Focus Article

Exploring the feasibility of low stabilization targets

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Climate change mitigation scenarios provide an integrated perspective on the technologies and policies that are required to achieve various mitigation targets as well as the related costs. With the threat of severe adverse impacts from climate change becoming more and more apparent and in view of the pledge by policy-makers to meet stringent stabilization targets, further exploration of low emission scenarios has become increasingly relevant. Although much progress has been made in recent years to provide the basis for a solid assessment of different stabilization targets and the related economic, environmental, and social consequences, a more structured approach within a more realistic framework is required. First, uncertainties in baseline assumptions that are independent of climate policy need to be taken into account. These uncertainties reflect the incomplete knowledge concerning drivers of real-world developments, e.g. assumptions on technology improvements or resource availability. In addition, it is necessary to analyze so-called second-best worlds in which constraints on the deployment of low-carbon technologies or imperfect climate policy regimes render the mitigation effort more difficult. The current challenge for Integrated Assessment Modeling is thus to explore feasibility and limitations of mitigation strategies along three directions: (1) ambitious mitigation targets, (2) explicit treatment of uncertainties in baseline assumptions, and (3) second-best policy or technology scenarios. With this article, we propose future research foci and priorities in the run-up to the IPCC's Fifth Assessment Report. *WIREs Clim Change* 2011 DOI: 10.1002/wcc.124

INTRODUCTION

Over the last several years, political declarations by the European Union,[1] the G8,[2] and the UN[3,4] have referred to the 2°C target for climate protection—an objective that is without doubt highly ambitious. The strong push for stringent climate stabilization may well be attributable to a clearer realization of at least two factors. First, scientists argue that global warming could result in the passing of critical thresholds of the climate system ('tipping points') and thus qualitatively alter the mode of operation of our planet.[5,6] Second, it is now realized that global warming will have severe impacts.[7–10] These scientific findings drive the sense that there is the need for ambitious mitigation scenarios to limit the damage expected from a continued rise in global mean temperature. In the following, we refer to those scenarios as 'low stabilization' scenarios as a short-hand name for mitigation strategies such that greenhouse gas concentrations reach relatively low levels compared to business-as-usual.

Despite the bold ambitions of politicians and negotiators, there is a remarkable dearth of integrated assessment studies of low stabilization. Only a small number of mitigation scenarios that would ensure a high probability of limiting global warming to 2°C were available for the IPCC's Fourth Assessment Report (AR4).[11] If the 2°C target is pursued by policy-makers, a robust assessment of the side risks and benefits of achieving this target will be required from the scientific community. To address the gap between political ambition and scientific underpinning, it is essential to cover a broader range of mitigation scenarios. This should include very ambitious mitigation levels and scenarios where these mitigation targets are evaluated against some crucial assumptions, for instance, by taking into account

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technological failures. Only if all facets of strong mitigation scenarios are considered and thoroughly assessed, policy-makers can either revise or confirm the 2°C mitigation target. Scenario development is thus a cornerstone of the iterative process between policy-makers and the scientific community that is necessary for determining goals and measures for climate change mitigation.

Some recent studies[12–18] conducted after the IPCC AR4 have assessed the issue of ambitious climate protection in greater detail. New and more balanced conclusions can be drawn from these studies. We suggest structuring these findings and future research along the following dimensions: (1) level of ambition of the mitigation target, (2) explicit treatment of uncertainty in baseline assumptions, i.e. in the absence of climate policy, and (3) analysis of second-best scenarios in terms of (un)availability of specific technologies or of fragmented policy regimes.

In the following, we report and discuss these three aspects and introduce examples of studies. We identify limitations of the current scenario literature and make suggestions for further research by outlining a strategy how scenario development can build a sound basis for exploring the 'feasibility frontier'[19] of climate change mitigation.

RECENT DEVELOPMENTS IN CLIMATE CHANGE MITIGATION SCENARIOS

Low Stabilization Scenarios

In the IPCC AR4, emissions pathways are clustered into six classes according to their mitigation target in terms of radiative forcing.[20] Radiative forcing can be translated into a likely range for the equilibrium warming level. Emissions of greenhouse gases affect the global mean temperature by changing the concentration of greenhouse gases in the atmosphere, thus increasing radiative forcing and consequently altering the radiation balance of the Earth. For the lowest IPCC category (CAT I), the anthropogenic radiative forcing is 2.5–3.0 W/m^2, corresponding to a concentration level of 445–490 ppm-eq. The likely range of resulting global mean temperature increase is 1.4–3.6°C relative to preindustrial levels.[20] Only three models, accounting for 6 out of a total of 177 mitigation scenarios, provided results for this category in AR4. This means that only limited conclusions about the feasibility of low stabilization could be drawn from this assessment. In the context of the new IPCC scenario process,[21,22] which aims at providing a consistent scenario basis across all working groups for the IPCC Fifth Assessment Report (AR5), a peak-and-decline pathway aiming at a stabilization level of 2.6 W/m^2 in 2100 will be explored (RCP3-PD pathway, see Figure 1). Since this pathway will be evaluated by many models, there is reason for optimism that new answers concerning the feasibility, costs, risks, and side-benefits of low stabilization will be given in AR5.

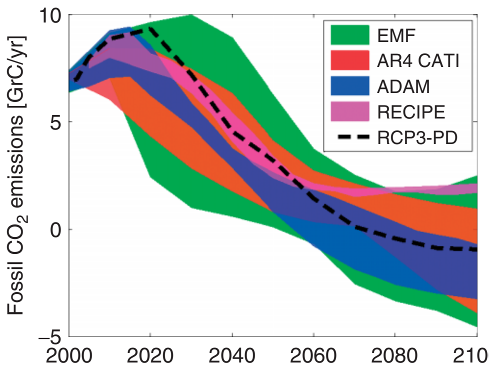

FIGURE 1 | Range of emission scenarios. Green: EMF-22 scenarios[16] (for the 450 ppm-eq target with 6 models and 12 scenarios); red: lowest category in AR4 (CAT I)[11] as given in Table 3.10 in Fisher et al.[20] (3 models and 6 scenarios); blue: ADAM[12,13] scenarios (400 ppm-eq long-term target with 4 models and 4 scenarios, without E3MG); pink: RECIPE[17,18] (for the 410 ppm target with 3 models and 3 scenarios) and the RCP3-PD pathway.

The term 'feasibility' is not clearly defined; it can be related to technical, economic, or political constraints. Strictly speaking, from a modeler's perspective, a mitigation target will be infeasible if models are not able to produce scenarios that are consistent with this target. From an economic or political perspective, a more restrictive but also vaguer definition can be provided: a mitigation target will be feasible, if neither economic costs nor political barriers of attaining the target are prohibitively high. It is conceivable that a model scenario is technically feasible, but that policy-makers regard the scenario as infeasible due to a lack of political acceptance. In the following, we use the term feasibility in a technical- and model-related sense. In the community of energy-economy modelers, the feasibility or infeasibility of ambitious mitigation targets is controversial.[23] Model results are inconclusive: while some studies deny the feasibility of ambitious mitigation,[24] others find low stabilization to be feasible.[12,25] Similarly, this discrepancy is due to differences in model assumptions. Some studies point out the importance of early and global action[16,17] or the reliance on specific technologies such as carbon capture and storage (CCS)[12,14,26] and in particular bioenergy with CCS (BECS).[27] However, more structured analyses are needed in which these differences in structural and parameter assumptions of models are made explicit and attributed to differences in results.

Since AR4, initial progress in this direction has been made. Three recent coordinated model inter-comparison exercises have considered ambitious stabilization levels: the ADAM[28] model inter-comparison[12,13,25] with five integrated assessment models, the EMF-22 study[16] by the Energy Modeling Forum including 10 models and the RECIPE model inter-comparison[17,18] with three models (Figure 1). ADAM focused on the comparison of scenarios that find the 2.6 W/m^2 target in 2100 to be feasible, based on an emission profile by van Vuuren and colleagues.[14] EMF-22 assessed different stabilization targets, including a similarly ambitious stabilization scenario to those in ADAM. The focus in EMF-22 was on the difference between overshoot and stabilization scenarios, combined with different assumptions on the nature of international participation in global mitigation. RECIPE focused on sectoral mitigation strategies. The costs for mitigation in these three studies are shown in Figure 2 as a function of cumulative CO_2 emissions from 2000 to 2050. According to Meinshausen et al.,[29] this emission budget is a proxy for the probability of exceeding 2°C warming. Due to structural differences, the models report different cost metrics for mitigation. In order to make numbers comparable, we expressed policy costs relative to the gross world product (GWP). While the numbers indicate well the overall trends in dependence of the stringency of the mitigation target, it is important to note that they are not fully equivalent. Most models calculate economic losses from climate policy. Under some instances and model settings, climate policy can result in negative costs. These are caused, *inter alia*, by the following factors: (1) sub-optimality of the baseline (e.g. due to idle capacities) that is moderated by the mitigation effort, (2) reaping of efficiency potentials in response to climate policy, (3) path dependencies due to the build-up of capital stocks and infrastructure in combination with imperfect foresight, and (4) learning effects in low-carbon technologies. While only one model (E3MG) reports distinctly negative costs, these effects tend to reduce mitigation costs in some other model scenarios as well. In general, this analysis confirms the order of magnitude for the mitigation costs given in IPCC AR4 (Ref 20, Fig. 3.25). For most models, costs grow moderately over a wide range of the carbon budget but increase disproportionately toward higher stringency. This convex behavior suggests the existence of a model-specific 'feasibility frontier', i.e. a level of stringency above which mitigation becomes either infeasible or prohibitively expensive. Since this feasibility frontier provides an indication of the attainability of low stabilization targets, it is of great importance to further explore the dependence of the frontier on crucial structural and parameter assumptions of the models.

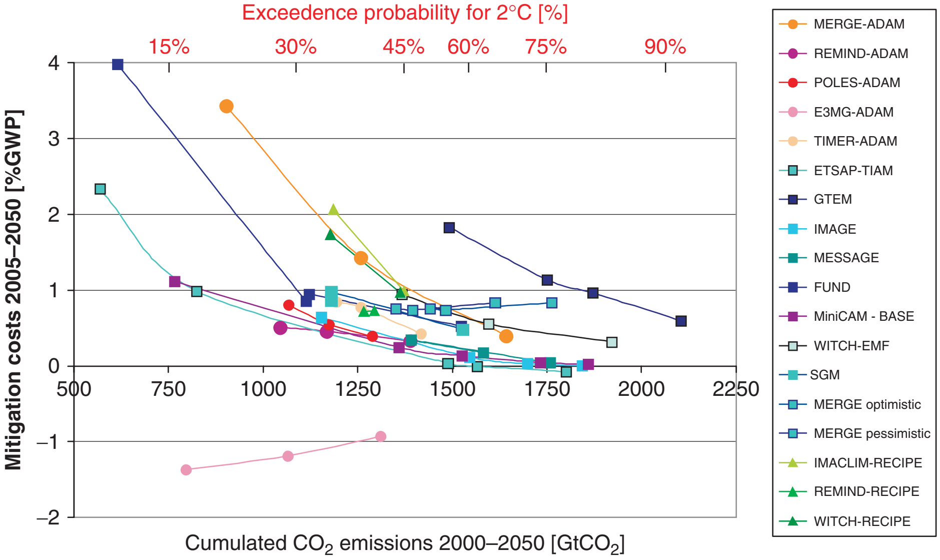

FIGURE 2 | Costs for mitigation as gross world product (GWP) losses or cumulative abatement costs (as area under marginal abatement cost curve) relative to baseline GWP (in %) for 2005–2050 in dependence of the cumulated fossil fuel CO_2 emissions from 2000 to 2050 (discounted at 5% discount rate). Results are reported for ADAM[12,13] scenarios (in red tones with bullets), EMF-22 scenarios[16] (in blue tones with squares), and RECIPE[17,18] scenarios (in green tones with triangles). Numbers are only given for the first-best worlds (with all technologies for ADAM and RECIPE, with full participation for EMF-22 and RECIPE). The cumulated emission budget is a proxy for the probability of exceeding 2°C (given on the upper *x*-axis).[29]

The new model analyses provide a broader assessment than was available for the AR4 and show that low stabilization is technically feasible and economically viable in principle. The costs reported in Figure 2 are costs in 'first-best' worlds with full flexibility of technologies and global participation in the mitigation effort. These costs should therefore be considered as a lower benchmark of what can be expected in reality. The conclusion of low costs and economic viability of low stabilization thus relies on assumptions about the availability of specific technologies and international participation (see below). This implies that feasibility is not only a matter of pure model analysis but also a matter of risk analysis concerning the implementation of specific technologies: the extensive use of biomass, for instance, could conflict with food production, or it could turn out that CCS entails a high risk of severe future environmental damage. Feasibility of low stabilization is therefore also a matter of ethical judgments about which kind of risks and which costs are considered acceptable in view of mitigating climate change.

Uncertainty in Baseline Assumptions

Integrated assessment modelers typically distinguish between baseline and climate policy scenarios. Baseline scenarios describe a business-as-usual world, i.e. development pathways in the absence of climate policy. Each baseline scenario describes a vision of a future world and reflects a specific set of implicit or explicit socio-economic assumptions, e.g. on economic or population development, on the development of fossil fuels prices, and on technological development. The effects and the needs of climate policies can be evaluated by comparing baseline scenarios with climate mitigation scenarios in which climate policies, typically via carbon taxes or emissions trading, are applied. The requirements for political or technical measures can then be deduced from the deviation of the mitigation scenario from the baseline case. In the models, climate policy can only be evaluated in a consistent way if the same assumptions are applied for baseline and policy scenarios. Only a set of a baseline and a policy case constitutes a full mitigation scenario as otherwise the effect of climate policy and the requirements to achieve mitigation cannot be separated from baseline assumptions.

The baseline development has a strong influence on the cost and achievability of mitigation targets. Quite intuitively, higher global emissions in the baseline require more abatement for a given mitigation target, and achieving the stabilization target becomes more demanding. Moreover, baseline assumptions about socio-economic and technological development or future fossil fuel prices are not only crucial for the emissions in the absence of climate policy but also strongly affect the global community's ability to respond to the climate mitigation challenge. For instance, in a world with high population growth, large-scale use of bioenergy—either in the baseline e.g. due to increasing oil prices or in the policy case—will be much more difficult due to the increased pressures on land-use and competition for land with food production.[30] On the other hand, an innovative, economically prosperous and regionally integrated world may find it easier to work toward new technological solutions for emission reductions. There is substantial uncertainty about the greenhouse gas emission levels in the baseline which are driven by factors such as demography, technological, and economic developments as well as the availability of primary energy resources. Rao et al.,[15] for instance, report an ambitious mitigation radiative forcing target of 2.6 W/m^2 to be infeasible if higher population growth or another land-use emission profile is assumed.

The IPCC's Special Report on Emissions Scenarios (SRES)[31] analyzed a large number of published scenarios available at that time and generated a substantial new set of stylized emission scenarios covering a wide range of alternative future developments. While socio-economic factors such as population growth and economic prosperity play an important role, the development of primary energy use per unit of economic output (energy intensity) and the carbon emissions per unit of primary energy consumption (carbon intensity) is even more crucial. The SRES do not only assume substantial energy intensity decreases (by a median of about 1.1% per year—well in line with what is observed historically) but most of them also assume decreases in carbon intensity, whereas for the past decade, carbon intensity has increased even with an accelerating growth rate.[32] The change of carbon and energy intensity occurring in the business-as-usual scenario is referred to as the autonomous part of technological change, since it is assumed to occur even in absence of climate policy.

The SRES provided a broad range of socio-economic assumptions and helped to cluster the scenarios according to storylines of future development. On the other hand, the SRES are non-intervention scenarios, i.e. by design they did not take into account any direct climate mitigation policy but provided emission scenarios as a result of different socio-economic drivers and assumptions. To analyze the effect of climate mitigation policy, however, all endogenous components and assumptions, e.g. on autonomous technological change, already need to be implemented in the baseline. Comparing the baseline scenario with a scenario in which a climate policy target is applied and in which the endogenous components are induced by climate policy, allows one to calculate the mitigation costs and to identify the measures that are required to reach the target.[33]

The SRES resulted in a best estimate for global mean temperature rise in the absence of climate policy of 2.4–4.6°C relative to preindustrial level.[34] Over the last years, however, policy-makers have shown a growing interest in scenarios that are consistent with long-term mitigation targets, e.g. the 2°C target or even the 1.5°C target,[35] and hence new scenarios, including ambitious mitigation scenarios, have been developed. This is one of the reasons why the scientific community together with the IPCC has set up a new scenario process.[21,22] Whereas the SRES only considered developments in the absence of climate policy, one important innovation in this new approach for the AR5 is to explicitly consider climate policy intervention scenarios that are based on the same set of socio-economic assumptions as the according baseline.[36,37]

In recent years, the need for policy intervention to reduce emissions has been recognized by most governments and many have already undertaken more or less ambitious actions. In view of this development, the established taxonomy of a baseline as a 'no climate policy'-case becomes problematic—a scenario with no climate policy whatsoever is already counterfactual. Modelers are beginning to explore 'policy-as-usual' scenarios in which they include national climate mitigation policies at the current level of ambition but in the absence of an overarching global stabilization target.

Second-Best Scenarios

Not only parameter choices for the socio-economic assumptions in the baseline but also structural model assumptions have a crucial effect on model results. By default, most mitigation scenarios consider climate change as the only market failure and assume that climate policy starts immediately, that emissions are reduced where it is cheapest and that the full portfolio of technological options is available for the low-carbon transition. In economic terms, such idealized scenarios where only one isolated market failure is considered that can be removed with a single policy are called 'first-best' scenarios. A crucial question that is increasingly being addressed by climate modelers is that of climate policy in a setting in which several other market failures exist. Examples include constraints on the availability of technologies, limited or fragmented participation in international climate policy efforts, or inadequate technology policies. Such analyses are referred to as 'second-best', since they consider optimal policies under the restrictions imposed by (additional) imperfections. Second-best is not related to a normative judgment, and such scenarios do not necessarily refer to a more realistic setting. But as extreme scenarios are explored, e.g. by assuming the unavailability of certain technologies or a high demand for biomass, insights are provided on the robustness of the model outcome.

Due to the assumed restrictions, second-best settings typically result in higher mitigation costs and make ambitious climate policy targets more difficult to achieve. A second-best analysis therefore adds an important aspect to the debate about feasibility or infeasibility of low stabilization scenarios. Applying second-best scenarios, and thereby gaining a clearer picture of the crucial assumptions and the relative importance of the different assumptions, is a major task for further research and within the AR5.

In AR4, the main question was whether ambitious climate mitigation can also be achieved. It has been concluded that this is possible at relatively low costs. By complementing assessments with second-best scenarios and sensitivity analyses, it has now been realized that low stabilization can only be achieved under certain assumptions. Often, (in)feasibilities can be traced back to (in)flexible model structures which in turn reflect the modeler's implicit assumptions about the underlying mechanics of the global energy-economic system. Some models, for instance, assume myopic behavior by investors and economic agents while others assume perfect foresight. Also, assumptions about the substitutability between energy carriers within the energy system differ across models and are crucial for the feasibility of large-scale transformations: a more inflexible model will have greater difficulties in achieving ambitious mitigation targets. To further increase our understanding of the economics of climate change mitigation, it will be indispensable to track down disagreement of models concerning the achievability of stringent climate targets to differences in specific model assumptions or to embrace the outcomes produced under varying input assumptions.

While some models take a techno-optimistic perspective and assume a large array of mitigation technologies to be available in their default scenarios, others are much more pessimistic, including a much more restricted technology portfolio. Based on the multi-model dataset of EMF-22,[16] Tavoni and Tol[23] present a statistical method to discern the influence of the availability of BECS within the models on the costs and on the achievability of low stabilization. The analysis reveals two kinds of biases. The first bias, explicitly mentioned by the authors, refers to a problem when assessing the achievability of low stabilization targets based on the existing literature: a selection bias will occur if only those models that were able to deliver results are considered but not those reporting infeasibilities. On the other hand, the analysis also reveals a second type of bias introduced by models considering only an incomplete set of technology options: when certain technologies such as BECS are not included, costs tend to be much higher compared to models where BECS is available and ambitious targets tend to be more difficult to achieve.

While such a purely statistical analysis can be a valuable starting point, we suggest using an explicit second-best framework in which technology options are switched on and off, as it is done e.g. in Azar et al.[27] to analyze the importance of CCS and in particular of BECS. Doing so should then lead to a better understanding of the underlying economic mechanics or technical model inflexibilities that may explain the differences between the models. A first step toward attributing discrepancies in mitigation costs to different model structure has been achieved within the RECIPE[17,18] study. The authors of this study find that model assumptions on substitutability within the energy system and the availability of options to decarbonize energy use outside the power sector, e.g. for transport, are crucial drivers for the costs. These results underscore the need to address structural uncertainties in model approaches by conducting coordinated model comparisons, where the models agree on a minimal set of assumptions. An important future challenge is to obtain an understanding of model disparities in terms of structural differences.

Recent scenario analyses have shown that technological feasibility and economic viability of mitigation scenarios depend decisively on crucial assumptions with respect to (1) the availability of newly developed technologies[12,14,16,17] and (2) the climate policy framework.[16,17] As policy-makers need to be informed about the robustness and the risks of specific strategies, a more realistic representation of the policy space is needed. Beyond the analysis of structural model uncertainties, this can only be achieved by exploring ‘second-best’ scenarios where some failures of specific technologies or diverging assumptions about the policy regime are taken into account within the scenarios. These have to be contrasted to the outcome within a first-best world to allow for assessing the risks and benefits of a specific strategy.

Such a systematic approach for the evaluation of second-best worlds within model comparisons were performed within all three model inter-comparison studies introduced above, ADAM,[12,13] RECIPE,[17,18] and the EMF-22 study.[16] The results of ADAM and RECIPE show that in first-best worlds (with full availability of low-carbon technologies) CCS or renewable energy sources are particular important mitigation options. However, since the feasibility of CCS or the massive expansion of renewable energy is not yet secured, the question remains how much the costs will increase if some of these options are not available at all or only to a limited extent. This leads to results for ‘second-best’ worlds, providing a broader picture of possible outcomes.

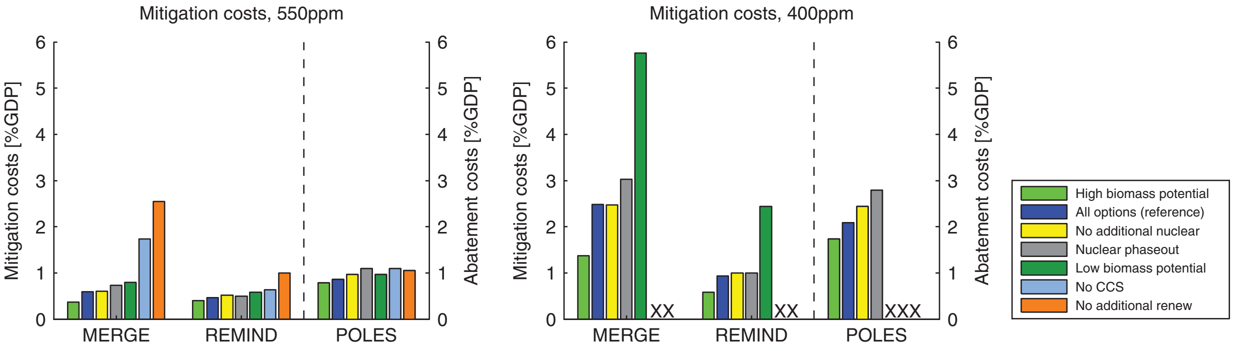

FIGURE 3 | Example I of assessing second-best worlds: Results from the ADAM[12,13] model comparison considering different technological failures. Global mitigation costs as aggregated GDP losses (for the models MERGE and REMIND) or abatement costs (POLES) by 2100 relative to the baseline. ‘X’ indicates a scenario where the target is not achieved with the given setting. ‘All options’ is the reference case where all technologies are available. In the case of high and low biomass potential, a potential of 400 EJ resp. 100 EJ instead of the default potential of 200 EJ is assumed. ‘No additional nuclear’ and ‘no additional renew’ refer to a constrained scenario where nuclear (resp. renewable energy sources) are limited to the use in the baseline. In the ‘nuclear phase-out’ scenario, no new investments in nuclear power are allowed. (Reprinted with permission from Ref 12. Copyright 2010 International Association for Energy Economics)

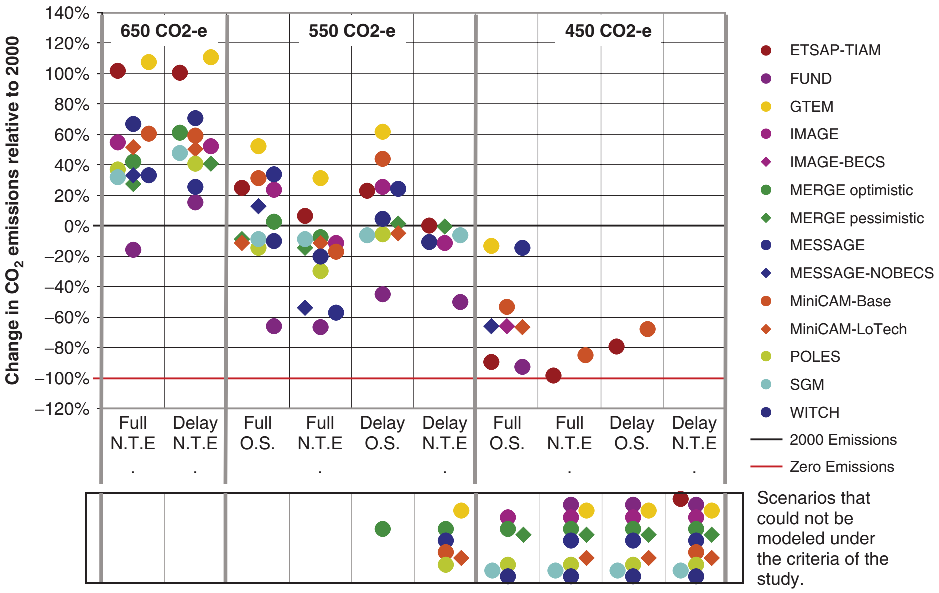

FIGURE 4 | Example II of assessing second-best worlds: Results from EMF-22 assessing different forms of international participation. Given are global fossil emissions in 2050 relative to 2000. O.S., overshoot; N.T.E., not to exceed; Full, full participation; Delay, delayed participation, where many regions do not join the global mitigation effort before 2030. (Reprinted with permission from Ref 16. Copyright 2009 Elsevier)

Within ADAM, uncertainty analysis made apparent that there is high flexibility in the deployment of different technologies for a medium mitigation target of 550 ppm-eq: one technology can easily be replaced with another, albeit with an increase of costs in some cases (Figure 3(a)). For the more ambitious target of 400 ppm-eq, by contrast, this flexibility is lost (Figure 3(b)): this target can only be achieved if a broad portfolio of technologies is available. Also, delays or imperfections in the setup of an international carbon market have a considerable impact. Under a stylized scenario of a delayed setup of a global carbon market, only 2 out of 10 models that participated in the EMF-22 study[16] found the 450 ppm-eq target to become feasible (Figure 4). The RECIPE study found that a delay of any climate policy action beyond 2020 renders the 450 ppm CO_2 target infeasible. Under the assumption that a global climate policy regime is established by 2020, overall mitigation costs decrease substantially with an increasing number of regions that start immediately with climate policy (Figure 5). Overall, the evaluation of second-best worlds exhibits that imperfections can have pronounced effects on the costs of mitigation. Costs of mitigation will increase in the case of technological failures or a low degree of international participation.

CONCLUSION

We examined recent developments in mitigation scenarios and progress in their analyses achieved since the finalization of the IPCC's AR4. We specifically focused on ambitious mitigation scenarios, the evaluation of baseline uncertainty and the assessment of second-best scenarios.

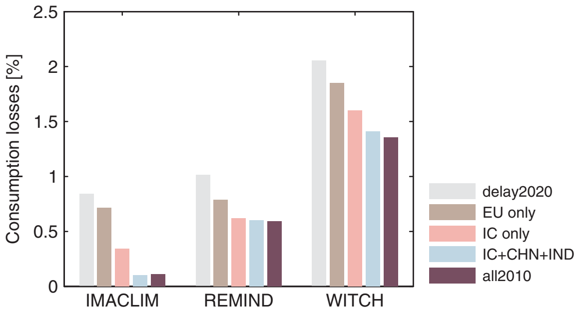

FIGURE 5 | Example III of assessing second-best worlds: Results from RECIPE[17,18] exploring various scenarios with delayed participation in a global carbon market and a benchmark case with global participation from 2010 ('all2010'). Percentage changes of consumption are given relative to baseline for the three models IMACLIM, REMIND, and WITCH. In 'delay2020', all regions postpone mitigation action until 2020. 'EU only' refers to a scenario the EU unilaterally pursues climate policy from 2010. In 'IC only' all industrialized countries take early action, while the coalition of early movers in 'IC+CHN+IND' encompasses also China and India. All scenarios assume that the rest of the world joins the climate coalition in 2020. (Reprinted with permission from Ref 17. Copyright 2009 Potsdam Institute for Climate Impact Research)

Ultimately, the decisive question for climate mitigation research is about the achievability of low stabilization targets. It will be important to explore the 'feasibility frontier', i.e. the most ambitious

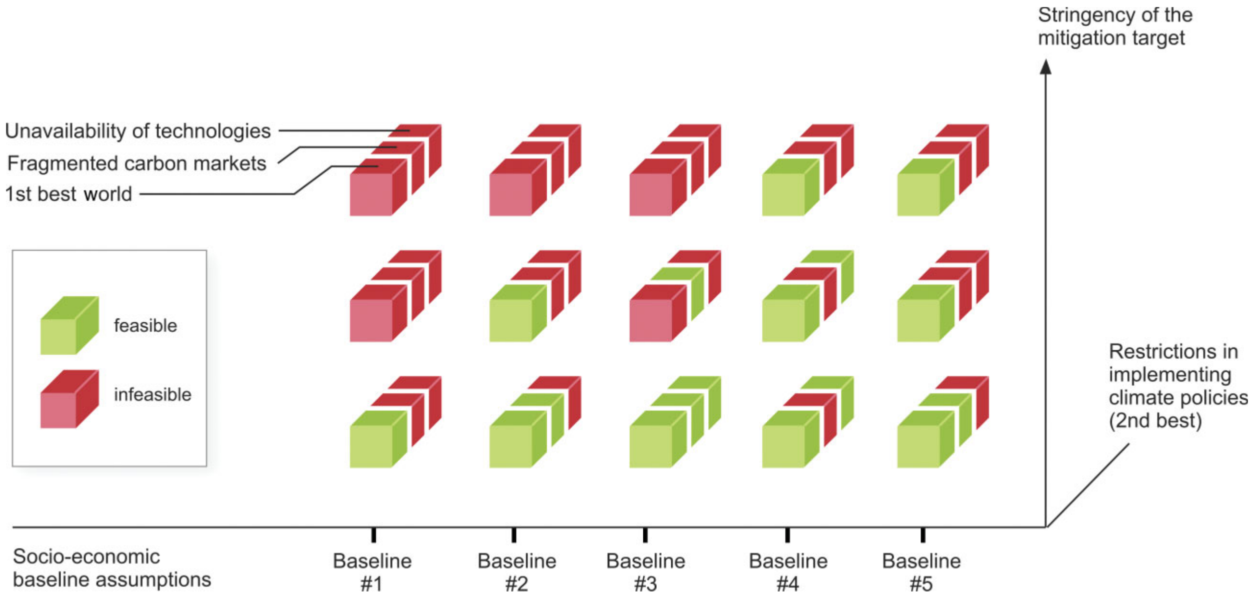

FIGURE 6 | Exploring the feasibility constraints of a model within the three-dimensional assessment space (see text for a detailed description of the axes). Feasible model solutions are indicated in green, infeasibilities in red. This figure has only an illustrative purpose and is not related to specific model results.

mitigation target that is still achievable and to assess to what extent it depends on scenario and model assumptions. A more systematic evaluation is needed to bring these different facets together and to assess the full solution space of the mitigation problem. Evaluating each model within a three-dimensional (3D) 'assessment space' could advance mitigation research and foster a more sophisticated policy assessment. These three dimensions include (Figure 6): (1) the description of different socio-economic baseline assumptions, for instance with respect to economic, demographic, and technological development or governance structures, (2) restrictions in implementing climate policies (second-best), e.g. extreme scenarios in terms of the unavailability of technologies or fragmented climate policy regimes, and (3) the stringency of the mitigation effort. The first two axes are discrete, and it is important to note that the policy framework for implementing climate policy is not entirely independent of the socio-economic baseline assumptions. For instance, a fragmented climate policy regime seems more likely in a divergent world than in a globalized world with a high level of international integration.

Each model incorporates specific assumptions and will report specific results with respect to (in)feasibilities of certain settings within the 3D assessment space. An assessment of feasibility patterns across models helps to identify the feasibility frontier for specific climate targets in combination with specific assumptions concerning the baseline and the policy dimension. In parallel, coordinated model intercomparisons have to be performed to consistently evaluate how discrepancies in model results relate to structural differences in model designs and the underlying implicit assumptions.

It is the task of the scientific community to come up with an assessment of the full solution space for mitigating climate change in order to inform policy-makers about their opportunities and alternative options. Since the IPCC AR4, new developments and major progress have been made concerning the evaluation of stringent climate mitigation targets and the assessment of these scenarios in a more realistic framework. In a first-best world, where all technologies are available and where full participation of all countries in global mitigation efforts is assumed, even stringent mitigation targets are attainable at moderate costs. In a second-best world or under different assumptions for a business-as-usual case, this may change dramatically. Feasibility thresholds are reported for technology assumptions, policy assumptions, and assumptions on socio-economic development. The Fifth Assessment Report of the IPCC should head toward a better understanding of the most crucial assumptions for the feasibility of mitigation scenarios. The only way to give such a consolidated appraisal is to explore the full assessment space. One of the foremost challenges for climate-economic research is therefore to explore the feasibility frontier of climate change mitigation along the three dimensions outlined above.

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