusive climate change mitigation and food security policy under 1.5
17 degrees C climate goal. (2018).

18 27 Leclère, D. *et al.* Bending the curve of terrestrial biodiversity needs an integrated strategy.
19 *Nature* **585**, 551-556 (2020).

20 28 Ohashi, H. *et al.* Biodiversity can benefit from climate stabilization despite adverse side
21 effects of land-based mitigation. *Nature communications* **10**, 1-11 (2019).

22 29 Realmonte, G. *et al.* An inter-model assessment of the role of direct air capture in deep
23 mitigation pathways. *Nature communications* **10**, 1-12 (2019).

1 30 Riahi, K. *et al.* in *Global Energy Assessment - Toward a Sustainable Future* 1203-1306
2 (Cambridge University Press and the International Institute for Applied Systems Analysis,
3 2012).

4 31 Fujimori, S., Kainuma, M., Masui, T., Hasegawa, T. & Dai, H. The effectiveness of energy
5 service demand reduction: a scenario analysis of global climate change mitigation. *Energy*
6 *policy* **75**, 379-391 (2014).

7 32 Grubler, A. *et al.* A low energy demand scenario for meeting the 1.5 C target and sustainable
8 development goals without negative emission technologies. *Nature energy* **3**, 515-527
9 (2018).

10 33 Höhne, N., den Elzen, M. & Escalante, D. Regional GHG reduction targets based on effort
11 sharing: a comparison of studies. *Climate Policy* **14**, 122-147,
12 doi:10.1080/14693062.2014.849452 (2014).

13 34 *Statement by H.E. Xi Jinping President of the People's Republic of China at the General*
14 *Debate of the 75th Session of the United Nations General Assembly,*
15 <https://www.fmprc.gov.cn/mfa_eng/zxxx_662805/t1817098.shtml> (2020).

16 35 EC. NDC Submission by Croatia and the European Commission on behalf of the European
17 Union and its Member States. ([https://unfccc.int/sites/default/files/resource/HR-03-06-](https://unfccc.int/sites/default/files/resource/HR-03-06-2020%20EU%20Submission%20on%20Long%20term%20strategy.pdf)
18 [2020%20EU%20Submission%20on%20Long%20term%20strategy.pdf](https://unfccc.int/sites/default/files/resource/HR-03-06-2020%20EU%20Submission%20on%20Long%20term%20strategy.pdf), 2020).

19 36 *Policy Speech by the Prime Minister to the 203rd Session of the Diet,*
20 <https://japan.kantei.go.jp/99_suga/statement/202010/_00006.html> (2020).

21 37 *Address by President Moon Jae-in at National Assembly to propose government budget for*
22 *2021,* <<https://english1.president.go.kr/BriefingSpeeches/Speeches/898>> (2020).

23 38 Fujimori, S., Hasegawa, T., Masui, T. & Takahashi, K. Land use representation in a global CGE
24 model for long-term simulation: CET vs. logit functions. *Food Security* **6**, 685-699,
25 doi:10.1007/s12571-014-0375-z (2014).

1 39 Fujimori, S., Masui, T. & Matsuoka, Y. AIM/CGE [basic] Manual Discussion Paper Series
2 (Center for Social and Environmental Systems Research, National Institute for Environmental
3 Studies, 2012).

4 40 Pedro, R. *Development of a global integrated energy model to evaluate the Brazilian role in*
5 *climate change mitigation scenarios* D.Sc. thesis, Programa de Planejamento Energético,
6 COPPE/UFRJ, (2016).

7 41 Capros, P. *et al.* Description of models and scenarios used to assess European
8 decarbonisation pathways. *Energy Strategy Reviews* **2**, 220-230,
9 doi:<https://doi.org/10.1016/j.esr.2013.12.008> (2014).

10 42 E3Mlab. GEM-E3 Model Manual 2017. (2017).

11 43 Stehfest, E. *et al.* Integrated Assessment of Global Environmental Change with IMAGE 3.0.
12 Model Description and Policy Applications. (PBL Netherlands Environmental Assessment
13 Agency, 2014).

14 44 Huppmann, D. *et al.* The MESSAGEix Integrated Assessment Model and the ix modeling
15 platform (ixmp): An open framework for integrated and cross-cutting analysis of energy,
16 climate, the environment, and sustainable development. *Environmental Modelling &*
17 *Software* **112**, 143-156, doi:<https://doi.org/10.1016/j.envsoft.2018.11.012> (2019).

18 45 van der Zwaan, B., Kober, T., Longa, F. D., van der Laan, A. & Jan Kramer, G. An integrated
19 assessment of pathways for low-carbon development in Africa. *Energy Policy* **117**, 387-395,
20 doi:<https://doi.org/10.1016/j.enpol.2018.03.017> (2018).

21 46 Criqui, P., Mima, S., Menanteau, P. & Kitous, A. Mitigation strategies and energy technology
22 learning: an assessment with the POLES model. *Technol. Forecast. Social Change* **90**,
23 doi:10.1016/j.techfore.2014.05.005 (2015).

24 47 Keramidas, K., Kitous, A. G., Després, J. & Schmitz, A. POLES-JRC Model Documentation. EUR
25 28728 EN. Report JRC107387 (Joint Research Center, 2017).

- 48 Kriegler, E. Fossil-fueled development (SSP5): an energy and resource intensive scenario for
the 21st century. *Glob. Environ. Change* **42**, doi:10.1016/j.gloenvcha.2016.05.015 (2017).
- 49 Luderer, G. Economic mitigation challenges: how further delay closes the door for achieving
climate targets. *Environ. Res. Lett.* **8**, doi:10.1088/1748-9326/8/3/034033 (2013).
- 50 Bosetti, V., Carraro, C., Galeotti, M., Massetti, E. & Tavoni, M. WITCH: a World Induced
Technical Change Hybrid model. *Energy J.* **27** (2006).
- 51 Emmerling, J. et al. The WITCH 2016 Model—Documentation and Implementation of the
Shared Socioeconomic Pathways (Fondazione Eni Enrico Mattei, 2016).
- 52 IEA. World Energy Outlook 2020. (IEA, Paris, 2020).
- 53 Andrijevic, M., Schleussner, C.-F., Gidden, M. J., McCollum, D. L. & Rogelj, J. COVID-19
recovery funds dwarf clean energy investment needs. *Science* **370**, 298-300,
doi:10.1126/science.abc9697 (2020).
- 54 Meinshausen, M. *et al.* Greenhouse-gas emission targets for limiting global warming to 2 C.
Nature **458**, 1158-1162 (2009).
- 55 Meinshausen, M., Raper, S. C. & Wigley, T. M. Emulating coupled atmosphere-ocean and
carbon cycle models with a simpler model, MAGICC6-Part 1: Model description and
calibration. (2011).
- 56 Rogelj, J., Meinshausen, M., Sedláček, J. & Knutti, R. Implications of potentially lower climate
sensitivity on climate projections and policy. *Environmental Research Letters* **9**, 031003
(2014).
- 57 Rogelj, J., Meinshausen, M. & Knutti, R. Global warming under old and new scenarios using
IPCC climate sensitivity range estimates. *Nature climate change* **2**, 248-253 (2012).

1 **Acknowledgements**

2 S.F, T.H and K.O. are supported by the Environment Research and Technology Development
3 Fund (JPMEERF20202002) of the Environmental Restoration and Conservation Agency of
4 Japan. S.F and T.H are further supported by the Sumitomo Foundation. All other authors
5 received funding from the European Union's Horizon 2020 research and innovation
6 programme under grant agreement no. 821471 (ENGAGE).

7 **Competing interests**

8 The authors declare no competing interests.

9 **Author contributions**

10 K.R. designed the study; C.B., O.F. and K.R. coordinated the scenario development and data
11 vetting process; D.H. provided the main figures as well as contributed to analysis; and J.R.
12 conducted the climate runs. V.B., A.M.C., A.D., L.D., S.Fr., S.Fu., M.H., T.H., V.K., G.L., L.P.,
13 R.S., M.W., B.vdZ., and Z.V. performed the model runs and developed the scenarios; vetting
14 was further carried out by F.D.L., J.D., F.F., K.F., M.G., F.H., K.K., P.K., E.K., L.N., K.O., A.P.,
15 P.R., G.Ü., B.vR., J.T., M.T., D.vV., and B.Z.; K.R. prepared the first draft and all authors
16 contributed to writing the paper.

17 **Additional information**

18 Supplementary information is available for this paper.

19 Correspondence and requests for materials should be addressed to K.R.

Figures

Figure 1

Emissions and temperature characteristics. Panel a (left-hand): GHG emissions in NDC scenarios (grey) compared to stringent mitigation scenarios that reach peak temperatures below 2°C while avoiding NNCE (net-zero budget scenarios, blue), and mitigation scenarios with the same long-term carbon budget allowing for NNCE (end-of-century budget scenarios, red). Panel b: Residual non-CO₂ emissions after the point of reaching net zero CO₂ emissions for specified temperature stabilization levels. Panel c: Relationship between cumulative net negative CO₂ emissions and resulting temperature drawdown after peak temperature (i.e., overshoot). Panel d: Timing of when net-zero CO₂ emissions are reached. Net-zero budget scenarios consistent with 1.5°C (low overshoot) and 2°C respectively (blue bars) are compared to scenarios with the same end-of-century carbon budget with net negative emissions (red bars).

Figure 2

Economic implications of scenarios with increased near-term stringency and avoided reliance on net negative CO₂ emissions. Panel a: Development of GDP in baseline scenarios following current national policies (NPI). GDP projections measured in power purchasing parity(straight lines) and in market exchange rates (dashed lines). Panel b: Development of GDP in mitigation scenarios without NNCE relative to scenarios with NNCE. In the near-term the GDP of net-zero budget scenarios is relatively smaller, but this is fully compensated in the second half of the century where GDP in net-zero budget scenarios grows bigger. Panel c: The ratio of the average price of carbon (net present value, 2020-2100) assuming different discount rates (1-5%). The price in net-zero budget scenarios without NNCE are compared to scenarios with the same end-of-century carbon budget with NNCE (ratio <100 means that scenarios without NNCE are overall less costly)

Figure 3

Net zero CO₂ emissions systems, and the contribution of different sectors (upper panels) and different regions (lower panels). Left panels (a,d): Development of sectoral/regional sinks and sources over time in an illustrative pathway (MESSAGEix-Globiom model and a net-zero budget of 1000 GtCO₂). Middle panels (b,e): Results from different models, showing the contribution of sectors/regions at the time when net zero CO₂ emissions is reached. Right panels (c,f): The timing of net-zero for different sectors and regions relative to the timing of net-zero global total CO₂ (blue line at zero). The histogram includes all pathways that limit temperature to <2°C.

Supplementary Files

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