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

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# 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 $CO_2$ 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 $CO_2$ 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 literature[1-4] and assessed by the Intergovernmental Panel on Climate Change (IPCC), for example, in its Fifth Assessment Report[5] and its Special Report on Global Warming of 1.5°C[6]. 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 $CO_2$ emissions (NNCE) that result from allowing temperature limits to be exceeded in the hope to recover from this overshoot later[9-12]. Recently, a solution to this issue was presented[12]. This solution applies a precautionary principle to the design logic of mitigation scenarios and was earlier illustrated in one modelling framework[12]. 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 $CO_2$ 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 $CO_2$ emissions are reached with scenarios based on the traditional end-of-century logic, that permits the use of net negative $CO_2$ 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 $CO_2$ 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 models[13]. Secondly, by comparing pathways that either allow or prevent net negative $CO_2$ 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 ($GtCO_2e$) | 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_2e$ (limiting negative impacts on food security due to high GHG prices). | (a) NPi: 23.9-59.2<br>(b) Near-term emissions depend on NDC implementation (see above) | Depends on near term policy assumptions:<br>(a) NPi: 200-3000 $GtCO_2$<br>(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<br>(b) Near-term emissions depend on NDC implementation (see above) | Depends on near term policy assumptions:<br>(a) NPi: 300-3000 $GtCO_2$<br>(b) NDC: 500-3000 $GtCO_2$ |

Table 1 | Scenario narratives and assumptions.

*Ranges of cumulative $CO_2$ 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 $CO_2$ emissions and thus limiting overshoot, requires a pronounced acceleration of the near-term transformation towards net-zero $CO_2$ emissions. To stay within a stringent carbon budget of 500 $GtCO_2$ (broadly consistent with a median temperature goal of 1.44-1.65°C), for example, $CO_2$ emissions reach net-zero between 2045 and 2065 (range across all models). However, when net negative $CO_2$ emissions are allowed and only the 'end-of-century' carbon budget is capped, the time of reaching net zero $CO_2$ 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 $CO_2$ 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 impossible[14]. 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 $CO_2$ emissions until net zero range from 300 to 1000 $GtCO_2$ across models in the case of no NNCE and assuming immediate implementation of ambitious policies and a middle-of-the road socioeconomic development[15]. 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 $GtCO_2e$ by 2030, which is significantly higher than the range of cost-effective emissions pathways consistent with 2°C (21.0-46.3 $GtCO_2e$), let alone 1.5°C, by 2030 (21.0-32.7 $GtCO_2e$). Assuming NDCs are not improved and comprehensive climate policies are thus delayed until after 2030, the lowest attainable cumulative $CO_2$ emissions until net zero increase to 500–1000 $GtCO_2$ 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 $CO_2$ emissions over the 21st century ranges from a few megatons to about 600 $GtCO_2$ 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 $CO_2$ emissions but can also be partially the result of reductions in non-$CO_2$ forcers after the point when net zero $CO_2$ emissions is reached (known as the Zero Emissions Commitment) [16]. The drawdown due to Non-$CO_2$ 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-$CO_2$ emissions is also a major determinant of the spread in temperature response of net negative $CO_2$ emissions across the scenarios (see red dots in Figure 1b).

The net-zero budget scenarios allow for the systematic quantification of the residual non-$CO_2$ emissions consistent with different peak temperature levels (Figure 1c). A large share of these residual non-$CO_2$ emissions is caused by the Agriculture, Forestry and Other Land-Use (AFOLU) sector, most prominently by enteric fermentation ($CH_4$) and fertilizer use ($N_2O$). The residual non-$CO_2$ emissions in the second half of the century range from slightly above 3 to more than 10 $GtCO_2e$ highlighting once more the dual importance of $CO_2$ and non-$CO_2$ mitigation measures (Figure 1c). We emphasize that while our net-zero budget scenarios exclude NNCE, for many policy goals, including those of the Paris Agreement[17] or the climate neutrality target of the EU[18], NNCE are needed in order to balance residual non-$CO_2$ emissions and reach net-zero greenhouse gas emissions.

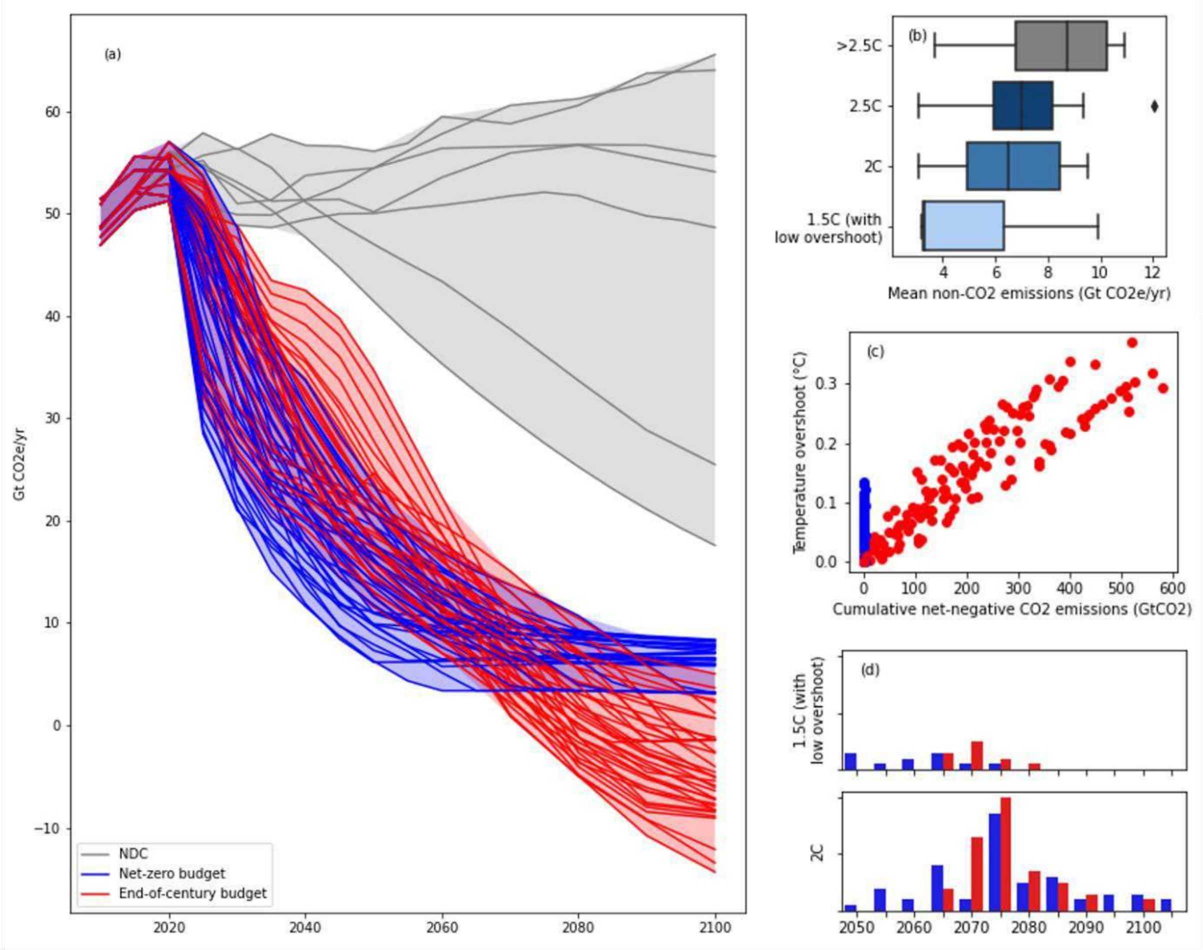

**Figure 1 | Emissions and temperature characteristics.** Panel a (left-hand): GHG emissions in NDC scenarios (grey) compared to stringent mitigation scenarios that reach peak temperatures below 2°C while avoiding NNCE (net-zero budget scenarios, blue), and mitigation scenarios with the same long-term carbon budget allowing for NNCE (end-of-century budget scenarios, red). Panel b: Residual non-$CO_2$ emissions after the point of reaching net zero $CO_2$ emissions for specified temperature stabilization levels. Panel c: Relationship between cumulative net negative $CO_2$ emissions and resulting temperature drawdown after peak temperature (i.e., overshoot). Panel d: Timing of when net-zero $CO_2$ 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 change[5]. These mitigation costs traditionally reflect the lowering of GDP while ignoring the benefits of mitigation due to avoided impacts[5]. 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 century[20].

Scenarios that avoid net negative $CO_2$ emissions, by contrast, entail the need for more rapid near-term transitions towards net zero $CO_2$ emissions (Figure 1 and Figure SI-1.8 in the supplementary information). Once net zero $CO_2$ 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 $CO_2$ emissions are completed and maintaining a constant level of net zero $CO_2$ emissions is less challenging.

Accelerating the transformation, avoiding temperature overshoot, and avoiding reliance on net negative $CO_2$ 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 studies[5], 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 $CO_2$ emissions, compared to those that do (Figure 2b). For a 2˚C target, the long-term (2100) GDP losses are 5-70% lower in scenarios that avoid NNCE and overshoot. Similarly, the peak carbon prices over the course of the century – a relevant indicator measuring policy stringency and disruptiveness[21,22] – is significantly lower in most scenarios without reliance on NNCE (see Figure SI.7 in the supplementary information).

Across all IAMs we find large-scale benefits of rapid transformations towards net zero $CO_2$ emissions, even without considering the benefits of avoided impacts that are traditionally not included in the type of scenario analysis presented here. With many countries coming forward with net zero targets, these insights are of high relevance to policy. From a methodological perspective, it illustrates the importance of assumed underlying discount rates. Confirming findings based on a different scenario design[20], we conclude that discount rates of less than about 2% would make the corresponding IAM scenarios without NNCE cheaper and thus cost-optimal overall (Figure 2c).

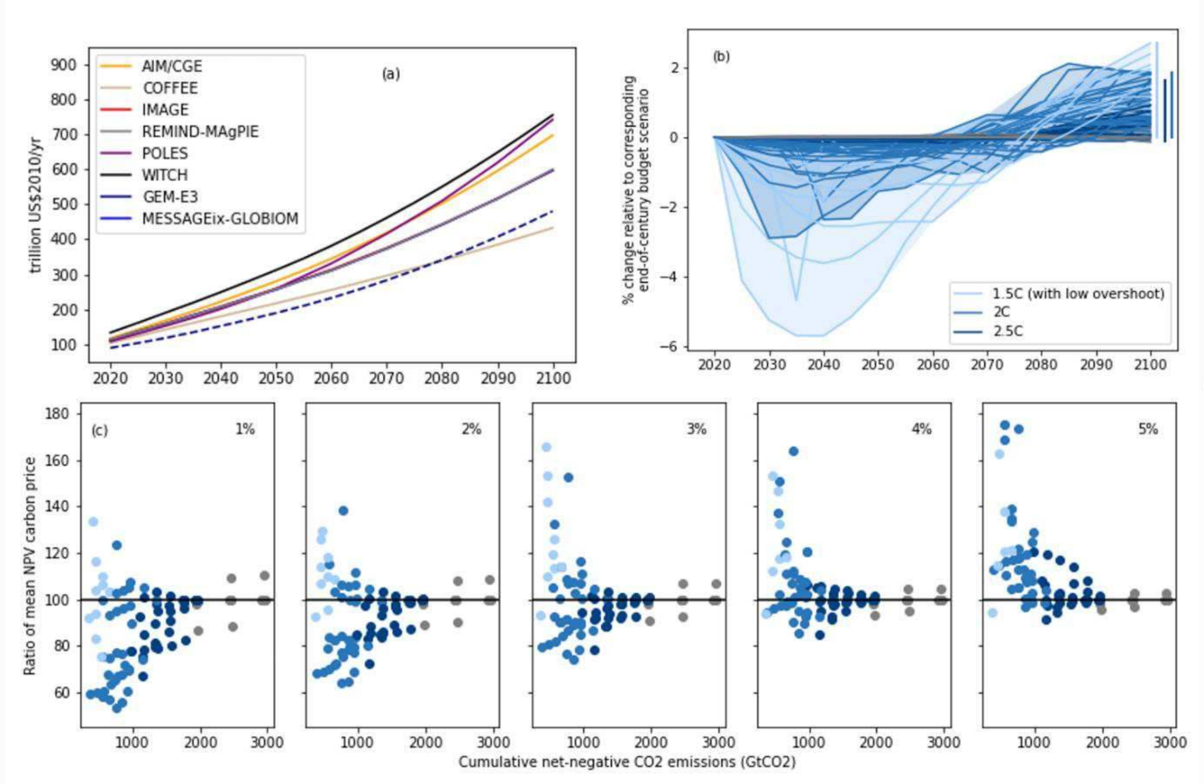

**Figure 2 | Economic implications of scenarios with increased near-term stringency and avoided reliance on net negative CO$_2$ emissions.** Panel a: Development of GDP in baseline scenarios following current national policies (NPi). GDP projections measured in power purchasing parity (straight lines) 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)

## Net Zero CO$_2$ Emissions Systems

A final novel dimension that can be explored through this study is the diversity in net zero CO$_2$ emission systems. Achieving a net zero emissions system globally requires deep emissions cuts across all economic sectors and regions. The distribution of the emissions reductions across space and time depends critically on a number of factors, including 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 $CO_2$ emissions. In a zero $CO_2$ 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 $CO_2$ 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 $GtCO_2$ per year (REMIND-MAgPIE and GEM-E3 models) to more than 10 $GtCO_2$ 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 $CO_2$ 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 $CO_2$ emissions. Globally $CO_2$ 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 $CO_2$ 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 $CO_2$ 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 $CO_2$ 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 $CO_2$ timing could well be set earlier.

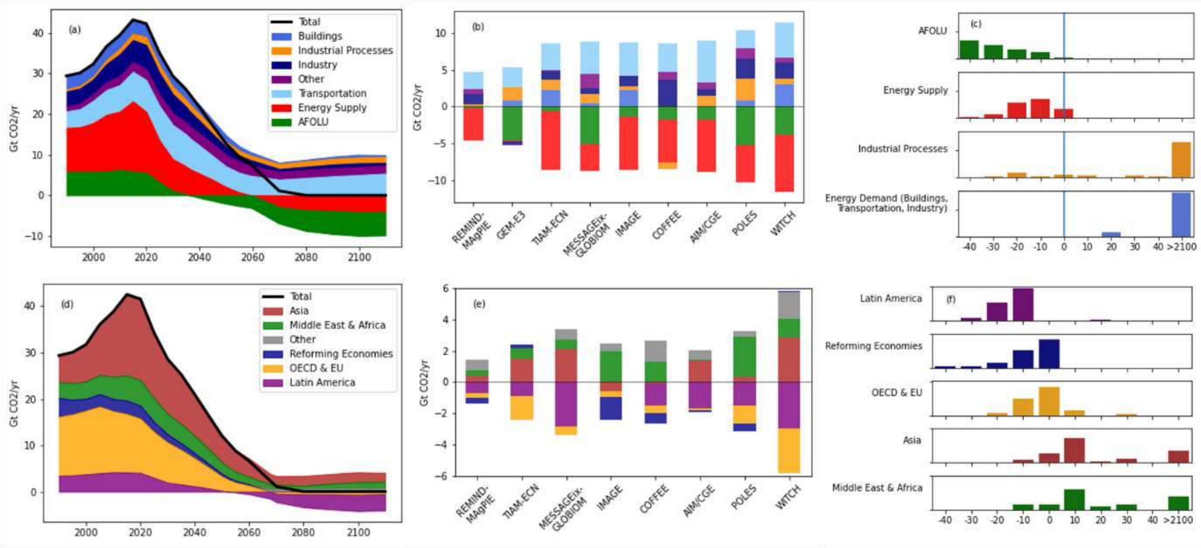

**Figure 3 | Net zero CO$_2$ emissions systems, and the contribution of different sectors (upper panels) and different regions (lower panels).** Left panels (a,d): Development of sectoral/regional sinks and sources over time in an illustrative pathway (MESSAGE$_{ix}$-Globiom model and a net-zero budget of 1000 GtCO$_2$). Middle panels (b,e): Results from different models, showing the contribution of sectors/regions at the time when net zero CO$_2$ 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 CO$_2$ (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 CO$_2$ 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 CO$_2$ 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 CO$_2$ 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 biodiversity[25-28]. 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$/tCO$_2$e. Some models include, in addition, explicit biodiversity protection constraints (MESSAGE$_{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 literature[29]. 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 challenge[30-32] 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 considerations[33]. In fact, we find large differences across regions to reach net zero $CO_2$ 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 China[34], EU[35] Japan[36], and South Korea[37] 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], COFFEE[40], GEM-E3[41,42], IMAGE[43], MESSAGEix-GLOBIOM[44], TIAM-ECN[45], 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 additional 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 $CO_2$ emissions limits of <3000 $GtCO_2$ (2018-2100) in 100 $GtCO_2$

increments (see supplementary information, Table SI-2.1 and SI-2.2). Mitigation of non-$CO_2$ GHGs follow the same equivalent carbon price as for $CO_2$ (driven by the cumulative $CO_2$ emissions budget constraint). For land use, a carbon price ceiling of \$200/t$CO_2$ was applied.

The NPi (baseline) scenario broadly incorporates middle of the road socio-economic conditions based on the second marker baseline scenario from the Shared Socioeconomic Pathways (SSP2)[4]. It also assumes that climate, energy and land use policies that are currently ratified are implemented (cut-off date 1 July 2019). The NDC scenario builds upon the NPi and assumes that the NDCs (both unconditional and conditional NDC actions) as submitted by April 2020 are implemented by 2030. For the NPi and NDC scenarios, a continuation of effort in the long-term was assumed. This was implemented by extrapolating the “equivalent” emissions reductions or carbon price in 2020/2030 (see supplementary information). We have not considered the impact of the COVID-19 pandemic quantitatively, effectively assuming a full recovery without significant effect on long-term, global emissions[52]. The scenarios explored here, however, can inform governments that aim for ‘green’ recovery packages[53], by illustrating the required pace and contribution of key mitigation sectors to reach net-zero $CO_2$ emissions.

GHG emissions here always refer to the gases of the Kyoto basket (that is, $CO_2$, $CH_4$, $N_2O$, HFCs, PFC and $SF_6$, aggregated with 100-year Global Warming Potentials from the IPCC AR5.

Global mean temperature projections were estimated with the probabilistic reduced-complexity carbon-cycle and climate model MAGICC [54,55] in a setup that captures the IPCC AR5 climate sensitivity uncertainty assessment [54,56,57], as used in the IPCC Special Report on Global Warming of 1.5°C[6] (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.

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## Competing interests

The authors declare no competing interests.

## Author contributions

K.R. designed the study; C.B., O.F. and K.R. coordinated the scenario development and data vetting process; D.H. provided the main figures as well as contributed to analysis; and J.R. 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., R.S., M.W., B.vdZ., and Z.V. performed the model runs and developed the scenarios; vetting 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., P.R., G.Ü., B.vR., J.T., M.T., D.vV., and B.Z.; K.R. prepared the first draft and all authors contributed to writing the paper.

## Additional information

Supplementary information is available for this paper.

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

# Figures

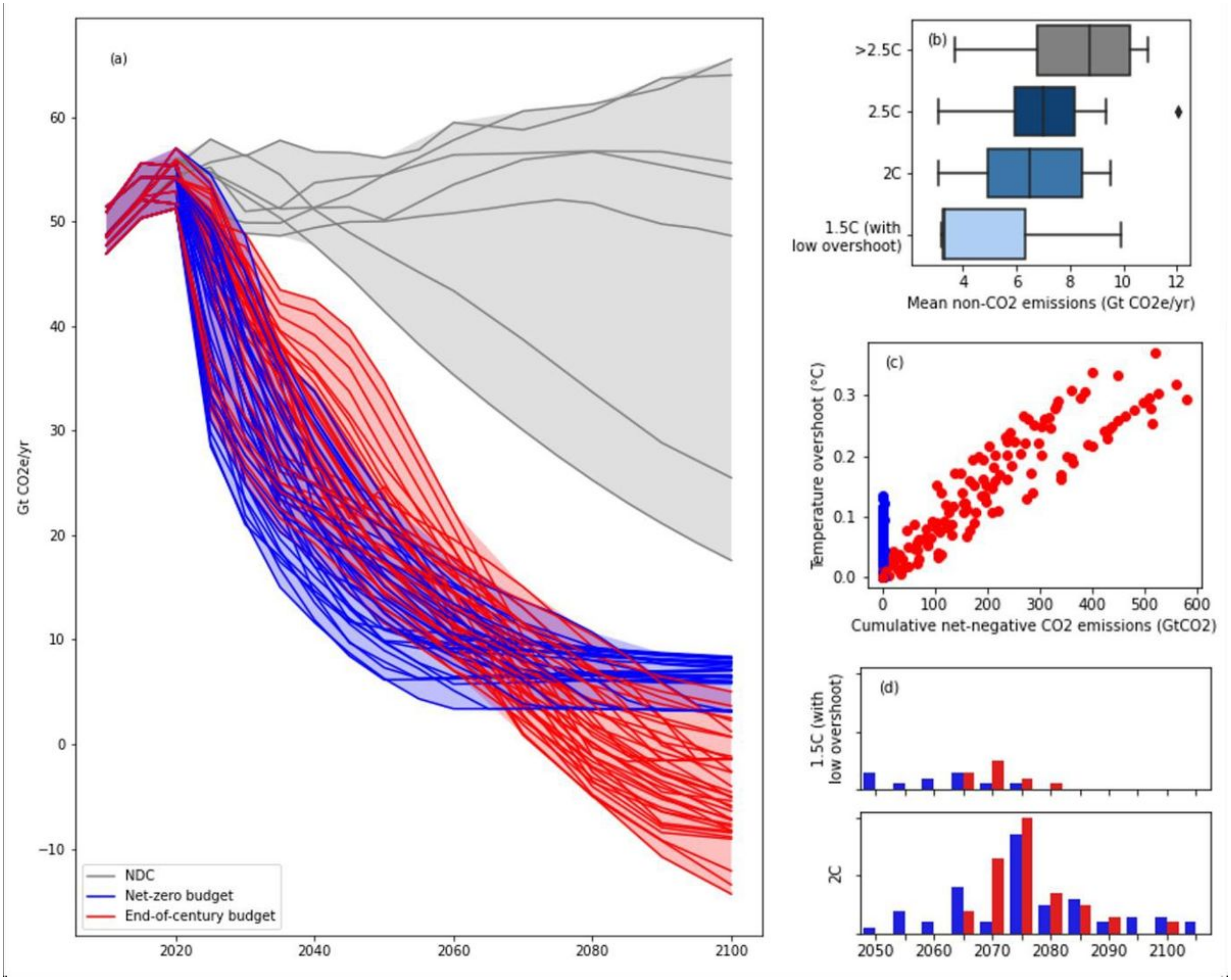

**Figure 1**

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).

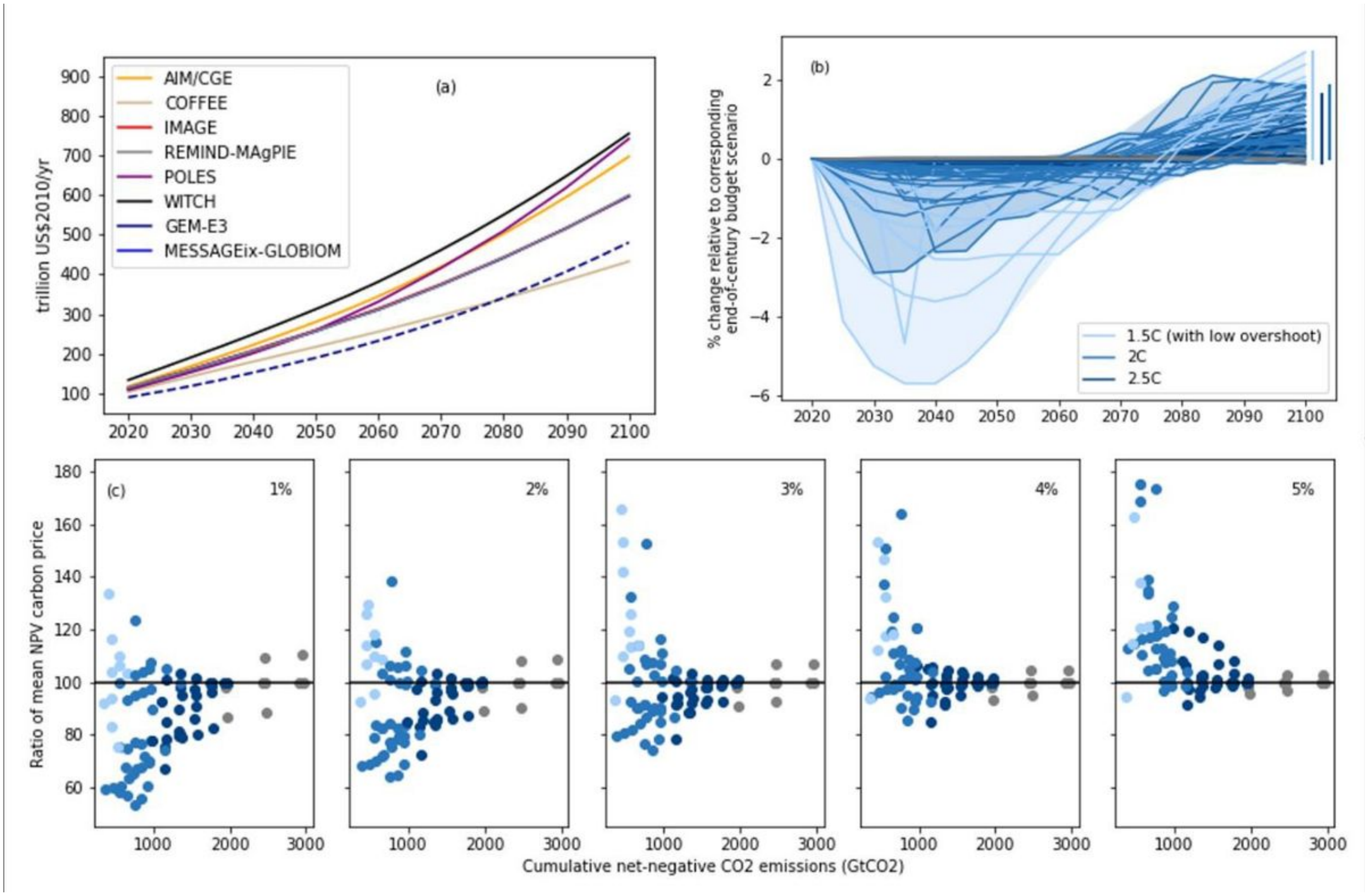

**Figure 2**

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)

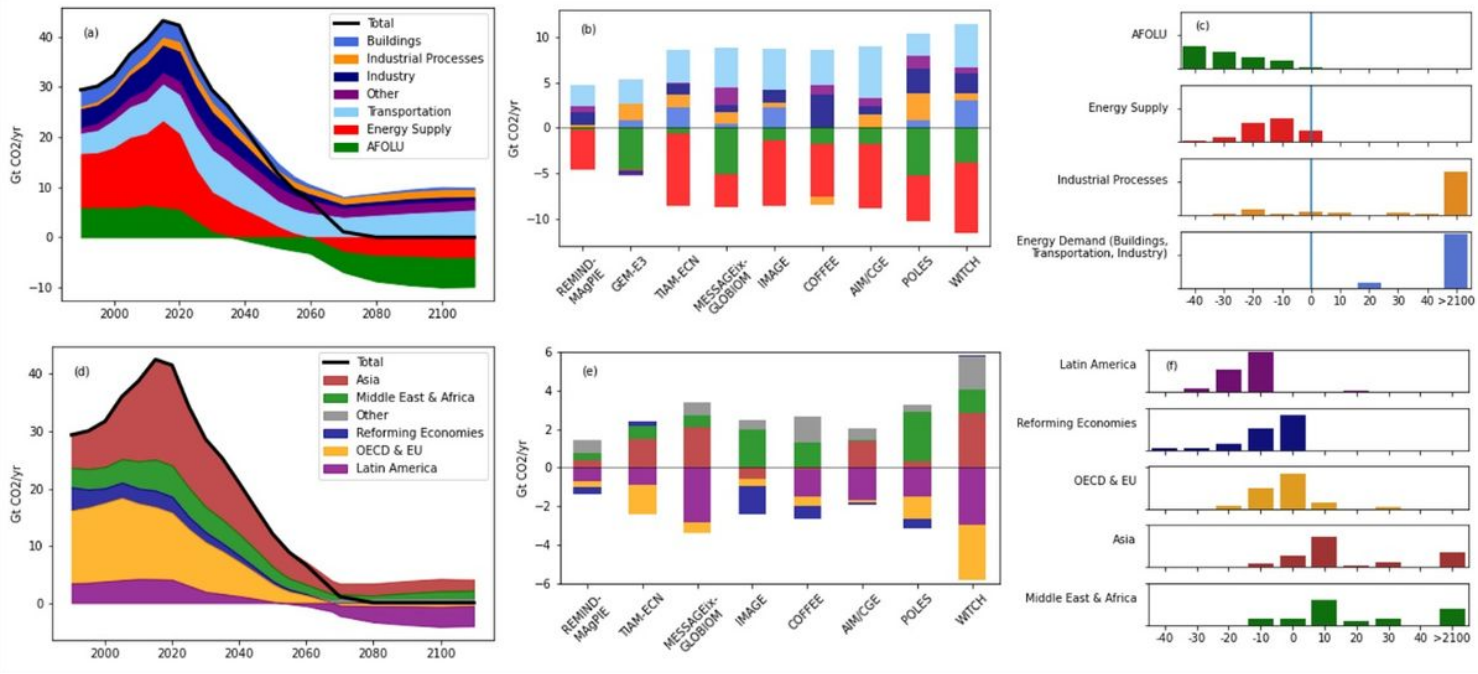

**Figure 3**

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

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterialNNNCEver2.pdf