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Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals

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ABSTRACT

This paper provides an overview of the AMPERE modeling comparison project with focus on the implications of near-term policies for the costs and attainability of long-term climate objectives. Nine modeling teams participated in the project to explore the consequences of global emissions following the proposed policy stringency of the national pledges from the Copenhagen Accord and Cancún Agreements to 2030. Specific features compared to earlier assessments are the explicit consideration of near-term 2030 emission targets as well as the systematic sensitivity analysis for the availability and potential of mitigation technologies. Our estimates show that a 2030 mitigation effort comparable to the pledges would result in a further "lock-in" of the energy system into fossil fuels and thus impede the required energy transformation to reach low greenhouse-gas stabilization levels (450 ppm CO_2e). Major implications include significant increases in mitigation costs, increased risk that low stabilization targets become unattainable, and reduced chances of staying below the proposed temperature change target of 2 °C in case of overshoot. With respect to technologies, we find that following the pledge pathways to 2030 would narrow policy choices, and increases the

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risks that some currently optional technologies, such as carbon capture and storage (CCS) or the large-scale deployment of bioenergy, will become "a must" by 2030.

1. Introduction

Limiting climate change has been the subject of international negotiations for more than 20 years. In this process, long-term aspirational goals have been identified by the Parties to the UNFCCC with more than 190 countries supporting goals to keep global temperature rise to below 2 °C compared to pre-industrial times [1]. Achieving this objective requires a fundamental transformation of the energy and other greenhouse gas emitting sectors in order to reduce emissions and to stabilize their concentrations in the atmosphere [2–6]. A globally comprehensive agreement with binding emission limits to achieve this goal is currently lacking. Instead, the Kyoto Protocol has been extended and countries have made pledges to reduce their emissions in the near term, i.e. by 2020, first as part of the Copenhagen Accord, later anchored in the 2010 Cancún Agreements [7].[1] The countries with pledges represent about 80% of current global emissions [8].

The implications of the near-term pledges for the feasibility and costs of long-term targets are poorly understood. Previous studies indicate that the emissions resulting from the pledges would be higher than the least-cost emission pathways of most scenarios reaching 2 °C (e.g. [9,10]). This is, for instance, assessed in the UNEP Emissions Gap Reports [8,11] and in Höhne et al. [12]. The pledges correspond thus to a relatively modest climate policy signal, leading in the near-term to an "emission gap" compared to optimal pathways toward 2 °C [13]. The explicit analysis of the long-term consequences of this emission gap has, with a few notable exceptions [14–16], not been conducted at this time.

In this paper we present an overview of the AMPERE model comparison with focus on the implications of modest short-term policies to 2030. In this context, we assess the emission consequences of the pledges for the year 2020, and specifically explore the implications if the policy stringency of the pledges would continue to the year 2030. In total nine international integrated assessment modeling teams have participated in the model comparison and developed a set of more than 300 scenarios based on harmonized assumptions about the pledges and other factors (see Section 2 on methods). The diversity of modeling approaches permits us to cover a wide range of dynamics and to explicitly explore uncertainty owing to structural as well as parametric differences between the models. Our paper is complemented by a second AMPERE modeling comparison exploring the implications of different regional accession rules for long-term climate policy objectives [17]. In addition, a series of papers in this issue present insights of individual modeling teams in greater detail [18–22].

Stabilizing global temperatures requires a limit on the cumulative amount of long-lived greenhouse gases emitted to the atmosphere [23–26]. Any lack of emission mitigation over the near term will need to be compensated thus by more stringent and more rapid emission reductions later in the century. Key questions addressed in the paper are, therefore, whether the "gap" can still be closed and long-term targets be attained if the world delayed stringent policies up to 2030? What are the implications for the pace of the future energy transformation, considering particularly the inertia of the system against rapid changes? How would the overall costs of mitigation be affected, and which technologies might be critical for bridging the near-term emission gap?

A distinguishing feature of our modeling comparison is the explicit consideration of short-term targets in order to explore trade-offs between the required near-term emission mitigation, and their consequences for the attainability of alternative climate targets in the long term. We specifically focus on the 2030 time-frame for the short-term targets. This time-frame is of high policy relevance as our analysis could provide important guidance for the required stringency of post-2020 targets on which the negotiations will need to increasingly focus during the coming years. For an assessment with focus on the 2020 time-frame see [27–30].

Choices about mitigation technologies as well as society's ability to limit energy demand play a critical role for the nature, direction, and attainable pace of the energy transformation and associated greenhouse gas emission reductions [2,15,31–35]. We thus conduct also a systematic technology sensitivity analysis and explore the implications if the deployment of certain mitigation technologies would become more restricted compared to their full potential. These restrictions reflect possible political choices with respect to more controversial options, such as nuclear or carbon capture and storage (CCS) (see, e.g., [36,37]), but can also be the result of technical or other implementation barriers (e.g., variable renewable energy that may face challenges with respect to systems integration [38,39], or biomass that may face restrictions due to competition over land [40]). The analysis of supply-side technologies is complemented by a sensitivity analysis on the demand-side to better understand the potential contribution of efficiency and energy intensity improvements. The technology sensitivity cases were closely coordinated with the parallel ongoing modeling comparison of the Energy Modeling Forum (EMF27) [41].

In this paper, we first describe methods and scenario design (Section 2), and then turn to the critical question of the implications of alternative near-term policies for the timing of mitigation and greenhouse gas emission pathways. Section 3 explores consequences for the required pace of the energy transformation, and Section 4 examines costs and feasibility issues. Section 5 concludes.

2. Methodology and scenario design

Our study employs nine different global integrated assessment models of the economy with alternative representations of the main greenhouse gas emitting sectors. We use the models for the development of a set of long-term climate stabilization scenarios for the 21st century.

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[1] The extension of the Kyoto Protocol implied that only some Annex-I Parties joined the Protocol and that their targets correspond to the low-ambition pledges that were made in Cancún.

In order to explore the consequences of near-term pledges, our scenarios consider a combination of different short-term and long-term targets, which divide the century-scale time horizon of the scenarios into two stages. During the first stage up to the year 2030, global emissions are required to follow a trajectory toward a 2030 emission target. After 2030, emissions are constrained further to stay within a cumulative emission budget for the full century (2000–2100) in order to achieve stabilization of greenhouse gas concentrations in the long-term. In this set-up, the amount of cumulative emissions that may be vented to the atmosphere in the second stage (after 2030) will critically depend on the short-term emission pathway to 2030. The distinct separation of the time-frames helps us to explicitly assess the consequences of actions over the short-term for the attainability and costs of long term objectives. This makes our study also different from the majority of earlier assessments that primarily focused on stabilization scenarios with “optimal” timing of the mitigation efforts [8,11].

2.1. Short-term emission targets

For deriving the short-term targets, we estimated the resulting global GHG emission levels from the pledges by 2020 and extrapolated the mitigation effort to 2030 (see Supplementary material). The estimated emissions of the pledges are based on den Elzen et al. [42]. Global emissions resulting from the pledges are subject to uncertainty, since some country pledges are coupled to conditions (such as financial support or action by other countries) or are defined relative to an uncertain business as usual path [8]. We use two common interpretations of the pledges for deriving “High” and “Low” emission targets for the year 2020. Our low emission target corresponds to a so-called conditional case where all pledges become fully implemented at a high level of ambition. The high emission target assumes implementation of the unconditional and low-ambition pledges only (see the Supplementary material for further detail). As a second step we extrapolate the global mitigation stringency of the 2020 pledges to derive the corresponding emission targets for the year 2030. This translates into a “Low” short-term greenhouse gas emission target growing from presently around 50 $GtCO_2e$ to about 51 $GtCO_2e$ by 2020 and reaching 53 $GtCO_2e$ by 2030. Emissions in the “High” pledge target are around 55 $GtCO_2e$ in 2020, and increase to 61 $GtCO_2e$ by 2030. The pledges lead to 2030 emissions that are lower than emissions under business as usual conditions (Fig. 1A).[2]

2.2. Long-term emission targets

We adopt two long term targets corresponding to the objective of stabilizing greenhouse gas concentrations at 450 and 550 ppm CO_2e. The 450 ppm CO_2e corresponds to about the lowest greenhouse gas emission scenarios in the literature [43] broadly consistent with keeping long-term temperature change below 2 °C compared to pre-industrial levels [44]. The 550 ppm CO_2e explores a target with intermediate stringency. While all modeling frameworks in our study cover CO_2 emissions from fossil fuels and industrial sources (the main contributor to anthropogenic climate change) only a limited set of models also cover emissions from the land-use sector and/or the full suite of greenhouse gases, including non-CO_2 GHGs and emissions of other radiatively and chemically active substances (such as aerosols from black carbon or sulfur). Previous studies indicate that cumulative CO_2 emission budgets for 2000–2100 are a good indicator for the stabilization level [23,45]. We use thus total cumulative CO_2 emission budgets (2000–2100) as a constraint for the long-term target across all models. The 450 ppm CO_2e target corresponds to a cumulative emission budget of 1500 $GtCO_2$ (2000–2100) and the 550 ppm CO_2e target to a budget of 2400 $GtCO_2$ (2000–2100). Models with full representation of non-CO_2 GHGs reduce emissions from these sources assuming the same CO_2-equivalent price as for CO_2 (see [46] Schaeffer et al. and the supplementary material).[3]

2.3. Harmonization of main input assumptions

Important features of our scenario design compared to earlier intermodel comparisons [4,6,35] are the harmonization of assumptions for main emission drivers, such as demographic and economic change and the future development of energy demand. The harmonization is important to improve comparability of the results. However, it also reduces the uncertainties associated with the socio-economic drivers.

Our baseline assumptions for GDP and population correspond to an intermediate pathway compared to the literature and were derived from [47,48] (see the Supplementary material). In order to explore sensitivity of our results to different demand assumptions, we distinguish two contrasting scenarios. In the reference case, global energy intensity is following broadly historical rates of improvement, leading to an increase in global energy demand by about a factor of two in 2050. We explore in addition a low energy demand case (LowEI) broadly consistent with the lower bound of demand projections in the literature, depicting stringent efficiency measures and behavioral changes to radically limit energy demand [2,49,50]. The rate of energy intensity improvement in the low demand scenario is about 50% higher than the historical rate of change (see Fig. 2 in the supplementary material).

2.4. Technology sensitivity cases

In addition to sensitivity cases for energy demand, we explore the feasibility of the transformation for a variety of different supply-side portfolios. These supply-side cases not only focus on possible restrictions for specific technologies that might arise due to political concerns and public perception, but also on implementation barriers or other concerns. Through the sensitivity cases, we try to better understand the role of individual

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[2] The extrapolation of the global emissions of the pledges to 2030 requires an assessment of the equivalent mitigation effort of the 2020 pledges for the future. We rely for this purpose on the distribution of the 550 ppm CO_2-e scenarios from AMPERE, which per design depict a continuation of equivalent effort over time to reach a long-term target. For the extrapolation between 2020 and 2030 we assume that global emissions would continue along the respective percentile pathway of the full distribution of the 550 ppm scenarios between 2020 and 2030. We further consider the emission reductions from the baseline in 2020 in order to assess the equivalent global emission levels by 2030. For further details see the supplementary material.

[3] For applying the CO_2 price to other non-CO_2 GHGs (N2O, CH4, SF6, CF4, and long-lived halocarbons), each model's default assumption on global warming potentials is used.

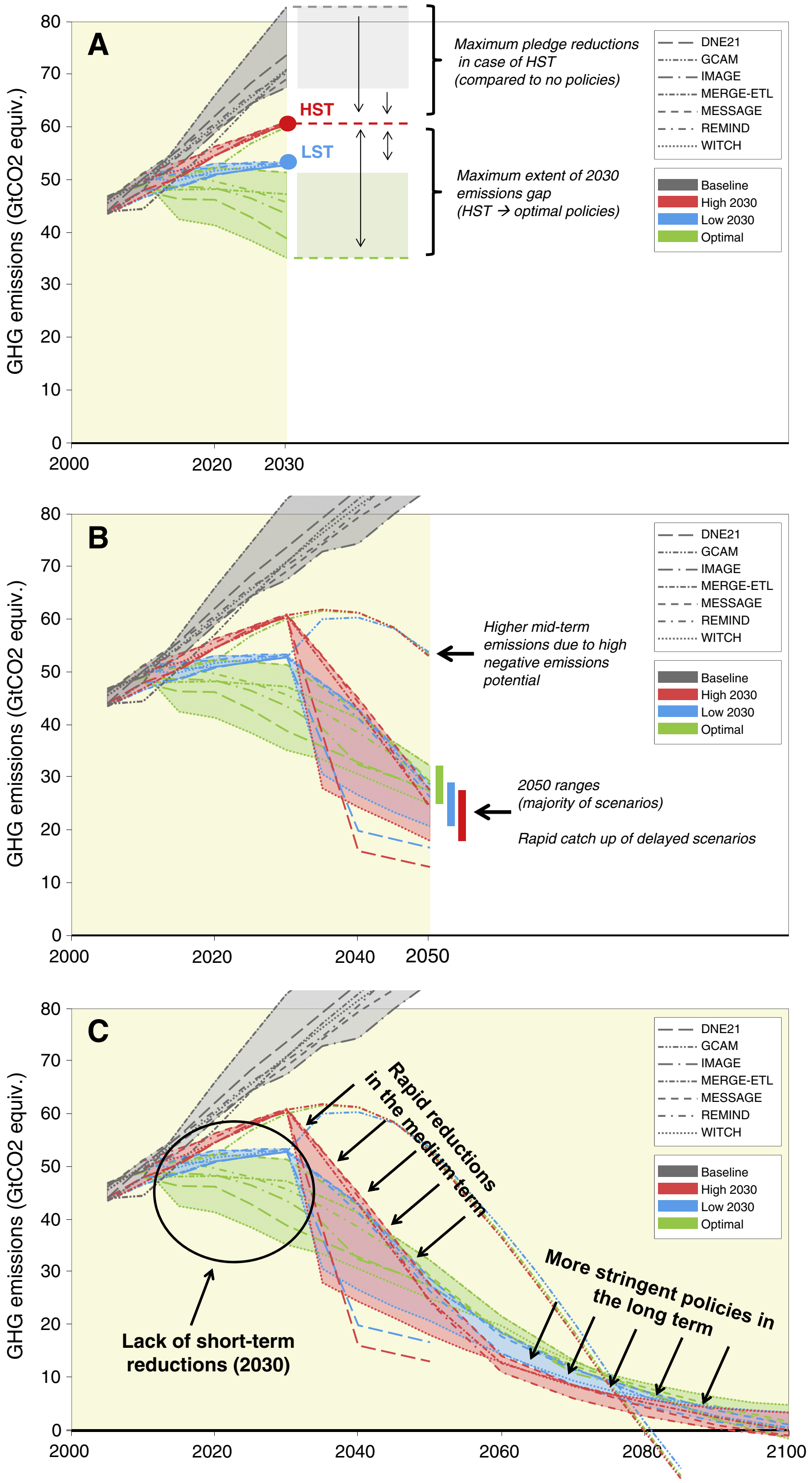

Fig. 1. Development of global GHG emissions in the “FullTech” 450 ppm CO_2e scenarios with high (HST), low (LST), and optimal 2030 emission levels. Shaded areas show ranges across long-term models to 2100, excluding GCAM, which shows emission development assuming high potential for negative emissions. Upper panel (A) shows the emission development to 2030 and the maximum extent of the emission gap. Middle panel (B) illustrates the development to 2050, and lower panel (C) to 2100.

Table 1
Technology sensitivity cases and short-term emission targets assumed in the AMPERE scenarios.

	Description	Scenario name
Short-term targets (2030)		
Low short-term target	Global emissions follow a high ambition pledge pathway reaching 53 $GtCO_2e$ by 2030. Thereafter ambitions are adjusted to meet the long-term targets (450 or 550 ppm CO_2e).	"LST"
High short-term target	Global emissions follow a low ambition pledge pathway reaching 61 $GtCO_2e$ by 2030. Thereafter ambitions are adjusted to meet the long-term targets (450 or 550 ppm CO_2e).	"HST"
Optimal policy	Global emissions follow an optimal pathway assuming immediate introduction of climate policies to meet the long-term targets (450 or 550 ppm CO_2e). No explicit short-term target for 2030 is assumed.	"OPT"
Technology cases		
Full technology	The full portfolio of technologies is available and may scale up successfully to meet the respective climate targets.	"FullTech"
Low demand and energy intensity	A combination of stringent efficiency measures and behavioral changes radically limits energy demand, leading to a doubling of the rate of energy intensity improvements compared to the past. The full portfolio of technologies is available on the supply side.	"LowEI"
No new nuclear	No new investments into nuclear power after 2020; existing plants are fully phased out over their life time.	"NucOff"
No CCS	The technology to capture and geologically store carbon dioxide (CCS) never becomes available. This impacts both the potential to implement lower emission options with fossil fuels and the possibility to generate "negative emissions" when combined with bio-energy.	"NoCCS"
Limited solar and wind	Limited contribution of solar and wind to 20% of total power generation, reflecting potential implementation barriers of variable renewable energy at high penetration rates.	"LimSW"
Limited biomass	Limited potential for biomass (maximum of 100 EJ/year), exploring strategies that would avoid large-scale expansion of bioenergy and thus avoid potential competition over land for food and fiber.	"LimBio"
Conventional solutions	Limited solar, wind and biomass potentials, leading to heavy reliance on conventional technologies such as fossil fuels in combination with CCS and/or nuclear.	"Conv"
Efficiency and renewables	A low demand case assuming "No CCS" and "no new nuclear", leading to heavy reliance on renewables and efficiency measures.	"EERE"

technologies, and identify the most important mitigation options for keeping low stabilization targets within reach. Table 1 provides a brief description of each of the cases. For further details about assumptions, see the Supplementary material.

2.5. Calculation of the climate change response

We use the reduced complexity climate and carbon-cycle model MAGICC [51,52], version 6, for the calculation of GHG concentrations and temperature outcomes of the scenarios. This allows us to explore climate responses of the scenarios based on a harmonized methodology consistent with the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). MAGICC6 is set up to probabilistically [23] span the uncertainties in carbon-cycle [53], climate system [54] and climate sensitivity [55] of the IPCC AR4, and is constrained by historical observations of hemispheric land/ocean temperatures [56] and historical estimates for ocean heat-uptake [57]. In addition to concentrations and median temperature change, MAGICC6 is used to compute the transient exceedance probabilities of the 2 °C temperature target of each scenario. Temperature increase relative to pre-industrial values is computed relative to the average temperature between 1850 and 1875. For further details see Schaeffer et al. [46].

2.6. Modeling frameworks

Our study compares results from nine global modeling frameworks that participated in the AMPERE modeling comparison (DNE21+, GCAM, IMACLIM, IMAGE, MERGE-ETL, MESSAGE-MACRO, POLES, REMIND, and WITCH). The models represent a wide range of different approaches, including general equilibrium, partial equilibrium, dynamic recursive, perfect foresight, systems engineering as well as hybrid approaches. The models further differ also with respect to representation of sectors, greenhouse gas emissions, and the timeframe. Seven of the models have a full representation of the Kyoto greenhouse gases and land-use CO_2 (DNE21+, GCAM, IMAGE, MERGE-ETL, MESSAGE-MACRO, REMIND, and WITCH), while other models focus primarily on fossil and industrial CO_2 only (IMACLIM, POLES).[4] In addition, DNE21 focuses on the transition to 2050, while the other modeling frameworks model the full century. Assumptions about near-term emission targets for 2030 were thus estimated in CO_2e as well as CO_2-only emissions, and unique cumulative CO_2 budgets were provided with and without land-use CO_2 and for time horizons up to 2050 and 2100 (see Supplementary material).

The diversity of approaches is an important asset, since it helps us to better understand structural uncertainties, and to focus on findings that are robust across a wide range of methodologies. An in-depth diagnostic analysis of the models is summarized in [58] and further details about the model characteristics can be found in the supplementary material of Kriegler et al. [17].[5]

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[4] Note that POLES has a partial representation of some of the non-CO2 GHGs. In our analysis POLES is however treated as other CO2-only models, since the coverage of non-CO2 gases is not comprehensive.

[5] References to papers describing the modeling approaches can be found in the supplementary material.

3. GHG emission pathways and temperature consequences

The development of the GHG emissions in the near term determines the required stringency of emission reductions in the long term. In order to achieve a specific stabilization target, any lack of short-term emission mitigation of long-lived greenhouse gases by, for example 2030, needs thus to be compensated by more stringent emission reductions later in time. In this section we discuss the implications of following the near-term pledges for the GHG emission pathway and the climate response in terms of temperature change.

Following a mitigation effort comparable to the pledges results in our analysis to near-term global emission targets between 53 $GtCO_2e$ to 61 $GtCO_2e$ for the year 2030. This corresponds to an increase of emissions by about 6 to 22% compared to the current emission level (50 $GtCO_2e$), and is also significantly above near-term emission levels from scenarios that assume an "optimal" timing of the mitigation effort to reach 450 ppm stabilization targets [8,45].

The lack of short-term mitigation leaves thus a near-term "emission gap" compared to an immediate and "optimal" phasing of climate policies. The size of the 2030 emission gap depends on the assumptions about the pledges and the stringency of the long-term target. The gap is most pronounced for the long-term stabilization target of 450 ppm CO_2e (Fig. 1A). Compared to the optimal emission levels of our ensemble, a lenient interpretation of the pledges to 2030 (our high short-term target "HST") results in an average emission gap across the models of 14.3 (0.7–25.6) $GtCO_2e$ by 2030 (Fig. 1A). Under the low short-term target ("LST") the gap is reduced to 6.6 (−7.2 to 18.2) $GtCO_2e$, and is even negative for some of the models.[6] The HST and LST emission levels by 2030 are broadly consistent with the long-term target of 550 ppm CO_2e without any significant emission gap (see Fig. 3 in the Supplementary material). Our discussion in this section thus focuses primarily on the implications for the 450 ppm CO_2e target.

Embarking on the HST pathway means that about 70% of the overall cumulative budget for 450 ppm CO_2e (1500 $GtCO_2$) is released to the atmosphere already by 2030. This leaves only little flexibility for the long term emission path in order to stay within the cumulative emission target. Compared to the optimal pathways, the HST-scenarios require thus more rapid emission reductions over the medium term between 2030 and 2050 as well as deeper emission reductions to lower (absolute) levels in the long term (Fig. 1B,C). While overall dynamics in the LST-scenarios are similar, there is more flexibility for the emission pathways post 2030 to reach the 450 ppm CO_2e target.

Interestingly, we find that across all models the emission gap is entirely closed already in 2050. Or in other words, annual emissions have been reduced rapidly in all HST scenarios to similar levels, often to even lower levels than in the optimal climate policy scenarios toward the 450 ppm CO_2e target (Fig. 1B). Despite the delays in mitigation in the HST scenarios, GHG emissions by 2050 in most models reach thus comparatively low levels and cluster around a narrow band of 18–28 $GtCO_2e$ by 2050. This poses a significant challenge for the HST scenarios, as it leaves only 20 years (2030 to 2050) for a fundamental transformation of the global energy-economic system. One model in our set finds such a rapid transformation not feasible under any of the assumed demand or technology variations (IMACLIM), and another model (IMAGE) finds the transformation only possible if energy demand is comparatively low ("LowEI" case). On the other hand, the GCAM model is indicating that emissions by 2050 may reach significantly higher levels than in the other models (in the HST, LST as well as in the case of optimal policies, see Fig. 1B). These comparatively high short-term emissions are primarily due to the model's high potential for negative emissions from Bio-CCS (biomass in combination with carbon capture and storage) and afforestation. Utilizing such high negative emission potentials would require scaling up bio-energy in combination with CCS to about 800 EJ over the course of the century (by comparison, the current global primary energy use of all energy carriers is about 500 EJ). With more limited potential for negative emissions due to, for example, limited biomass availability, GCAM must lower 2050 emissions to similar levels as the other models in our study (see Fig. 4 in the Supplementary material). For more information on the importance of negative emissions on the timing of GHG mitigation and the attainability of low stabilization targets see also [34,45,59–61], and for a further analysis of the role of negative emissions in our study, see [18].

Atmospheric GHG concentrations span a relatively wide range across the scenarios (Table 2). This is partly due to our scenarios set-up, which defines the long-term target in terms of cumulative CO_2 emissions. The realized long-term concentrations differ thus across the models, and depend on concurrent reductions of non-CO_2 gases and the assumed development of aerosol emissions (in particular sulfur). The full range across the "450 ppm" AMPERE scenarios is 450 to 520 ppm CO_2e (overall 66% uncertainty range, including carbon-cycle and climate-system uncertainties). The median across the AMPERE "450 ppm" scenarios is 480 ppm CO_2-e, and lies thus slightly above the target concentration.[7]

The maximum temperature change in the 450 ppm CO_2e scenario is below 2 °C for most of the models with an overall median of the estimates around 1.9 °C for optimal policies and around 2.0 °C for the HST and LST scenarios. Scenarios with high potential of negative emissions and thus larger overshoot in emissions in the medium term (Fig. 1B) show the biggest transient temperature response of up to 2.5 °C. By comparison, temperature increases on average to about 2.4 °C in our 550 ppm scenarios.

For assessing the likelihood of the scenarios for the 2 °C target, we conduct a probabilistic analysis using MAGICC6 (see Schaeffer et al. [46]). We find that the HST scenarios with a long-term target of 450 ppm CO_2e show on average a 5 percentage point higher probability to exceed the 2 °C

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[6] Numbers in parentheses correspond to the full range of the gap across all models.

[7] As explained in the methodology section, the climate outcomes of the scenarios were calculated with the climate model MAGICC6. MAGGIC6 shows a slightly higher emissions-to-concentration response than the climate module of the original AMPERE models. Concentrations from MAGICC6 as reported in Table 2 are thus slightly above the indigenous concentrations that were calculated by many of the original AMPERE models (see also the AMPERE database: https://secure.iiasa.ac.at/web-apps/ene/AMPEREDB/).

Table 2
GHG emissions, atmospheric concentrations, and temperature consequences in the "FullTech" scenarios. Numbers correspond to the median and the full range across the scenarios. Note that for the climate simulations, emissions were harmonized to the same base year using inventories from [76,77].

	CO_2 emissions	CO_2e emissions	Cumulative CO_2 emissions	CO_2e concentrations	Temperature change	Probability of exceeding 2 °C
	(2030)	(2030)	(2005–2100)	(2100)	(Max)	(Max)
	$GtCO_2$	$GtCO_2e$	$GtCO_2$	ppm	°C	%
Baseline	53 (50–67)	71 (68–83)	6268 (5670–8755)	1143 (1023–1338)	4.6 (3.5–5.9)	100 (100–100)
450 optimal	31 (24–45)	46 (35–60)	1330 (1242–1350)	485 (453–522)	1.9 (1.5–2.4)	42 (26–84)
450 LST	39 (37–42)	53 (53–53)	1335 (1263–1379)	488 (455–524)	2.0 (1.5–2.5)	45 (28–84)
450 HST	46 (44–49)	61 (60–61)	1344 (1274–1382)	484 (452–520)	2.0 (1.6–2.5)	47 (28–84)
550 optimal	40 (31–47)	55 (49–63)	2234 (2211–2250)	569 (524–618)	2.3 (1.8–3.0)	75 (64–93)
550 LST	39 (37–42)	53 (52–53)	2238 (2199–2283)	570 (525–620)	2.3 (1.8–3.0)	75 (66–93)
550 HST	46 (44–49)	61 (60–61)	2235 (2190–2269)	567 (523–617)	2.3 (1.8–3.0)	76 (66–93)

target than the optimal scenarios (Table 2). This corresponds to an increase in the probability of exceeding 2 °C from about 42% in the optimal scenarios to about 47% in the HST cases, which is consistent with the small but noticeable higher median warming noted further above. Perhaps most importantly, the risks to exceed the 2 °C target are by far the highest (about 84%, see Table 2) in scenarios of our ensemble that are characterized by a large overshoot and where emissions continue to increase even above the HST level (GCAM 450 ppm CO_2e).

That the HST emission levels lead to only modest increases in probability to exceed 2 °C in our analysis, is influenced by the fact that 1) the HST scenarios reduce emissions very rapidly in the medium term (2030–2050), and 2) some models were not able to stay within the predefined budget for the HST case. Obviously, the emission pathways from these infeasible runs are not part of our sample. Our estimates miss thus the "climate penalty" from these models, which would have exceeded the long-term target and thus would have shown higher temperature response. Schaeffer et al. [46] find in addition that all HST scenarios are leading to a faster short-term warming, posing an increased challenge to adaptation efforts.

4. Implications for the pace of the transformation

An important characteristic of the energy sector is its long-lived capital stock, with lifetimes for infrastructure and energy conversion facilities of 30–60 years and sometimes longer. This longevity translates into high inertia in energy supply systems, which impedes rapid transformation [2,62,63]. It explains also the path-dependency of the system [64] and that once technological change is introduced into one direction, it is becoming increasingly difficult to change its course [32,65]. Decisions about the stringency of GHG policies over the next two decades are thus critical for the overall pace at which the transformation to low emissions needs to occur. Lack of near term climate policies may also add to the transformation challenge by increasing the inertia of the system due to additional lock-in of fossil-intensive infrastructures over the coming years. While Bertram et al. [66] and Eom et al. [18] explore lock-in effects of the pledge pathways in great detail, we focus in this section on the implications for the required pace of the transformation. Specifically, we explore the consequences of the HST and LST targets for the overall pace of CO_2 emission reductions and underlying energy system changes post 2030.

The previous section has shown the critical importance of the emission reductions by 2050 in order to close the near term emission gap of the HST and LST pathways. We thus focus on the required annual emission reductions over the time frame between 2030 and 2050 (Fig. 2), and compare these to historical precedents for various different countries where emission declines have been observed in the past.

The average global CO_2 emission reduction rate in our optimal 450 ppm CO_2e scenarios is about 3.7% per year between 2030 and 2050. Most models cluster in a relatively narrow band of 2.8–4.2% per year with a full uncertainty range of 1.2 to 5.5%.

Following the HST pathways to 2030 requires an acceleration of the global rate of emission reductions to 2050 by almost a factor of two compared to the optimal policy scenarios. The average emission reduction rate in the HST scenarios, for example, is about 7% per year between 2030 and 2050. Also the uncertainty band is shifted considerably to 1.3–10% per year as compared to the optimal policy cases (with the majority of HST scenarios clustering around 5.9–8.5% per year). The decarbonization of the LST scenarios to 2050 is also more rapid than in the optimal policy cases, but somewhat less fast than in the case of HST scenarios (Fig. 2).

These high reduction rates are achieved by fundamental and rapid structural changes of the energy system to bridge the emission gap by 2050 (Bertram et al. [66]). Sustained long-term decarbonization rates to the end of the century are generally slower than the reduction rates between 2030 and 2050 (Fig. 2). However, scenarios that strongly rely on negative emissions as, for example, illustrated by the GCAM model, are an exception. While negative emissions in the long term allow compensating for relatively higher short-term emissions, they also translate into the need for sustaining higher reduction rates in the second half of the century. The GCAM model thus shows higher long-term reduction rates (5% per year between 2030 and 2100), which roughly doubles the rate of other models in our ensemble.

While stringent climate policies have so far not been introduced in most parts of the world, it is useful to bring these global reduction rates into perspective using historical rates achieved by some countries. A distribution of national historical 20-year average annual emission reduction rates is presented in Fig. 2 [67]. Public support of nuclear power has led to annual declines in emissions in France of about 2% per

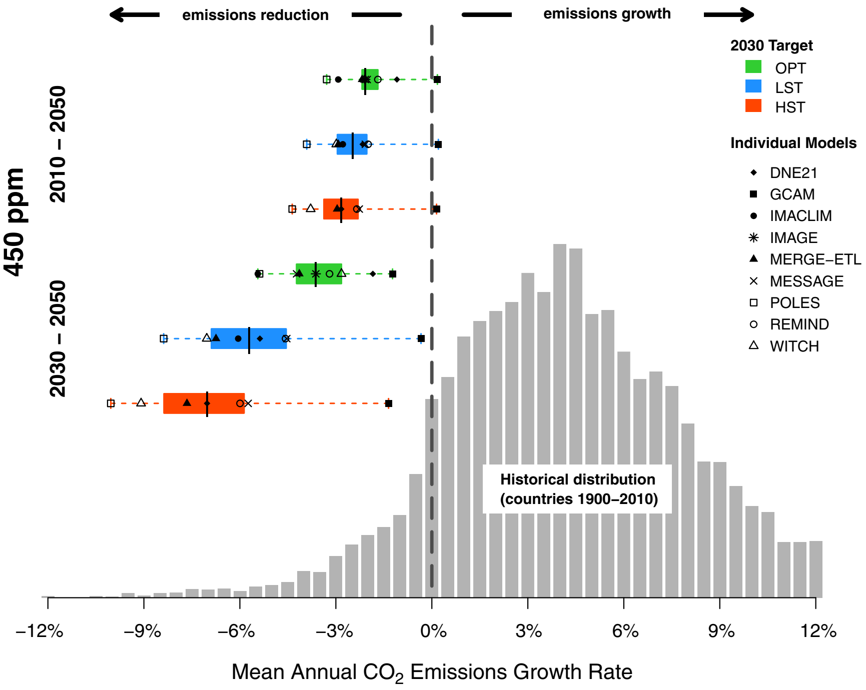

Fig. 2. Average annual rate of CO_2 emission growth/reductions in the "FullTech" 450 ppm CO_2e stabilization scenarios with different short-term targets (horizontal bars), and historical distribution of annual emission reduction rates across different countries of the world (20 year averages between 1900 and 2009 from [67]). Note that not all countries report time-series for the full historical period. For CO_2 emission reductions rates of other scenarios see the supplementary material.

year between 1980 and 2000. Similar decline rates can be observed in Sweden from 1974 to 2000 as a result of policies in response to the 1973 oil crisis and the greening of the Swedish energy system thereafter (2–3% per year). Similar growth rates can also be observed in Denmark and some other countries. While the decline rates of these countries are broadly consistent with the global rates from the majority of the optimal policy scenarios (2.8–4.2% per year), we emphasize that they were achieved at a completely different scale. What can be introduced at the national scale is only a weak indicator for the global challenge, which requires that all major emitting countries together, characterized by very different local circumstances, would need to accomplish such rapid changes. With this caveat in mind, it is noteworthy that higher emission reduction rates observed historically have primarily been achieved only due to economic recessions, as for example the collapse of the Soviet Union, which resulted in emission decline rates between 2 and 4% per year for Eastern European and former Soviet Union countries. Achieving global emission reduction rates due to dedicated policy interference on the order of 5.9–8.5% as required by the majority of the HST pathways is thus unprecedented even at the national scale. Analysis by Bertram et al. [66] and Eom et al. [18] shows that reducing emissions at this pace will require on the one hand the premature phase-out of a large number of fossil power plants, while on the other hand low-carbon technologies would need to be scaled up rapidly. The enormous challenge of such rapid transformations is also indicated by the fact that two of the AMPERE models cannot reach the target once short-term emissions increase to the HST level.

Achieving these emission reductions requires the substitution of fossil fuels by low-carbon alternatives, such as renewables, nuclear and the application of CCS (both in combination with biomass and fossil fuel conversion technologies). The ultimate share of low-carbon energy is dictated by the fact that global emissions will eventually need to be reduced to about zero or even become negative by the end of the century in order to attain the 450 ppm CO_2e target. Scenarios that try to reduce the concentrations to such low levels require thus an almost complete transformation of the system before the end of the century. In terms of the required long-term share of low-carbon energy, there is thus hardly any difference between our scenarios.[8] The median across the HST, LST and the optimal policy scenarios all show an increase of the low-carbon share to 90–95% by 2100 (Fig. 3). This compares to the current share of low-carbon energy of about 15%, which consists primarily of hydro and

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[8] Low-carbon energy includes renewables, nuclear and fossil fuels in combination with carbon capture and storage (CCS). Note that the AMPERE models treat renewables and nuclear as carbon neutral, and thus do not account for the associated life-cycle emissions during, e.g., the production of the technologies. Technological progress in especially uranium enrichment has recently yielded energy intensity reductions that have significantly lowered the GHG footprint of nuclear power [68]. This effect can be taken into account only in models that have a representation of nuclear fuel processing technologies (such as GCAM, MESSAGE and DNE21 +).

nuclear power, and non-commercial biomass in the developing world.

While the end-point of the energy transition is determined by the stabilization target, there are significant differences across the scenarios with respect to the pace at which low-carbon energy options need to be scaled up over time.

The low-carbon energy share is projected to double every 20 years in the optimal 450 ppm scenarios. This corresponds to a world-wide increase of the contribution of low-carbon energy to about 30% by 2030, and to about 60% by 2050 (Fig. 3) — a pace that is also consistent with other internationally proposed global energy targets, such as those from the UN's Sustainable Energy for All initiative [69,70] that has proposed a doubling of renewable energy shares by 2030 as one of its main objectives.

The comparatively modest policy signal of the pledges translates in the HST and LST pathways to much lower shares of low carbon energy in the near term. Particularly in the HST scenario, there is almost no progress with respect to the share of low-carbon energy, which remains at roughly current levels by 2030. The pledges result thus not only in an emission gap, but also to a pronounced “low-carbon energy gap” (see Bertram et al. [66]).

This low-carbon energy gap has severe implications for the upscaling needs of low-carbon options to 2050. During the period between 2030 and 2050 the share of low-carbon energy needs to more than quadruple in the HST pathways (from about 15 to 65%, see Fig. 3). In other words, about half of the global energy infrastructure would need to be replaced in a narrow time frame of two decades only. This would require not only double digit growth rates from many mitigation technologies, but also the premature replacement of existing fossil fuel capacities after 2030. Even the LST pathways require almost a tripling of the zero-carbon share between 2030 and 2050, an effort, which is significantly faster than the smooth transition of the optimal policy pathways. Eom et al. [18] analyze the associated future “upscaling needs” of individual technologies in terms of physical deployment measures, and compare those to observed historical rates. Their analysis shows that expansion requirements of capacity in the HST pathways might become particularly dramatic, for example, for some of the renewable technologies (for further details see [18]).

The comparatively modest policy signal of the pledge pathways poses thus a twin-challenge. On the one hand, they lead to a further lock-in of the energy system into fossil-intensive infrastructure, and on the other hand they reduce the flexibility of the energy system by requiring a much more rapid system transformation in the medium term (to 2050).

5. Mitigation costs and feasibility

This section presents implications of the pathways for the mitigation costs and the feasibility of the transformation. In order to assess the importance of different mitigation technologies to reach the climate targets, we extend the discussion in this section beyond the so-called “FullTech” scenarios, and present also the results for the technology sensitivity cases (Table 1).

Owing to methodological differences of the models, costs are presented and compared for two different metrics. For models that calculate macroeconomic impacts (REMIND, MESSAGE, MERGE-ETL, WITCH, and IMACLIM), mitigation costs are measured in terms of GDP losses. For other models (GCAM, IMAGE, and POLES) we report costs in terms of the area under the marginal abatement cost (MAC) curve. The two cost metrics might not be directly comparable, but tend to be of similar order of magnitude in models that report both dimensions.[9]

As shown by the diagnostic analysis of Kriegler et al. [58], models that have a higher technology resolution and that tend to be more “flexible” in terms of their mitigation response, are generally also reporting lower overall mitigation costs. Vice versa, models that tend to have lower flexibility report comparatively higher costs. Mitigation costs thus vary significantly across models. Despite this apparent uncertainty surrounding the individual estimates, however, the full ensemble of models reveals a number of robust insights.

Mitigation costs in the 450 ppm scenarios, expressed as the net present value (NPV) over the course of the full century, are generally higher than in the 550 ppm scenarios by at least a factor of two (Fig. 4A). Similar to earlier model comparisons (e.g., [4]), we find thus significant differences in abatement costs between the scenarios that reach 550 and 450 ppm targets.

Another important finding is that the cost-implications of the near-term targets (LST and HST) are relatively small in the 550 ppm scenarios. This might be less of a surprise, given that the short-term emission pathways of the pledges (LST and HST) are rather similar to the observed emission trends of the optimal 550 ppm scenarios (see Fig. 3 in the Supplementary material). In other words, LST and HST pathways are broadly consistent with 550 ppm, and there is thus no big need to compensate for the lack of short-term emission reductions that may translate to significant implications for the mitigation costs.

By contrast, the pledge pathways (LST and HST) have, however, major implications for the costs of meeting the 450 ppm target (see panel b of Fig. 4). For example, the median mitigation costs across models increase in the case of the HST target by about 30% compared to the median of the optimal policy cases. The full range across models is between a 1% and 55% increase compared to the optimal case. Recall also that two models found that it was not possible to reach 450 ppm CO_2e from the HST pathway. Costs from these models are thus not included. Following the low short-term target (LST) increases costs across the models on average by about 7% for the full century (full range is between 2 and 20%). The costs are discounted over the full century with a discount rate of 5%. They include the mitigation costs up to the year 2030 as well as the long-term costs to 2100. These are thus net costs, fully taking into account near-term cost–benefits of the modest mitigation effort of the pledge pathways to 2030. Overall, our results show the paramount

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[9] Note that the analysis of mitigation costs focuses on the results from the long-term models that cover a time-horizon of the full century. Results for the short-term models can be found in the AMPERE database: https://secure.iiasa.ac.at/web-apps/ene/AMPEREDB/.

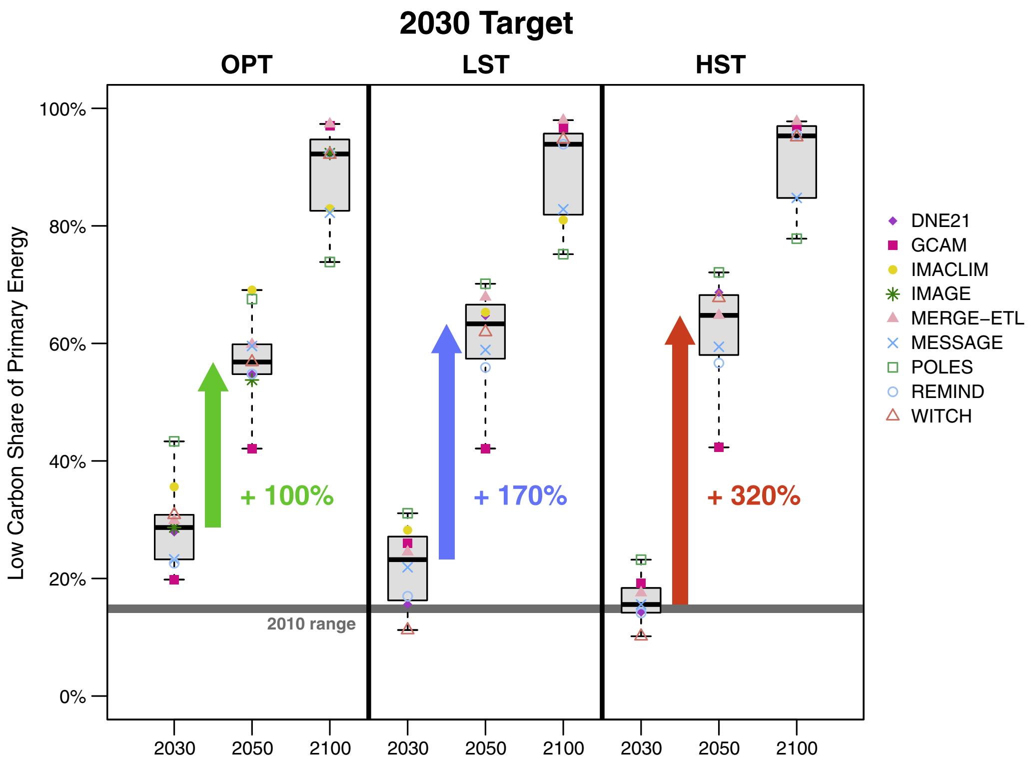

Fig. 3. Share of low-carbon energy in total primary energy of "FullTech" scenarios with different short-term targets (HST, LST and optimal pathways). Low-carbon primary energy includes contributions from renewable energy, nuclear, and the share of fossil fuels that are used in combination with carbon capture and storage (CCS). Primary energy is accounted in direct equivalents.

importance of the policy signal over the next two decades for the costs-effectiveness over the entire century in order to reach the 450 ppm CO_2e target (Fig. 4A,B).

Limiting the costs of emission mitigation to a specific maximum threshold and avoiding possible economic discontinuities have been suggested by earlier studies as metrics to enhance political acceptability of emission reduction targets for the post-Copenhagen negotiations [16,71]. We thus also explore mitigation costs over time, and specifically look into the differences across the scenarios with respect to peak or maximum mitigation costs of the 450 ppm scenarios (Fig. 5).[10] We find that impacts of the HST and LST pathways on peak costs to be even more pronounced than the NPV over the century. In the HST pathways the maximum mitigation cost increases on average by about 50% across the models compared to the optimal case (full range across models is between 3 to 110%, see Fig. 5). Also in the LST scenarios, the peak mitigation costs are substantially higher than in the optimal cases (compare, e.g., Figs. 4b and 5). The pronounced increase in the peak costs occurs in most models between 2030 and 2050, i.e., the time-frame where HST and LST pathways need to achieve a fundamental and rapid transformation to reach the long-term target of 450 ppm. The impact of the pledge pathways on the mitigation cost is the smallest in models that have the biggest flexibility to compensate high near term emissions through large contributions of negative emissions in the second half of the century (e.g., GCAM).[11]

Similar to other cost metrics, we observe considerable differences across the model estimates for the associated marginal abatement costs or carbon prices (see Fig. 9 in the Supplementary material). For example, in the optimal 450 ppm scenarios carbon prices differ by about an order of magnitude, from less than 100 $/$tCO_2$ to more than 1000 $/$tCO_2$ by the year 2050. There is strong agreement across the estimates, however, that the price of carbon would increase considerably in the HST cases by at least 50% (up to 300%) compared to the optimal scenarios. The effect in GCAM is again smaller than in the other models.

Comparing our results to the scenarios of the modeling comparison project LIMITS [27–30] further emphasizes the importance of the near-term emission reductions to 2030. LIMITS has been conducted in parallel to AMPERE, and puts its main focus on the implications of fragmented policies to 2020. The study finds that 2020 targets have, in contrast to 2030, only limited implications for the mitigation costs (even during the medium-term transition phase). This finding is important, since it illustrates the critical role of climate

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[10] The peak (or maximum) costs in our study are defined as the maximum decadal mitigation costs (as % of the baseline GDP) for the timeframe 2030–2100. Fig. 5 shows the ratio between the peak costs of the LST/HST and OPT scenarios. Costs presented here differ thus from the transitional growth reduction metric (defined as the maximum reduction of decadal consumption growth) that has been used by other studies [16].

[11] Transient costs as well as other scenario data of the AMPERE scenarios can be downloaded from the interactive AMPERE web-database at: https://secure.iiasa.ac.at/web-apps/ene/AMPEREDB/.

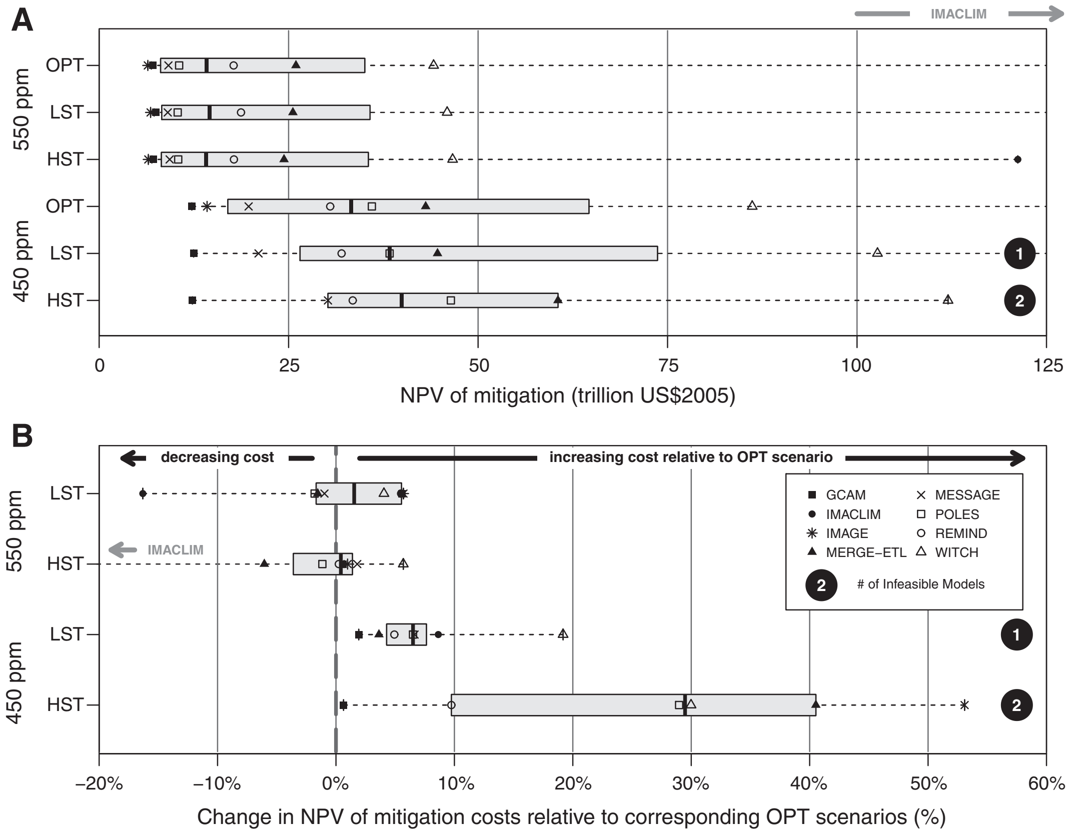

Fig. 4. Mitigation costs in the "FullTech" stabilization scenarios with different short-term targets (LST, HST). Upper panel (A) shows costs in absolute terms, and lower panel (B) shows the impact of the HST and LST assumptions on costs relative to the optimal policy (OPT) case. Mitigation costs correspond to the net present value of the cumulative abatement costs between 2010 and 2100, assuming a discount rate of 5%. GDP loss is used as the cost metric for REMIND, MESSAGE, MERGE-ETL, WITCH, and IMACLIM; the area under the marginal abatement cost (MAC) curve is used for GCAM, IMAGE, and POLES. Costs based on different metrics are not exactly comparable. Note that the FullTech-450 scenario with the HST target was infeasible for the IMAGE and IMACLIM models. For mitigation costs in terms of consumption losses as percentage of baseline GDP, see the Supplementary material.

policies between 2020 and 2030 in order to reach low stabilization targets.

The availability and future potential of mitigation technologies have important implications for the costs and feasibility of climate stabilization [2,31,72]. Fig. 6 shows the results for the mitigation costs of our technology sensitivity cases for the HST and OPT scenarios (Table 1). In order to understand the cost implications of different technology-setups, the mitigation

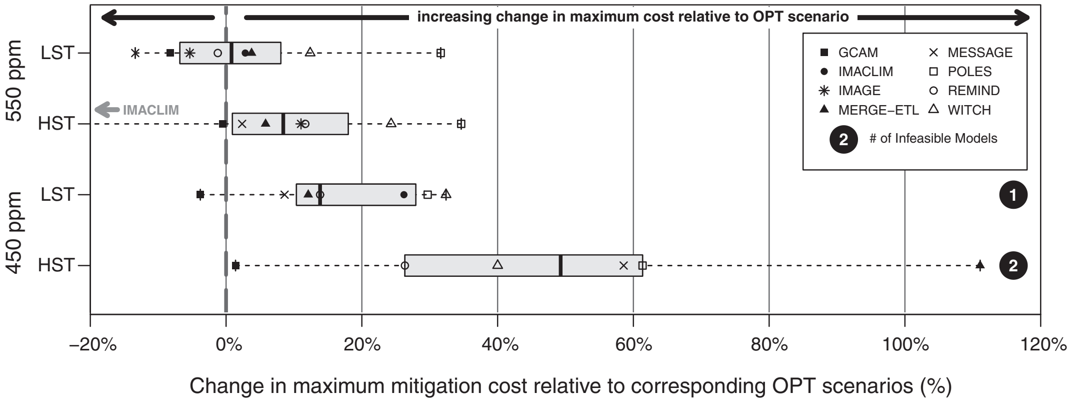

Fig. 5. Change in the maximum (peak) decadal mitigation costs between 2030 and 2100 in the LST and HST scenarios relative to the corresponding optimal policy case (OPT). GDP loss is used as the cost metric for REMIND, MESSAGE, MERGE-ETL, WITCH, and IMACLIM; the area under the marginal abatement cost (MAC) curve is used for GCAM, IMAGE, and POLES. For both cost metrics the mitigation costs are measured in terms of percent of baseline GDP. Note that the FullTech-450 scenario with the HST target was infeasible for the IMAGE and IMACLIM models.

costs are shown relative to the full technology case (FullTech), which assumes that the full portfolio of technologies is available at their full potential. In order to explore also the critical question of the attainability of the targets, we track also the number of "infeasible" model runs. The focus of this section is on the 450 ppm scenarios and the differences in costs between the optimal policy scenarios and the HST target (Fig. 8 in the Supplementary material shows in addition also the results for the LST-450 ppm scenarios).

An "infeasible" scenario means that a specific model in our set could not find a solution given a particular combination of short- and long-term targets. Infeasibilities may occur due to different reasons, such as lack of mitigation options to stay within the cumulative emission constraints; binding constraints for the diffusion of technologies or extremely high price signals under which the modeling framework cannot be solved any more. Infeasibility is thus an indication that under a specific model parameterization the transformation cannot be achieved. It provides useful context to understand technical or economic concerns. These concerns need to be strictly differentiated from the feasibility of the transformation in the real world, which hinges on a number of other factors, such as political and social concerns that might render feasible model solutions unattainable in the real world. While there might also be solutions in the real world that are not anticipated by the models, we interpret infeasibility across a large number of models as an indication of increased risk that the transformation may not be attainable due to technical or economic concerns. For a comprehensive overview of model infeasibilities, including a comparison to technology sensitivity cases of EMF27 [73], see the Supplementary material.

Our results show that the mitigation costs increase as the deployment of supply-side technologies becomes restricted (Fig. 6). This increase in costs (compared to the "FullTech" scenarios) can be interpreted as the opportunity cost or value of different options to reach the long-term climate target.

We discuss first the cost implications of the technology sensitivity cases for the optimal pathways shown in Fig. 6A. While the costs across the models again show a relatively wide range, there seems to be a clear ranking of different options. The phase-out of nuclear has the smallest implications for the overall mitigation costs, followed by limited solar and wind deployment (LimSW), limited biomass potential (LimBio), and finally the elimination of CCS as a mitigation option (NoCCS), which shows the largest increase in mitigation costs associated with achieving the 450 ppm target (Fig. 6A). Strategies that emphasize binary preferences for either conventional technologies (Conv) with limited contribution of renewables, or on the other extreme, efficiency measures and renewable technologies (EERE), show also a relatively high increase in costs. These results emphasize the importance of maintaining a broad portfolio of available technologies for cost—effectively achieving the 450 ppm target (see also [2,41,73]). Biomass and particularly CCS are of central importance for keeping mitigation costs relatively low, which has also been emphasized by other studies [2,34,74]. A phase-out of nuclear, on the other hand, seems to have only modest consequences for the overall mitigation costs (see also [75]).

Fig. 6B shows the cost and feasibility implications of the technology sensitivity cases when trying to reach the 450 ppm CO_2e target in the HST cases. Generally, the ranking of different mitigation options in terms of costs is similar to the ranking observed for the optimal 450 ppm CO_2e scenarios. The cost implications of restricting the technology portfolio in the HST cases are, however, much more pronounced than in the optimal pathways. Moreover, for many technology sensitivity cases, the majority of the models can no longer find a feasible solution when the short-term emissions climb to the HST level. Compared to the optimal policy cases, the HST pathways show thus significant risks that the 450 ppm target is getting out of reach. For example, more than 75% of all models are unable to achieve the 450 ppm target in the "NoCCS" or "EERE" cases. About half of the models can no longer achieve the target in the "Conv" case or when biomass is constrained, and more than 25% of the models indicate that it is no longer feasible to achieve the HST target with either low solar and wind deployment or the phase-out of nuclear.

Following the HST pledge pathways thus narrows policy choices, and increases the risks that some of the currently optional technologies, such as the large-scale deployment of bioenergy, will become "a must" by 2030 in order to achieve low stabilization targets. Our results show also that the technical and economic risks that the 450 ppm target becomes unattainable are particularly high in the case that CCS would not become available. Following the HST pledge pathway would thus require that current obstacles to the deployment of CCS are resolved [37].

Another important finding illustrated by our results is the paramount importance of energy efficiency and behavioral and other measures to limit energy demand. The "LowEI" case achieves the 450 ppm target with the lowest costs across all sensitivity cases and models, and it is also the only case where the target is found attainable by 89% of the models even if the HST pledge pathway is followed to 2030. Dedicated measures to reduce energy intensity and to limit energy demand may thus not only reduce the cost of the transformation, but can also hedge against the risk that low stabilization targets might get out of reach if the world is following a pledge pathway to 2030 in the near term.

6. Conclusions and discussion

We find that following a mitigation effort comparable to the pledges would result in near-term global emissions between 53 $GtCO_2$e to 61 $GtCO_2$e for the year 2030. These emission levels are significantly higher than emissions in low stabilization scenarios with optimal and immediate introduction of climate policies to reach 450 ppm CO_2e. Similar to earlier studies, we find thus that the pledges would result in a near-term "emission gap".

The explicit consideration of short-term emission targets has enabled us to go beyond earlier modeling comparisons and to directly assess the consequences of these near term targets. We find that there is only a small window of time between 2030 and 2050 in order to close the emission gap. This implies only little flexibility for the system to compensate for the lack of emission reductions in the short-term with pronounced implications for the required pace of emission reductions and the energy system transformation. We find, for example, that following an HST pledge pathway to 2030 would require across most models a doubling of the pace of emission reductions

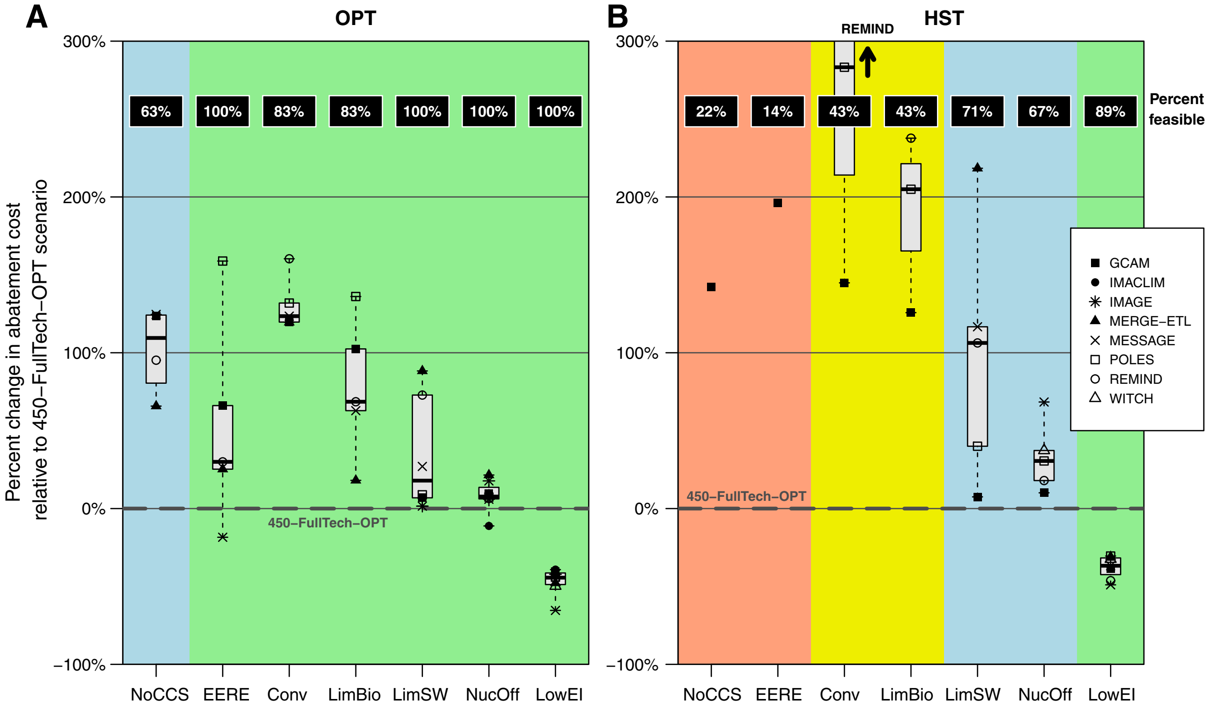

Fig. 6. Ranges of mitigation costs for different technology sensitivity cases for the 450 ppm CO2e target. Left-hand panel (A) shows results for the optimal policy scenarios (OPT), and right-hand panel (B) for high 2030 emissions (HST). Black boxes indicate the share of feasible model runs for each of the technology sensitivity cases. The colored shadings indicate the combined technical and economic risk of infeasibility: green = low risk (>80% feasible solution), blue = intermediate risk (50–80% feasible solutions), yellow = high risk (30–50% feasible solutions), orange = very high risk (<30% feasible solutions). Mitigation costs are shown relative to the costs of the FullTech-OPT case. Mitigation costs correspond to the net present value of the cumulative abatement costs between 2010 and 2100, assuming a discount rate of 5%. GDP loss is used as the cost metric for REMIND, MESSAGE, MERGE-ETL, WITCH, and IMACLIM; the area under the marginal abatement cost (MAC) curve is used for GCAM, IMAGE, and POLES. Costs based on different metrics are not exactly comparable.

between 2030 and 2050. This poses a twin-challenge: on the one hand, the high near-term emission pathway of the pledges creates a lock-in of the energy system into fossil-intensive infrastructure, and on the other hand they reduce the flexibility of the energy system by requiring a much more rapid system transformation.

Following the pledge pathways to 2030 has also major implications for the mitigation costs. Despite large uncertainty across models, we find that on average the net mitigation costs for 2010–2100 may increase by about 30% in the case of the HST pledge pathways. Because of the need to massively accelerate the transformation, peak costs between 2030 and 2100 are on average even higher by about 50% in the HST scenarios. Models with large potential of negative emissions show the biggest flexibility to compensate the lack of short-term emission reductions associated with the pledge pathways. Negative emissions may help thus to keep long-term targets within reach at relatively modest costs. However, the tradeoff is a significant increase in the risk of exceeding the temperature change objective of 2 °C. Specifically, the probability of exceeding the target increases to about 85% compared to the median across models of 45 to 47%.

A further finding of our analysis is that the pledge pathways increase the technical and economic risks that the 450 ppm CO_2e becomes unattainable. We derive this conclusion through a systematic technology sensitivity analysis exploring the feasibility and cost implications of different technology restrictions. A head-line conclusion from this analysis is that the pledge pathway, in particular the HST pathway, narrows policy choices and increases the risks that some of the currently optional technologies, such as the large-scale deployment of biomass or CCS, will become “a must” by 2030 in order to achieve low stabilization targets.

Finally, an important finding illustrated by our results is the paramount importance of energy efficiency and behavioral and other measures to limit energy demand. These measures not only reduce the cost of the transformation, but can also hedge against the risk that low stabilization targets might become unattainable when following a high emission pathway to 2030 in the near term.

Overall, our analysis shows that following a pledge pathway to 2030 would raise a number of concerns: 1) it would increase the overall mitigation costs, particularly in the medium term; 2) it would reduce the system flexibility by requiring more rapid energy transformations; and 3) it would increase the risk that stringent long-term targets, such as 450 ppm CO_2e, become unattainable because of technical and economic reasons. Considering also other possible barriers to GHG emission reductions, such as social and political constraints, the transformation may be even more difficult than assessed by the scenarios in our study. These findings have important implications for the international negotiations and the Durban action plan, which aim at establishing post 2020 emission targets. Our analysis shows that the level of emissions in 2030 will be decisive in order to keep the 2 °C objective within reach. Further deep cuts in GHG emissions will be required by 2050 in order to avoid large-scale overshoot of the objective in the 21st century. Continuing on a mitigation path to 2030 with a similar stringency as the 2020 pledges will increase the risks that society will fall short in achieving this objective.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.techfore.2013.09.016.

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