Cost and attainability of meeting stringent climate targets without overshoot

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Global emissions scenarios play a critical role in the assessment of strategies to mitigate climate change. The current scenarios, however, are criticized because they feature strategies with pronounced overshoot of the global temperature goal, requiring a long-term repair phase to draw temperatures down again through net negative emissions. Some impacts might not be reversible. Hence, we explore a new set of net-zero CO_2 emissions scenarios with limited overshoot. We show that upfront investments are needed in near term for limiting temperature overshoot, but that these would bring long-term economic gains. Our study further identifies alternative configurations of net-zero CO_2 emissions systems and the roles of different sectors and regions for balancing sources and sinks. Even without net-negative emissions, carbon dioxide and removal (CDR) is important for accelerating near-term reductions and for providing an anthropogenic sink that can offset the residual emissions in sectors that are hard to abate.

The 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 (AR5)[5] and its Special Report on Global Warming of 1.5°C (SR1.5)[6]. Studies explore aspects of the timing and costs of emissions reductions and the contribution of different sectors[3,7,8]. However, there has been critique that, with the exception of a few notable studies[9-12], the scenarios in the literature first exceed the prescribed temperature limits in the hope to recover from this overshoot later through net negative emissions[13-16]. Some pioneering studies[12,10] have explored implications of limiting overshoot and zero emissions goals, or have looked into the role of BECCS in reaching different temperature targets[9]. All these studies have relied on one or two models and/or a limited set of temperature targets.

We bring together nine international modelling teams and conduct the first comprehensive modelling inter-comparison project (MIP) on this topic. Specifically, we explore mitigation pathways for reaching different temperature change targets with limited overshoot. We do this by adopting the scenario design from ref.[11] and contrast scenarios with a fixed remaining carbon budget until the time when net zero CO_2 emissions (net-zero-budget scenarios) are reached with scenarios that use an end-of-century budget design. The latter carbon budget for the full century permits the budget to be temporarily overspent, as long as net negative CO_2 emissions (NNCE) bring back cumulative CO_2 emissions to within the budget by 2100. This approach dominates the current literature and leads to a temporary overshoot of the associated temperature target. Importantly, the earlier introduced 'net-zero-budget scenarios' limit cumulative CO_2 to a maximum without exceeding the emissions budget. These scenarios thus keep global warming below a certain threshold (without exceeding it) and stabilize the temperature thereafter.

The new pathways fill important knowledge gaps. First, they cover the range of carbon budgets consistent with low stabilization targets in a systematic way and across a wide range of diverse global models. The pathways thus explore important uncertainties, including the attainable scenario space across different models and target definitions. This information is critical for international assessments, such as those by the IPCC[17]. Secondly, we explore the impacts of the country pledges from the post-Paris process for the attainability of overshoot and non-overshoot targets. Thirdly, we investigate salient temporal trade-offs with respect to mitigation costs; and finally we explore distinct differences in terms of the possible regional and global designs of net-zero CO_2 emissions systems. The main narratives of the pathways and assumptions are provided in Table 1.

Implications for emissions pathways

Reaching stringent temperature targets with limited overshoot, requires a pronounced acceleration of the near-term transformation towards net-zero CO_2 emissions. Staying within a budget of 500 $GtCO_2$ (consistent with a median warming of 1.44-1.63°C), for example, requires CO_2 emissions to reach net-zero between 2045 and 2065 (range across models). When an 'end-of-century' carbon budget is employed, the time of reaching net zero CO_2 emissions is delayed between 5 to 15 years (to 2060-2070). This delay, combined with the higher emissions over that period, results in 0.08-0.16°C higher peak temperatures compared to scenarios that are identical in all but their allowance to overshoot the carbon budget.

A broad set of behavioral, biophysical, economic, geophysical, legal, political and technological factors render transformations to net zero more or less challenging[18]. The modelling exercise here informs primarily challenges related to economic, geophysical and technological feasibility. The lowest attainable net-zero CO_2 emissions budget (limiting overshoot) is 400 to 800 $GtCO_2$ across the models (assuming immediate implementation of ambitious policies and a middle-of-the road socioeconomic development[19]). This budget range corresponds to a median peak warming during the 21st century between 1.42 and 1.72°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 (see Methodology) will lead to GHG emissions of 46.8-56.3 $GtCO_2e$ by 2030, which is significantly higher than the range of cost-effective emissions pathways consistent with 2°C (25-48.6 $GtCO_2e$), let alone 1.5°C, by 2030 (19.4-35.3 $GtCO_2e$). We adopt the definition of 1.5°C and 2°C goals from the SR1.5 (see Methodology). Assuming NDCs are not tightened and comprehensive climate policies are thus delayed until after 2030, the lowest attainable net-zero CO_2 budget across the models is 500–1200 $GtCO_2$, which corresponds to a warming of 1.61 and 1.89°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 pathways feature net negative emissions from a few megatons to about 500 $GtCO_2$ across models, depicting a techno-economic potential for declining warming after its peak between 0.13 to 0.34˚C by 2100 (Figure 1b). This temperature reversal is mainly driven by NNCE but can also be partially the result of reductions in non-CO_2 forcers[20] (see Methodology and Supplementary Figures 1.1-5,6,9,10 for the relationship between peak temperature, overshoot and NNCE).

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 annual 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[21] or the climate neutrality target of the EU[22], NNCE are needed in order to balance residual non-CO_2 emissions and reach net-zero greenhouse gas emissions.[16]

Upfront costs and long-term economic benefits

The IPCC AR5 emphasizes that mitigation costs would rise over time as a result of efforts to limit climate change[5]. These mitigation costs traditionally reflect the impacts on 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[4,5,11,23]. This evolution is primarily a result of most IAM studies focusing on targets for the end of the century, which, by design, favors postponement of mitigation action until later in the century[11,24].

Scenarios that limit temperature overshoot (i.e., the net-zero-budget scenarios), pace mitigation actions differently, requiring significantly more rapid emissions reductions in the near term (see Figure 1 and Supplementary Figure 1.1-8). Avoiding overshoot is thus associated with higher upfront investments and higher near-term mitigation costs. We find that GDP in the near term is 0.5 to 4.8 % lower in scenarios that keep warming below 1.5°C with no or limited overshoot and 0.1 to about 1.6% lower in scenarios that limit warming to 2°C with no or limited overshoot (compared to end-of-century budget scenarios with overshoot).

Once net zero CO_2 emissions are reached, however, the mitigation effort in the net-zero-budget scenarios with limited overshoot can be relaxed, since no further emissions reductions are necessary. This results in a slow-down or even decline of carbon prices while keeping CO_2 emissions constant at net zero (see Supplementary Figure 1.1-6). During this phase (in the latter half of the century) the economy accelerates since lower mitigation expenditures are required and GDP growth is becoming higher in the net-zero-budget scenarios with no or limited overshoot (compared to the end-of-century-budget scenarios).

Perhaps most importantly, we find that this GDP rebound in the long term to be by far larger than the upfront dampening effects on GDP due to efforts to limit temperature overshoot. In other words, the higher near-term GDP losses of limiting overshoot are fully compensated by higher GDP growth in the second half of the century (Figure 2a). The absolute GDP levels in the long term (2100) are thus higher across all models and mitigation scenarios that limit the overshoot (Figure 2a), which is consistent with the reduced stringency of the target at the end of the time horizon. This observation holds also on the regional level with relatively higher losses in the near term in fossil fuel exporting regions (see Supplementary Figure 1.1-12). For a 1.5˚C and 2˚C target, the long-term GDP (2100) is about 1.2% higher (range 0.1% to 2.4%) in scenarios that limit overshoot. Similarly, the peak carbon prices over the course of the century – a relevant indicator measuring policy stringency and disruptiveness[25,26] – is significantly lower in most scenarios without overshoot (see Supplementary Figure 1.1-6 and 1.1.-7). The difference between net-zero-budget and end-of-century budget becomes smaller at weaker temperature targets and diminishes fully at high budgets where CO_2 emissions do not need to become net zero over the course of the century (depending on the model this corresponds to a budget of 1000 to 2500 $GtCO_2$).

Across all IAMs we find that accelerating the transformation towards net zero CO_2 emissions would have benefits for the long-term GDP, even without considering the benefits of avoided impacts that are traditionally not included in the type of scenario analysis presented here.

From a methodological perspective, it is important to emphasize that our results are not suggesting that avoiding overshoot is leading to lower “overall” cumulative mitigation costs over the entire century. The perceived overall cumulative cost of each pathway depends critically on the discount rate and how one weights the near-term GDP losses against the long-term GDP gains[24]. To explore the impact of the discount rate on the overall cumulative costs we conduct an ex-post sensitivity analysis, systematically varying the discount rate between 0% to 5% (and apply them to the existing cost pathways of the scenarios). We find that discount rates of less than about 2% would make the perceived cumulative costs of the majority of 1.5˚C and 2˚C scenarios overall less costly without overshoot (see Figure 2c for the cumulative GDP losses and Supplementary Figure 1.1-13 for the net present value of the carbon price). Assuming higher discount rates on the other hand would favor more delayed mitigation with overshoot. Perhaps most importantly, irrespective of the discount rate, we find long-term GDP in 2100 to be higher in scenarios with limited or no overshoot (see also Section 1.2 of the Supplementary Information for a discount-rate sensitivity analysis).

Another important cost factor are the NDCs. Their modest mitigation effort in the near term leads to relatively reduced costs in 2030 (Figure 2b). Importantly, however, the NDCs have negative economic effects 2040 and beyond, where the acceleration of the mitigation effort for limiting temperature to 2˚C would result in GDP losses for the entire century (Figure 2b).

Net Zero CO_2 Emissions Systems

Our study explores a range of diverse net zero CO_2 emission systems. The distribution of the emissions reductions across sectors, 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 to act as sources of residual emissions, which are balanced by sinks in other sectors/regions that remove CO_2 from the atmosphere 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 - see also sensitivity analysis in Section 1.6 of the Supplementary information), are responsible for the bulk of the gross negative emissions in the scenarios. Their contributions vary markedly 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 addressing the residual emissions in these demand sectors, which in turn would lower the pressure on supply-side transformations, including the need to enhance the anthropogenic sink. 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 across all demand sectors.

The sectors differ significantly with respect to the timing of when they achieve net zero CO_2 emissions. Globally CO_2 emissions reach net zero around 2050-2075 and 2055-2100 in 1.5˚C pathways with low overshoot and 2˚C pathways, respectively (Figure 1d and Supplementary Figure 1.1-4). However, in most scenarios, the AFOLU sector is fully decarbonized more than 10-40 years earlier, and the energy supply sector often 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). Across demand sectors, limiting demand through improved efficiency and behavioral change, as well as rapid electrification play an important role. Avoiding non-CO_2 emissions is critical in the agricultural sector where significant reductions of N_2O and CH_4 emissions are achieved. CDR plays three significant roles in all scenarios (also in scenarios that avoid net negative CO_2 emissions): 1) helping to accelerate emissions reductions early in the century, 2) offsetting residual emissions to achieve net zero CO_2, and 3) achieving net negative emissions in the long term to reduce warming after the peak (if necessary). See also Section 1.3 on the role of CDR in the Supplementary Information.

Also, the timing of when different regions reach net zero CO_2 emissions varies significantly (Figure 3c). Regions with a larger 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 (see also Supplementary Figures 1.1-14 to 1.1-16). 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.

Discussion

We have shown that scenarios with an accelerated transition towards net zero emissions avoid a systematic (discounting) bias in favor of temperature overshoot. Furthermore, we identify sectors and regions that may provide an entry point for rapid and deep cuts towards zero CO_2 emissions and illustrate that avoiding overshoot would be associated with economic gains in the long-term (even without considering benefits of avoided climate impacts). Our study uses a net-zero carbon budget design which is a close proxy for peak warming. Other scenario designs, e.g., limiting global temperature directly or using different metrics for the temperature equivalence, are possible as well [10,12] and would affect the substitution dynamics of different greenhouse gases.

Net-zero CO_2 emissions systems imply the deployment of CDR measures with very different implications for the sustainability of the overall mitigation portfolio. BECCS may lead to possible trade-offs with sustainable development, depending on the scale of deployment, implementation practice, and local context[18,27,28]. The CDR portfolio thus varies across models, providing policy flexibility with respect to technology choices. Some pathways rely on BECCS (e.g., REMIND-MAgPIE), while other pathways rely more heavily on nature-based solutions or use more balanced approach across these options (WITCH, POLES, MESSAGE_{ix}-GLOBIOM. The IAMs do not include all possible CDR options[29]. CDR can serve three purposes in mitigation pathways: it can help to accelerate early emissions reductions, and thus supporting to achieve net zero CO_2 emissions as soon as possible; it can offset residual emissions from sectors that might be difficult to decarbonize completely; and it can provide a long-term risk-hedging strategy to generate net negative emissions and gradually reverse warming if desired. In all three instances, deep reductions in gross CO_2 emissions remain crucial.

The importance of demand-side measures cannot be overemphasized[30-32]. Generally, efficiency, behavioral change, and the deployment of granular and small-scale technologies is enabling rapid technology diffusion and substitution processes[33-35]. In addition, demand-side mitigation is key for reducing residual emissions. Bottlenecks include particularly the industry sector's demand for carbonaceous fuels and the transport sector, as well as the materials and consumption goods sectors. Particularly, material substitution and options for demand-side electrification need to be represented in a more bottom-up and granular fashion in the models.

The regional scenario results indicate opportunities for mitigation, and do not imply political feasibility, which would need to consider a diverse set of ethical and other considerations[36]. 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, because it requires international collaboration and markets for cross-regional policy frameworks. In this context, it is encouraging to observe that net zero emissions targets in a number of key countries, like China[37], EU,[38] Japan[39], and South Korea[40] are broadly consistent with the pace of the transformation as depicted by our study.

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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.

Competing interests

The authors declare no competing interests.

Tables

Scenario name *[# of scenarios]*	***Narrative***	***Near-term policy assumptions, 2020-2030***	***Long-term climate policy assumptions***	***2030 GHG emissions range ($GtCO_2e$)***	***Range of cumulative CO_2 emissions (2020-2100, $GtCO_2$)****
NPi *[8]*	*GHG emissions follow currently implemented national policies (NPi). No additional new policies assumed in the future.*	*No additional policies compared to today*	*No additional policies compared to those implemented today*	*54.1-65*	*3552-4645*
NDC *[8]*	*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)*	*46.8-56.3*	*2162-3872*
End-of-century budget *[a. 101, b.84]*	*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 temperature overshoot and 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: 24.3-58.3* *(b) Near-term emissions depend on NDC implementation (see above)*	*Attainable range depends on near term policy assumptions:* *(a) NPi: 200-3000 $GtCO_2$* *(b) NDC: 300-3000 $GtCO_2$*
Net-zero-budget *[a. 88, b. 62]*	*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 limit the temperature overshoot and do not rely on global net-negative CO_2 emissions to keep warming below the intended temperature limit.*	*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 until net zero CO_2 emissions are reached. No net negative CO_2 emissions (NNCE) are thus required for warming to be limited to the intended maximum level. Non-CO_2 emissions assumptions are the same as in the end-of-century budget scenarios (see above).*	*(a) NPi: 19.3-58.4* *(b) Near-term emissions depend on NDC implementation (see above)*	*Attainable range depends on near term policy assumptions:* *(a) NPi: 400-3000 $GtCO_2$* *(b) NDC: 500-3000 $GtCO_2$*

Table 1 | Scenario narratives and the corresponding range of attainable 2030 CO_2 emissions and the attainable carbon budgets (2020-2100).

* Numbers represent the attainable scenario space by the models (Supplementary Table 2.1-1 and 2.1-2). The radiative forcing, temperature change, and emissions ranges are shown in Supplementary Figures 1.1-1 to 1.1-3.

Figure legends

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 with limited overshoot (net-zero-budget scenarios, blue), and mitigation scenarios with the same long-term carbon budget with temperature overshoot (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. The box shows the quartiles of the dataset while the whiskers extend to show the rest of the distribution. Panel c: Relationship between cumulative net negative CO_2 emissions and resulting temperature drawdown after peak temperature (i.e., overshoot). Net-zero scenarios (red) and end-of-century scenarios (blue). 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). The height of the bars indicates the number of scenarios that reach net zero at the specific year.

Figure 2 | Economic implications of scenarios with increased near-term stringency and limited temperature overshoot. Panel a: Development of GDP in mitigation scenarios with limited overshoot and no NNCE relative to scenarios with overshoot and NNCE in the second half of the century. In the near-term the GDP of net-zero-budget scenarios is relatively lower, but this is compensated in the second half of the century where GDP in net-zero-budget scenarios grows bigger. Panel b: Development of GDP in immediate-action scenarios relative to scenarios with an equivalent carbon budget which follow NDC pathways until 2030. In the near-term the GDP of NDC scenarios is higher because mitigation action is delayed, but this is compensated by 2040 when GDP in the NDC scenario falls below the immediate action scenarios (and never catches up). Panel c: The ratio of cumulative GDP loss (net present value, 2020-2100) assuming different discount rates (0-5%). The discount rates are applied exogenously to the GDP pathway of each scenario. The perceived overall costs of each scenario (cumulative GDP loss from mitigation policy) differ for each discount rate reflecting the different weights of costs over time. The panel shows the NPV price ratio between net-zero-budget scenarios with limited overshoot and their corresponding end-of-century carbon budget scenarios (ratio <100 means that scenarios with limited overshoot are perceived to be overall less costly under the specific assumptions). Each dot represents the ratio for a pair of scenarios with a specific carbon budget (x-axis). See Supplementary Figure 1.1-13 showing the same ratios for the NPV of the carbon price. The development of the GDP in the baseline scenarios is shown in Supplementary Figure 1.1-11.

Figure 3 | Net zero CO_2 emissions systems, and the contribution of different sectors and regions in cost-effective scenarios. 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 or regions, respectively at the time when net zero CO_2 emissions are reached (REMIND-MagPie is not shown since for a carbon budget of 1000 GtC_2 it does not reach net-zero CO_2 emissions). 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 histograms include all pathways that limit temperature to <2˚C.

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Methodology

The nine integrated assessment model (IAM) frameworks, drawn upon in this study include AIM-Hub[41,42], COFFEE[43], GEM-E3[44,45], IMAGE[46], MESSAGEix-GLOBIOM[47], TIAM-ECN[48], POLES[49], REMIND-MAgPIE[50,51] and WITCH-GLOBIOM[52,53]. 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. All models, however, represent land-based negative emissions options related to either bioenergy production and/or re-forestation. Some of the models consider in addition the possibility of negative emissions through feedstocks in industrial products (GCAM, COPPE), and three models (POLES, WITCH and REMIND-MAgPIE) in addition also considers direct air capture (DAC). Cost assumptions of different technological CDR options are summarized in Section 1.4 of the Supplementary Information and a sensitivity analysis on BECCS is provided in Section 1.6 of the Supplementary information. In terms of macroeconomic representation, our study considers a number of general equilibrium models where price-induced effects on GDP and productivity is computed (e.g., GEM-E3, REMIND-MAgPIE, MESSAGE-MACRO, AIM-Hub). These models assume an exogenous reference path for GDP as the basis from which price-induced and path-dependent GDP losses are calculated. The models account for the macroeconomic path-dependency in terms of shifts in capital stocks, investments, saving, and consumption patterns.

A common scenario design and modelling protocol was implemented by all models (see Supplementary Information Section 2 on modelling protocol). 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 Tables 2.1-1 and 2.2-2). We thus assess the lowest attainable budget for each model. In scenarios with no net negative CO_2 emissions, sources and sinks across sectors and regions may balance each other out, but total CO_2 emissions are not allowed to become net negative. Mitigation of non-CO_2 GHGs follows the same equivalent carbon price as for CO_2 (driven by the cumulative CO_2 emissions budget constraint). GHG mitigation on the land sector will hinge upon appropriate policy designs that avoid competition over land for food or other basic ecosystem services, water resources and/or biodiversity[54-57]. 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_2e$. Some models include, in addition, explicit biodiversity protection constraints ($MESSAGE_{ix}$-GLOBIOM). Peak and decline of temperature due the reduction of non-CO_2 emissions is between 0°C–0.14°C across the models by 2100 (see blue dots in Figure 1b). In contrast to the CO2-induced temperature overshoot, the effect of non-CO2 on overshoot is relatively limited.

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. In addition, we have explored a sensitivity analysis with an update of the NDCs for big emitting countries as submitted in December 2020 (China, EU, Brazil) and find that the implications for the emissions and the long-term results to be very small (see Supplementary Information, Section 1.5 for a sensitivity analysis). 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, Section 2.2 on NPi and NDC extrapolation methods). We have not considered the impact of the COVID-19 pandemic in a comprehensive way, effectively assuming a full recovery without significant effect on long-term, global emissions[58]. Sensitivity analysis based on selected scenarios indicate only a small impact on mitigation. The scenarios explored here, however, can inform governments that aim for ‘green’ recovery packages[59], by illustrating the required pace and contribution of key mitigation sectors to reach net-zero CO_2 emissions.

The wide range of mitigation costs reflect parametric and structural differences across the models and their resulting marginal abatement cost (MAC) curves. A classification of the models with respect to abatement costs is provided in ref.[60] . Note that the marginal abatement costs increase rapidly when approaching the (model-specific) attainability frontier, and thus reported carbon prices increase significantly (>>1000 US$/t$CO_2$).

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.

The GHG emissions resulting from the different scenarios by the IAM models were fed into the probabilistic reduced-complexity carbon-cycle and climate model MAGICC for the estimation of global mean temperature projections consistent with the scenarios. MAGICC[61,62] is used in a setup that captures the IPCC AR5 climate sensitivity uncertainty assessment[61,63,64], 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. Through this methodology we assess the resulting global warming of different pathways, and the corresponding peak warming that is associated with the cumulative emissions (budgets) of the scenarios.

Data Availability

The underlying data is available at ref.[65].

All scenarios are made accessible online also via the ENGAGE Scenario Portal: https://data.ece.iiasa.ac.at/engage

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 Section 3 of the Supplementary Information.

A GitHub repository for the source code of the figures is available here:
https://github.com/iiasa/ENGAGE-netzero-analysis

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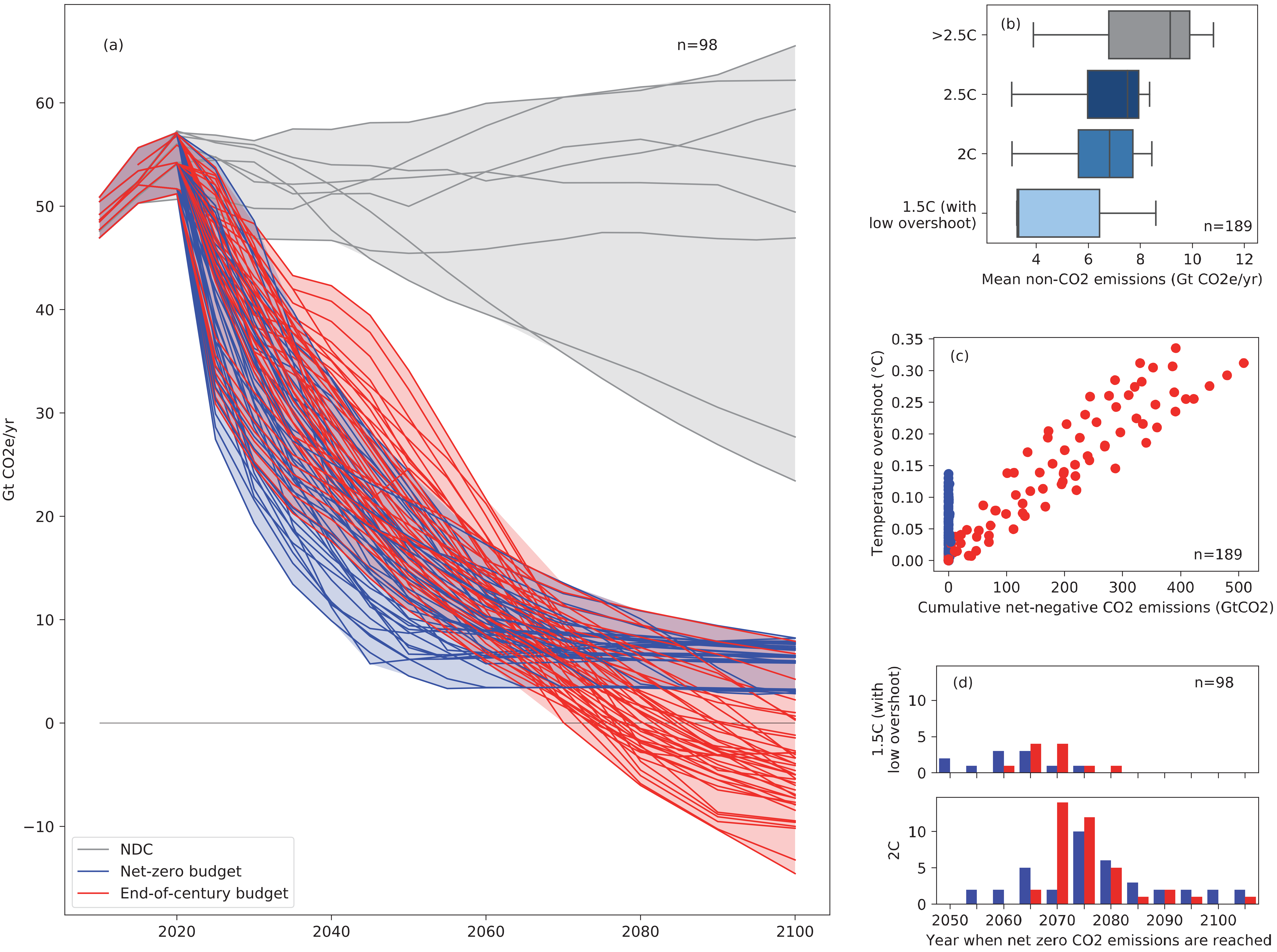
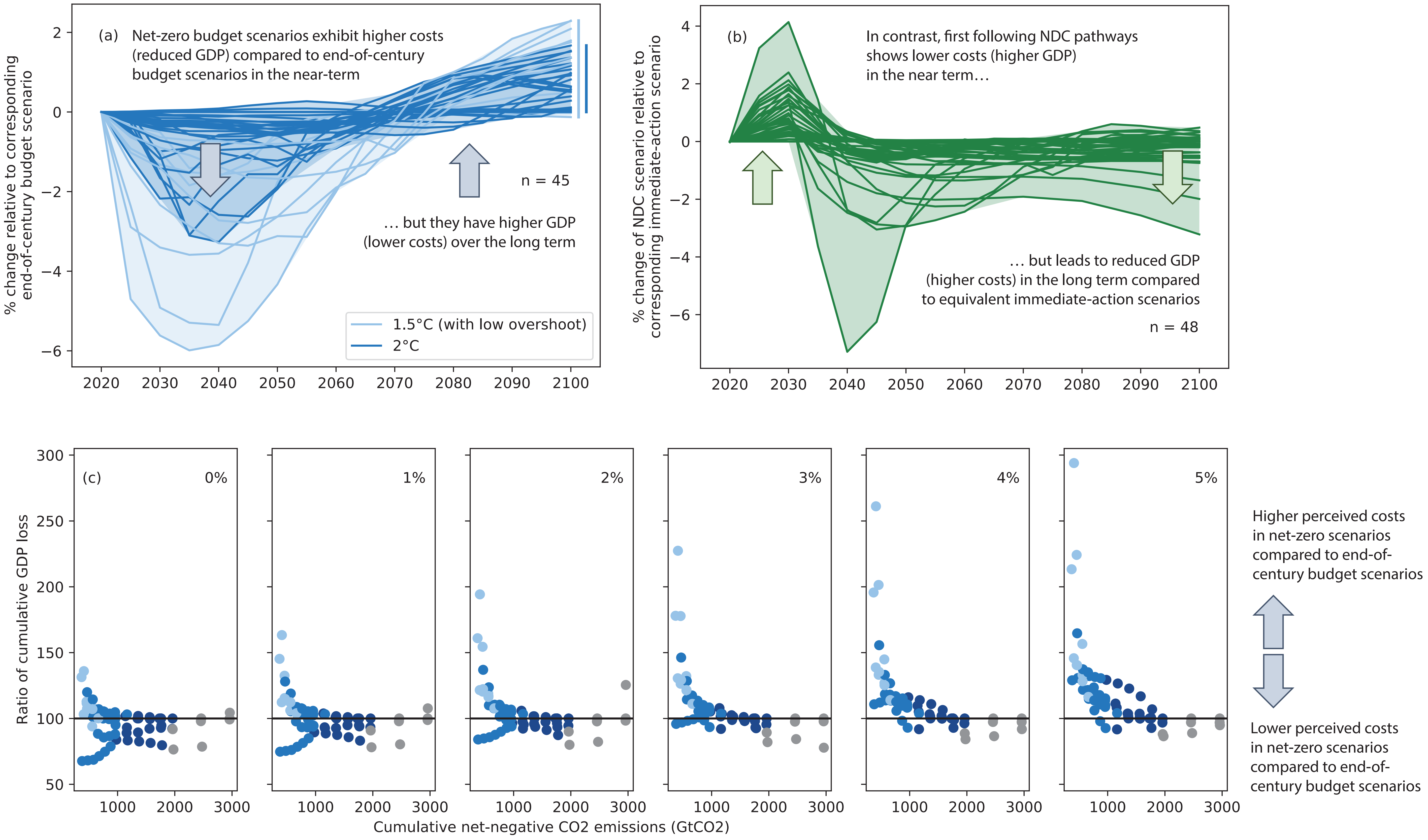
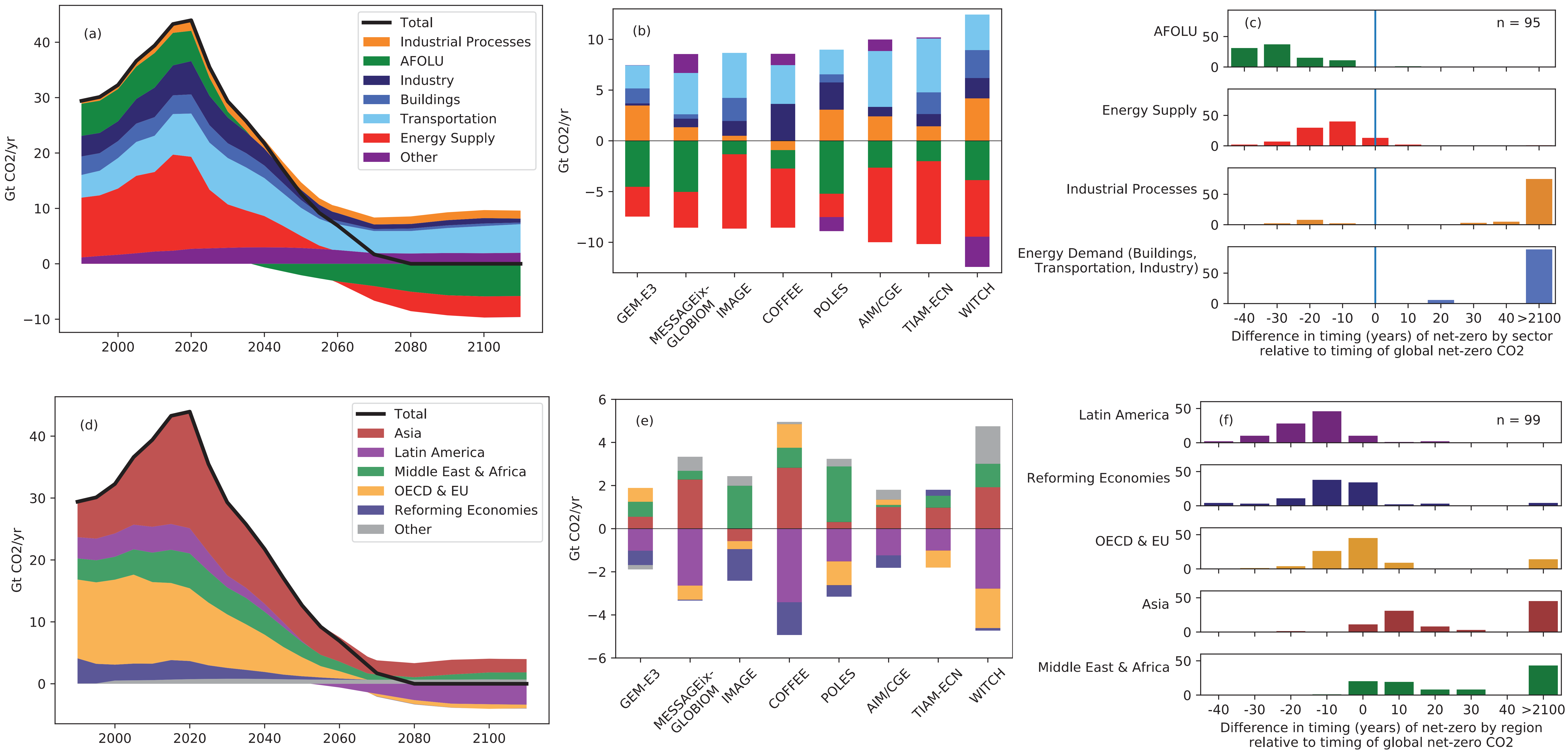

(a)
n=98
Gt CO2e/yr
60
50
40
30
20
10
0
−10
2020
2040
2060
2080
2100
NDC
Net-zero budget
End-of-century budget
(b)
>2.5C
2.5C
2C
1.5C (with low overshoot)
n=189
4
6
8
10
12
Mean non-CO2 emissions (Gt CO2e/yr)
(c)
Temperature overshoot (°C)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
n=189
0
100
200
300
400
500
Cumulative net-negative CO2 emissions (GtCO2)
(d)
n=98
1.5C (with low overshoot)
10
5
0
2C
10
5
0
2050
2060
2070
2080
2090
2100
Year when net zero CO2 emissions are reached


(a) Net-zero budget scenarios exhibit higher costs (reduced GDP) compared to end-of-century budget scenarios in the near-term
… but they have higher GDP (lower costs) over the long term
n = 45
1.5°C (with low overshoot)
2°C
% change relative to corresponding end-of-century budget scenario
2
0
−2
−4
−6
2020
2030
2040
2050
2060
2070
2080
2090
2100
(b) In contrast, first following NDC pathways shows lower costs (higher GDP) in the near term…
… but leads to reduced GDP (higher costs) in the long term compared to equivalent immediate-action scenarios
n = 48
% change of NDC scenario relative to corresponding immediate-action scenario
4
2
0
−2
−4
−6
(c)
0%
1%
2%
3%
4%
5%
Ratio of cumulative GDP loss
300
250
200
150
100
50
1000
2000
3000
Cumulative net-negative CO2 emissions (GtCO2)
Higher perceived costs in net-zero scenarios compared to end-of-century budget scenarios
Lower perceived costs in net-zero scenarios compared to end-of-century budget scenarios


(a)
Total
Industrial Processes
AFOLU
Industry
Buildings
Transportation
Energy Supply
Other
Gt CO2/yr
40
30
20
10
0
−10
2000
2020
2040
2060
2080
2100
(b)
Gt CO2/yr
10
5
0
−5
−10
GEM-E3
MESSAGEix-GLOBIOM
IMAGE
COFFEE
POLES
AIM/CGE
TIAM-ECN
WITCH
(c)
n = 95
AFOLU
Energy Supply
Industrial Processes
Energy Demand (Buildings, Transportation, Industry)
50
0
-40
-30
-20
-10
0
10
20
30
40
>2100
Difference in timing (years) of net-zero by sector relative to timing of global net-zero CO2
(d)
Total
Asia
Latin America
Middle East & Africa
OECD & EU
Reforming Economies
Other
Gt CO2/yr
40
30
20
10
0
2000
2020
2040
2060
2080
2100
(e)
Gt CO2/yr
6
4
2
0
−2
−4
−6
GEM-E3
MESSAGEix-GLOBIOM
IMAGE
COFFEE
POLES
AIM/CGE
TIAM-ECN
WITCH
(f)
n = 99
Latin America
Reforming Economies
OECD & EU
Asia
Middle East & Africa
50
0
-40
-30
-20
-10
0
10
20
30
40
>2100
Difference in timing (years) of net-zero by region relative to timing of global net-zero CO2