Mitigation implications of midcentury targets that preserve long-term climate policy options

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Midcentury targets have been proposed as a guide to climate change policy that can link long-term goals to shorter-term actions. However no explicit mitigation analyses have been carried out of the relationship between midcentury conditions and longer-term outcomes. Here we use an integrated assessment modeling framework with a detailed representation of the energy sector to examine the dependence of climate change outcomes in 2100 on emissions levels, atmospheric concentrations, and technology characteristics in 2050. We find that midcentury conditions are crucial determinants of longer-term climate outcomes, and we identify feasibility thresholds describing conditions that must be met by midcentury to keep particular long-term options open. For example, to preserve the technical feasibility of a 50% likelihood of keeping global average temperature at <2 °C above preindustrial in 2100, global emissions must be reduced by about 20% below 2000 levels by 2050. Results are sensitive to several assumptions, including the nature of future socio-economic development. In a scenario with high demand for energy and land, being below 2 °C with 50% likelihood requires a 50% reduction in emissions below 2000 levels by 2050, which is only barely feasible with known technologies in that scenario. Results suggest that a greater focus on midcentury targets could facilitate the development of policies that preserve potentially desirable long-term options.

climate change | integrated assessment | emission target | mitigation

The ultimate goal of international climate change policy as stated in Article 2 of the Framework Convention on Climate Change is to "avoid dangerous anthropogenic interference with the climate system." This goal has motivated a wide array of analyses of potentially dangerous climate change impacts and of mitigation strategies that might limit greenhouse gas concentrations or global average temperature increases. Political attention has increasingly focused on limiting warming to 2° C, reflected most recently in the acknowledgment by the Copenhagen Accord (1) of the scientific basis for such a limit. However a firm international agreement on a long-term climate policy target has yet to be achieved. At the same time, growing emissions of greenhouse gases continue to increase the amount of climate change to which we are committed (2). Over the next few decades, these growing emissions may make some potentially desirable long-term goals unattainable (3).

Interim climate policy targets for the midcentury have been proposed as a guide to designing policies affecting emissions over the next several decades. Rationales for interim targets include preserving a range of options for the eventual choice of long-term goal (4), providing more guidance to policy decisions on emissions paths over the next few decades than long-term goals alone would provide (5), and providing clearer policy signals to decision-makers with multidecade planning horizons.

Policy proposals that include midcentury goals have already begun to appear. The G8 has advocated a goal of reducing global emissions by at least 50% by 2050 (6). Several business communities (7, 8) as well as governments have suggested or adopted emissions targets for 2050, including Germany, Australia, the UK, and the state of California. The European Commission has stated that reductions of global greenhouse gases of up to 50% below 1990 levels by 2050 would be consistent with the EU position that long-term warming should be limited to 2 °C above preindustrial (9), and legislative proposals in the US would imply reducing US emissions to 15–80% below 2000 levels by 2050 (10).

In the scientific literature, the importance of midcentury conditions has also been recognized, regarding emissions (11–15), radiative forcing (16), technology (17, 18), or the climate consequences of idealized emissions paths (19). Working Group 3 of the IPCC Fourth Assessment Report summarized relationships between emissions levels in 2050 and long-term climate change outcomes in scenarios (20), although these scenarios did not explicitly consider interim targets. More generally, decision analyses have illustrated how optimal emissions reduction strategies under uncertainty are affected when there is an opportunity to adjust decisions over time (21), sometimes including the possibility that achieving long-term goals may become infeasible (22). Such analyses have been carried out with relatively simple models employing stylized definitions of infeasibility.

We build on this previous work by carrying out the first explicit analysis of the relationship between midcentury targets and long-term outcomes using a model of the global energy system with detailed technological representation. Explicit analysis of interim targets is valuable because it directly incorporates uncertainty in long-term goals and their attainability given shorter-term mitigation. Our conclusions about the implications of midcentury conditions differ therefore from traditional stabilization scenarios driven only by long-term goals. Use of an energy technology model that can represent inertia and path dependency in energy systems is also important, because the feasibility of long-term climate goals is determined to a large extent by the flexibility of the energy system at midcentury, a characteristic best assessed with models that represent factors such as rates of capital stock turnover, limits to market penetration rates of particular technologies, and relationships between production and distribution systems.

Methodology

In this study we employ the IIASA integrated assessment modeling framework (23), including the global, 11-region MESSAGE model that accounts for all greenhouse gas emissions (24) and has a detailed, technology-specific energy sector for the explicit representation of path dependency and inertia. To limit the number of model runs, we assess a set of individual scenarios rather than performing an optimization under uncertainty, and we limit

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the analysis to two independent time periods using a myopic version of the model (25). In each individual scenario, demand is met over the first-half of the century to achieve a specified target in 2050 without knowing what the long-term goal will turn out to be (or, for that matter, what energy demand, technology costs, or any other aspect of the future beyond 2050 will be). In 2050, the long-term goal is learned, and demand over the second half of the century is met to reach this goal. While having no knowledge of long-term goals and conditions until 2050 and only one opportunity to adjust the initial mitigation strategy are both simplifications of reality, they are improvements over more typical assumptions of perfect foresight and no adjustments to strategy (20). We assess the trade-off between mitigation costs and the risk of exceeding various long-term goals as a function of the midcentury target.

Long-term goals are defined as concentrations or temperature change in 2100, and we model temperature change outcomes probabilistically (26, 27). Althought climate consequences beyond 2100 are important (19), our main focus is on technology-specific modeling of plausible mitigation paths, an approach best suited to timescales of decades, not centuries. We investigate midcentury targets expressed in terms of emissions, concentrations, and the share of energy from zero-carbon sources. Among other outcomes, we quantify how achieving particular medium-term targets can influence the probability of staying below specific temperature increases at the end of the century, and we identify critical midcentury thresholds that, if surpassed, would make achieving particular long-term goals infeasible within our modeling framework. Infeasible is defined here as not possible to achieve with technologies that are currently at least in early demonstration or commercialization phase, which includes a wide range of renewables, nuclear, and efficiency improvements but excludes, for example, nuclear fusion and geo-engineering. Further details on methodology are provided in *SI Text*, and main results for the emissions scenarios and probabilistic climate modeling can be found at http://www.iiasa.ac.at/~riahi/Interim_Targets.

Results

The development of emissions and concentrations for the full set of scenarios we analyze is shown in Fig. 1. To account for uncertainty in development pathways, we use two different baseline scenarios, recent implementations of the IPCC B2 and A2r scenarios (23, see also *SI Text*). We impose a wide range of midcentury targets, from $<1/2$ to more than a doubling of emissions by 2050, compared to 2000. From these midcentury targets we have explored the attainability and costs for a range of concentration targets in 2100 ranging from <450 ppm to $>1,000$ ppm CO_2-eq. By doing so we allow for scenarios that temporarily overshoot the target during the century.

Fig. 2 summarizes results for all feasible combinations of midcentury and end-of-century targets. The first row of panels shows the relationship between total energy system costs over the century and midcentury CO_2 emissions levels (including emissions from energy, industry, and land-use change), for each end-of-century equivalent CO_2 concentration goal. The second row of panels is similar, but shows results with midcentury conditions expressed in terms of shares of global primary energy from zero-carbon sources, rather than in terms of emissions. Additional figures with midcentury conditions expressed as atmospheric concentrations are provided in *SI Text*.

There are two key features of these results. The first is that for each long-term goal, there is a range of midcentury emissions, or of the zero-carbon energy share, that minimizes total costs. For example, considering the long-term goal of 550 ppm equivalent CO_2 concentration in 2100 and assuming the B2 baseline scenario, energy system costs over the century are minimized if CO_2 emissions in 2050 are between 7 and 10 GtC/yr (as compared to about 8.3 GtC emitted in 2000), or if zero-carbon shares are between 52% and 58% (as compared to about 25% in 2000). If conditions in 2050 are outside these ranges, costs rise substantially. Comparing the *Left* and *Right* panels of Fig. 2 also clearly illustrates the impact of the baseline-specific technological and socio-economic assumptions. Similar midterm conditions do not guarantee similar costs for a given long-term target, nor are the cost-minimizing midterm conditions necessarily the same for both of the baselines.

At first sight Fig. 2 might seem at odds with typical mitigation cost curves, in which costs rise monotonically with increasing emissions reductions. However, the u-shaped cost curve is simply a consequence of expressing total costs over the whole century as

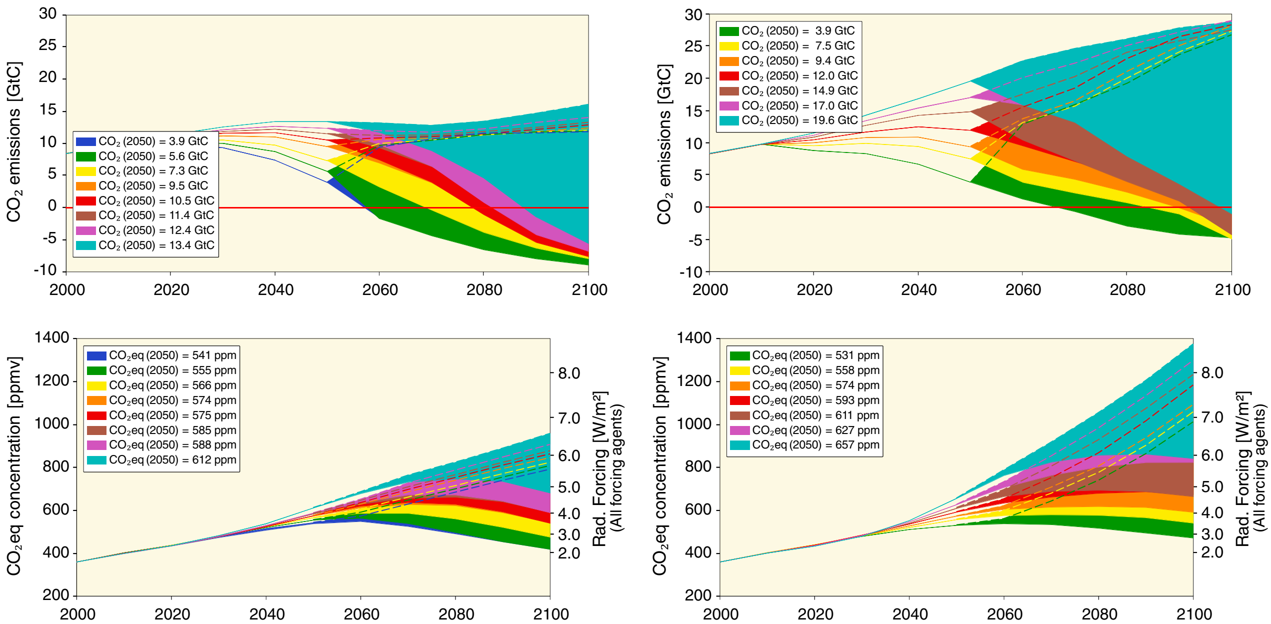

Fig. 1. Emissions and CO_2-eq. concentration pathways to 2050 and resulting attainability ranges for the long-term (2100), assuming the B2 (*Left*) or A2r (*Right*) reference scenarios. Emissions include CO_2 from fossil fuel burning and land-use change. Colored shaded areas depict the feasible range of outcomes over the second half of the century associated with each 2050 emissions target.

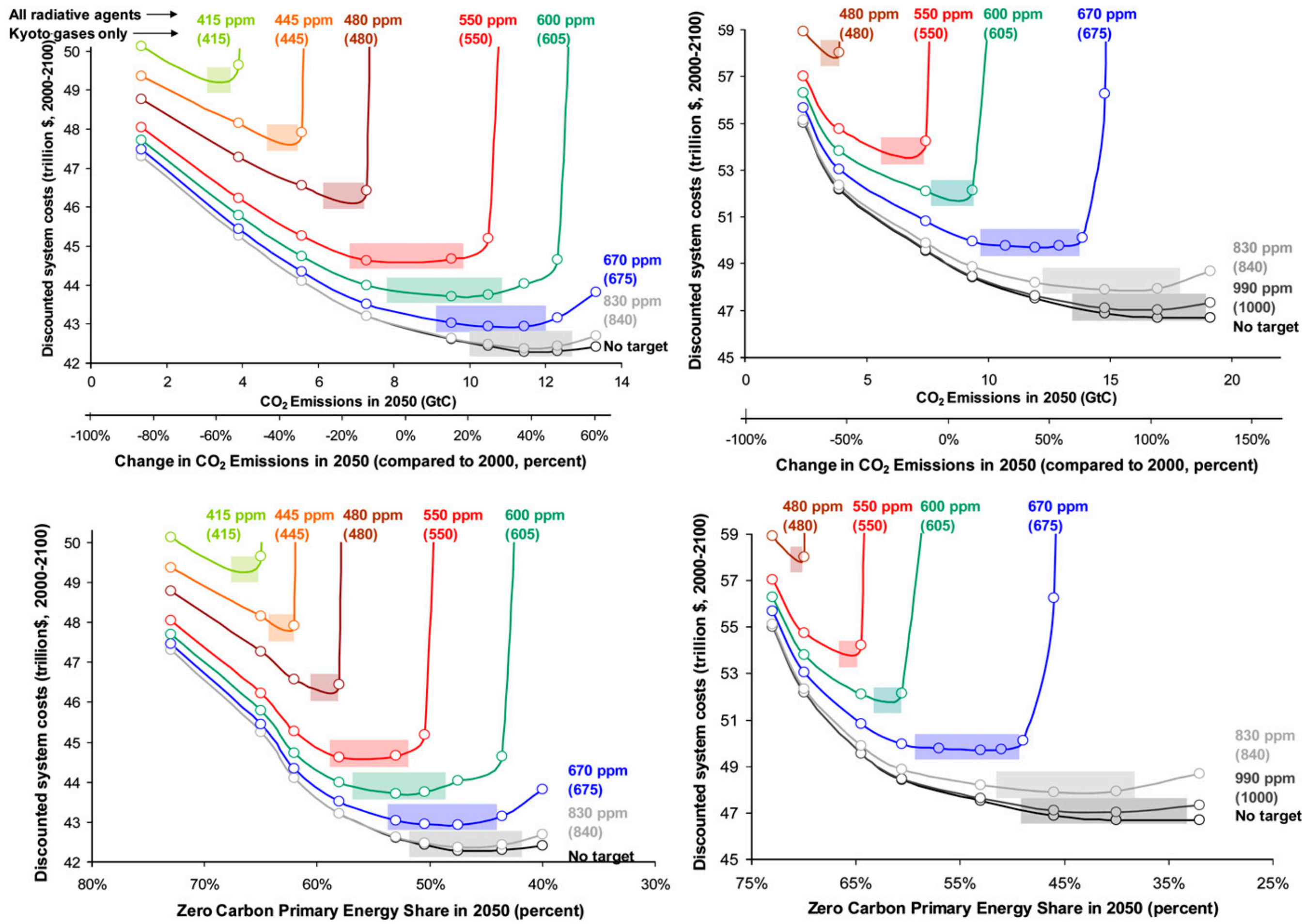

Fig. 2. Relationship between midcentury conditions and total energy system costs for a range of long-term CO_2-eq concentration targets, assuming the B2 (*Left*) or A2r (*Right*) reference scenarios. *Upper* panels show midcentury conditions for CO_2 emissions, *Lower* panels for share of zero-carbon sources in primary energy. Colored lines depict the relationship for each long-term CO_2-eq. concentration target, with the horizontal bars indicating the corresponding cost-optimal midcentury condition. The u-shape of the curves reflects rising costs if either too little or too much mitigation is undertaken by 2050, relative to the optimum. Costs are higher in the A2r scenario due to higher energy demand and slower rates of technological change relative to B2. The nearly vertical rise in costs indicate the location of the feasibility frontier; emissions higher than this level in 2050 make the long-term goal infeasible.

a function of midcentury conditions. Costs over the first half of the century do indeed rise monotonically as the midcentury target becomes more stringent. In contrast, for any given end-of-century target, costs over the second half of the century decrease for more stringent midcentury targets. Thus, total costs depend on the balance between first-half and second-half mitigation costs, resulting in a particular emissions level or zero-carbon energy share in 2050 that minimizes their sum.

The existence of cost-minimizing midcentury conditions holds for both baseline scenarios and all long-term targets considered, suggesting that midcentury targets could be used as a means of minimizing costs of achieving uncertain long-term goals. Results in Fig. 2 cannot be translated directly into desirable midcentury goals if the long-term goal is not yet known, but they can inform such choices, as we discuss further in the section below on risk-cost trade-offs.

Feasibility Thresholds. The second key feature of the results is that for each long-term goal there is a critical threshold of midcentury conditions beyond which achieving the 2100 target becomes infeasible with currently known technological options. This level is indicated in Fig. 2 by the rapid, nearly vertical rise in costs as the midcentury emissions level increases, or zero-carbon energy share decreases. For example, results for the B2 baseline scenario show that if CO_2 emissions in 2050 are above about 10.5 GtC/yr, or zero-carbon energy shares are below about 50%, achieving the 550 ppm CO_2-eq. goal in 2100 becomes infeasible. Higher long-term targets become infeasible at successively higher midcentury emissions levels (or successively lower zero-carbon energy shares). Fig. 2 also indicates that the lower the long-term goal, the closer the feasibility threshold becomes to the optimal midcentury conditions. This outcome reflects the fact that for the most stringent goals, there are fewer choices for how to achieve them.

Infeasibility occurs because, given the atmospheric concentrations already reached in 2050, the state of the energy system at that time, and the energy demand to be met over the second half of the century, the model is unable to supply enough energy from known sources at a low enough carbon intensity to achieve the 2100 goal. The midcentury emissions level at which the feasibility threshold occurs is influenced by assumptions about resource availability and the rate at which low- or zero-carbon technologies can penetrate the market to meet demand, as well as by the assumed reference scenario.

The feasibility thresholds can be compared to results published by the Intergovernmental Panel on Climate Change (IPCC). The IPCC assessment relates long-term concentration targets to emissions at midcentury based on a summary of the mitigation scenario literature (20). Fig. 3 shows the range of midcentury emissions that occur in scenarios with different long-term concentration targets. Similar to our analysis, the IPCC scenario set includes stabilization as well as overshoot scenarios aimed at staying at or below the long-term target by 2100. However these scenarios are not based on any explicit consideration of feasibility; rather, they typically represent least-cost pathways to known long-term goals, as calculated by different models. Our feasibility thresholds lie at or above the upper end of the IPCC ranges. This result suggests that, under some conditions, it may be possible to achieve the long-term concentration outcomes with emissions that are considerably higher than indicated in the IPCC table. For example, the IPCC range indicates that stabilization at 490–535 ppm (category II) is consistent with 2050 emissions that are 30–60% below 2000 levels, whereas we find that in the B2 scenario, it is feasible, albeit far from cost optimal, to reach the same stabilization level with midcentury emissions that are 20% above 2000 levels. However, this comparison is sensitive to scenario assumptions. In the A2r scenario, if midcentury emissions are significantly above the IPCC ranges, the long-term goal becomes infeasible.

Long-Term Temperature Goals. We next examine the relationship between midcentury targets and long-term temperature change outcomes. Fig. 4 summarizes both the least-cost midcentury emissions levels and the feasibility threshold results. Instead of expressing outcomes at the end of the century in terms of equivalent CO_2 concentrations, as in Figs. 2 and 3, we express them as the likelihood that the full path of radiative forcing experienced over the century would lead to <3 °C (*Left*) or <2 °C (*Right*) of temperature change in 2100, relative to preindustrial. The figure shows that, in general, the greater the desired certainty in achieving the long-term goal, the lower the least-cost emissions level at midcentury, and also the lower the feasibility threshold. For example, to have a 50% chance of limiting warming to <2 °C in 2100, the least-cost emissions level in 2050 would be 5.5–6.5 GtC/yr, assuming the B2 baseline scenario. However, if emissions were slightly above this range (e.g. 7 GtC/yr by midcentury) it would be infeasible to limit warming to <2 °C with 50% certainty. These results can be compared with the EU expectation (9) that achieving the goal of limiting warming to 2 °C with 50% likelihood would be consistent with reductions in global emissions

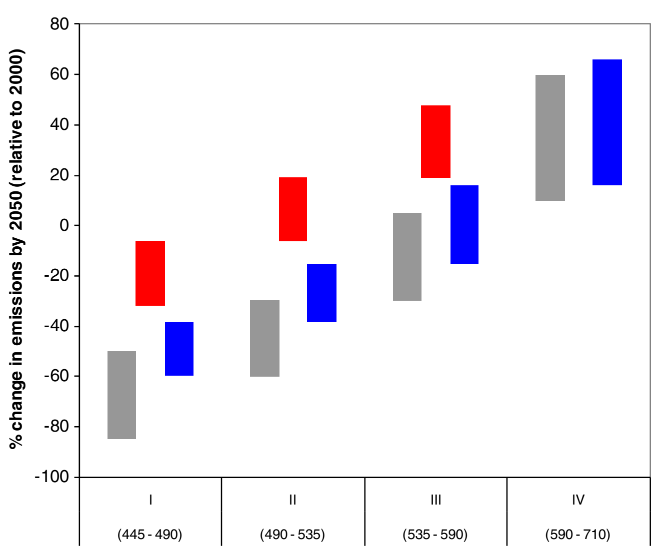

Fig. 3. Feasibility frontier for the B2 (*Red*) and A2r (*Blue*) baseline scenarios compared to ranges of midcentury emissions associated with mitigation scenarios in the literature assessed in IPCC AR4 (*Gray*, 21). In our analysis, the B2 feasibility frontier does not apply to the IPCC stabilization category IV, because this target is attainable in the B2 baseline scenario without any mitigation by 2050.

at midcentury of up to 50% below 1990 levels (or about 57% below 2000 levels). The EU figure is substantially more aggressive than our results for the B2 scenario, which indicate optimal midcentury reductions of about 22–35%, and an infeasibility threshold at about 20%, below 2000 levels. However, scenario assumptions are crucial in this case: In the A2r scenario, achieving 2 °C with 50% likelihood is only barely feasible under any circumstances, and then only with reductions of >50% by 2050. The difficulty in achieving this long-term goal in the A2r scenario is driven by a combination of high energy demand and slow rates of technological change.

Results also indicate that for a 3 °C target in 2100, optimal midcentury conditions and infeasibility thresholds are substantially relaxed. In general, the 3 °C target remains feasible at a higher likelihood than 50% for midcentury emissions that are substantially above the 7 GtC that applies to our 2 °C example. For example, achieving the 3 °C target with 75% likelihood is feasible even if emissions in 2050 approach about 10 GtC/yr (in the B2 scenario). Another way to compare results for the two long-term goals is to compare what the same midcentury conditions imply in the two cases. For example, the optimal midcentury conditions and feasibility thresholds for achieving a 2 °C target with 50% likelihood are essentially the same as those that would apply to achieving a 3 °C target with 95% likelihood.

The supporting information provides an overview table with a cohesive summary of our results, showing the direct consequences of selecting alternative midcentury emissions, zero-carbon energy, or concentration targets for the feasibility of staying below long-term temperature and concentration thresholds (as well as corresponding ranges for the "cost-optimal" long-term concentration targets). It also indicates that in most cases our feasibility threshold results are conservative with respect to outcomes beyond 2100. Because in most cases temperatures are declining in 2100, the likelihood of achieving a target would typically increase beyond the end of the century. On the other hand, this also implies that the likelihood of being below the target before 2100 in these scenarios is lower than the probability given for the year 2100.

Risk-Cost Trade-Offs. Lower midcentury emissions targets reduce the risk of crossing an (uncertain) feasibility threshold, which would make a given long-term target impossible to achieve. However, this reduced risk comes at some cost, and our results give some insight into this risk-cost trade-off. For example, Fig. 2 shows the costs over the full 2000–2100 period of achieving a long-term 550 ppm concentration goal for a variety of midcentury emissions levels. The long-term goal is infeasible if emissions are above about 10.5 GtC/yr in 2050. Given that the precise location of this threshold is uncertain, the risk of inadvertently crossing it would be reduced if emissions at midcentury were substantially below 10.5 GtC/yr. The cost results indicate that over the range of 7–10 GtC/yr, energy system costs as measured over the century are roughly similar and begin to rise substantially only when emission are reduced below 7 GtC/yr. These results suggest that in some cases reducing the infeasibility risk, by reducing emissions somewhat below the feasibility threshold, can be accomplished at little or no cost.

More generally, these results can be used to evaluate risk–cost trade-offs associated with a given midcentury target and a range of long-term goals that might be under consideration but not yet decided upon. For example, suppose one wanted to evaluate how appropriate a 7 GtC/yr emissions target for 2050 might be if long-term goals were uncertain but might lie between 480 ppm CO_2-eq. (associated in Fig. 4 with about 45% likelihood of staying below 2 °C, and 90% likelihood of staying below 3 °C) and 600 ppm CO_2-eq. (associated with about a 15% likelihood of staying below 2 °C and 60% likelihood of staying below 3 °C). Fig. 2 shows that a 2050 emissions level of about 7 Gtc/yr is just at the edge of feasi-

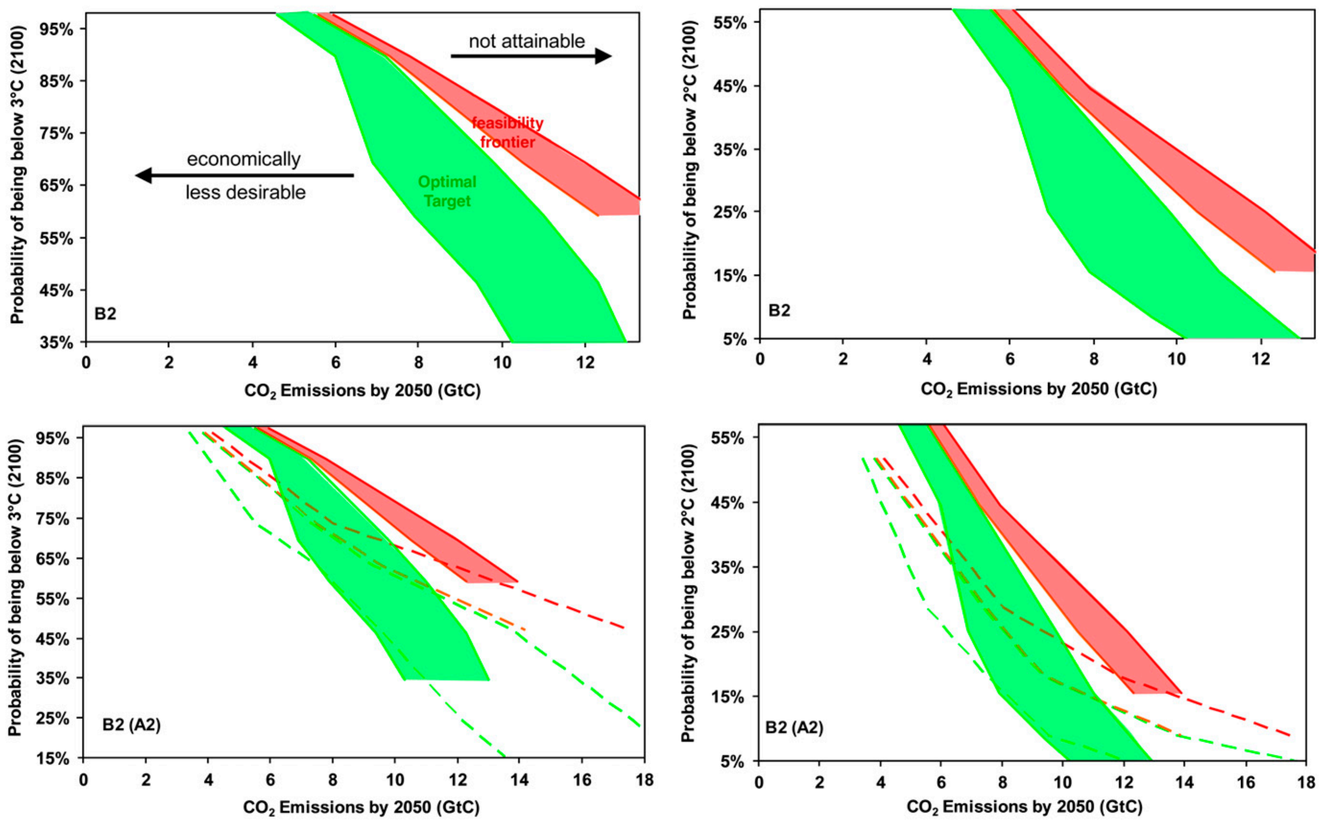

Fig. 4. Relationship between midcentury CO_2 emissions and the probability of being below a temperature change of 3 °C (*Left*) or 2 °C (*Right*) in 2100. Red area marks division between feasible (to the left) and infeasible (to the right) combinations of 2050 emissions levels and likelihoods of being below temperature thresholds in 2100. Green area marks ranges of least-cost midcentury conditions for different likelihoods of being below thresholds. *Upper* panels show the relationship for the B2 mitigation scenarios based on a single climate sensitivity PDF (26). *Lower* panels illustrate the baseline uncertainty, comparing results for the B2 (*Shaded*) and the A2r scenarios (dashed lines). Note different scales on the axes. Lower emissions levels by 2050 increase the likelihood of keeping temperature change <2° C or <3° C in 2100. For a given emissions level in 2050, the likelihood of a long-term temperature goal being feasible is generally lower in the A2r scenarios due to the greater energy demand to be met (*Lower*).

bility for achieving a 480 ppm long-term goal. This outcome would incur energy system costs of about 46.5 trillion US dollars, and would require the maximum feasible emissions reductions after 2050. If in 2050 it were decided instead that meeting a 550 ppm long-term goal were sufficient, total costs would decline to about 45 trillion US dollars. This lower cost would be driven primarily by the much less stringent reductions required after 2050. Similarly, if it were decided in 2050 that a long-term outcome of 600 ppm CO_2 were acceptable, costs would decline further to about 44.5 trillion US dollars. In this last case, costs would not be optimal: If it had been known at the start of the century that the long-term goal were 600 ppm, a higher midcentury target would have produced lower total costs. However, this would have also sacrificed the possibility of limiting concentrations to 480 ppm, because a higher midcentury emissions level would have made that outcome infeasible. Here, these results allow us to evaluate the cost of hedging against the possibility that achieving a lower long-term concentration goal may become desirable.

Midcentury targets could also inform an iterative risk management strategy on a shorter timescale. Although in our analysis mitigation strategies are set at only two points in time (now and in 2050), new scientific, political, or economic information obtained over the next decade or two could be used to (*i*) revise the range of long-term options to be preserved, (*ii*) revise the assessment of midcentury goals, and (*iii*) adjust the initial mitigation strategy to be consistent with these revised assessments.

Discussion

Our analysis indicates that goals for limiting climate change in the long-term are associated with midcentury conditions that must be achieved to prevent long-term objectives from becoming infeasible. Feasibility thresholds identified here in some cases lie considerably above 2050 emissions targets that are frequently argued to be necessary to achieve to reach long-term goals. For example, depending on assumptions about baseline development paths, thresholds can lie substantially above midcentury emissions levels identified by the EU as necessary for achieving its 2 °C target, or by the IPCC Fourth Assessment Report as associated with various long-term concentration stabilization levels.

The difference between our feasibility thresholds and these commonly cited midcentury targets does not necessarily imply that they are inconsistent. Our results allow for overshooting the long-term goal, whereas the EU 2 °C goal does not; the feasibility threshold depends on the desired probability of attaining the goal one wishes to preserve as well as on the assumed baseline scenario; and perhaps most importantly, interim targets would probably best be set below, not at, the estimated feasibility threshold. Nonetheless, our results indicate that current policy goals should be interpreted as choices involving trade-offs, not necessarily as requirements from the technological point of view.

Our conclusions on feasibility thresholds refer only to technological feasibility (see *SI Text* for a discussion of causes of infeasibility) and should be interpreted in a larger context of plausibility. On the one hand, the development of new technologies not considered in our analysis could expand the range of achievable long-term climate change outcomes. On the other, consideration of social, political, and institutional constraints not incorporated here (28) would restrict that range. The quantitative results are specific to the modeling framework we use, both to the structure of the model and to assumptions it contains regarding technology costs and constraints on penetration rates, as well as to assumptions regarding resource constraints. It would be valuable for other modeling groups to carry out similar analyses to test the robustness of the findings.

In addition to identifying feasibility thresholds, we find that there are also important economic trade-offs with regards to the balance of the mitigation effort between the first and second half of the century. We identify midcentury conditions that would be optimal, from the point of view of mitigation costs, given that specific long-term goals were not known until the middle of the century. More broadly, midcentury conditions can be seen as a way to manage jointly the risks and costs of uncertain long-term goals. If the long-term goal is uncertain, there is a risk that by the time it is decided upon, potentially desirable options will no longer be feasible (or will be prohibitively expensive) to achieve. There is a trade-off between reducing this risk and the cost of emissions mitigation, which can be managed through the use of midcentury targets.

Our analysis suggests that, although we have implemented midcentury targets in terms of emissions levels in 2050, outcomes strongly depend on concentrations and zero-carbon energy shares as well, raising the possibility that targets set in those terms could also be effective. Several studies have proposed that a policy approach based on cumulative emissions budgets would be more robust to scientific uncertainties than targets expressed as emissions levels in a given year (29–31), but these studies focused on CO_2-only and total allowable emissions regardless of timeframe rather than emissions over the 2000-2050 period. Like our analysis, Meinshausen et al. (15) consider multigas scenarios and the midcentury time frame. They conclude that both cumulative emissions through 2050 and emission levels in 2050 are robust indicators of the likelihood of achieving a 2 °C warming target. We did not explicitly assess targets set in terms of cumulative emissions. However, when our scenario outcomes are expressed in cumulative terms (see *SI Text*), they suggest that long-term climate outcomes strongly depend on cumulative emissions over the first half of the century as well as on midcentury emissions levels. Further work on the implications of different metrics for midcentury targets would thus be useful.

There are several caveats to the results presented here. Results are influenced by economic parameter choices such as the discount rate. Although the discount rate does not affect the feasibility threshold, a lower discount rate will make near-term reductions less expensive relative to those made in the long-term and will therefore lower the least-cost midcentury emissions level. Results are also sensitive to climate system uncertainties. We employ a particular probability density function for climate sensitivity that is near the middle of the range in the literature. The identification of feasibility thresholds and least-cost midcentury conditions is sensitive to the choice of pdf (see *SI Text*). In addition, our analysis allows for temperatures to overshoot the long-term targets before achieving them in the year 2100. In fact, all B2 scenarios, and some A2 scenarios, at the feasibility frontier are overshoot scenarios, implying declining temperature change post-2100. Limiting scenarios to never exceed the target would likely affect results. Furthermore, uncertainties regarding the temperature response to rapid emissions reductions (32) could also affect results.

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