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Carbon lock-in through capital stock inertia associated with weak near-term climate policies

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ABSTRACT

Stringent long-term climate targets necessitate a limit on cumulative emissions in this century for which sufficient policy signals are lacking. Using nine energy-economy models, we explore how policies pursued during the next two decades impact long-term transformation pathways towards stringent long-term climate targets. Less stringent near-term policies (i.e., those with larger emissions) consume more of the long-term cumulative emissions budget in the 2010–2030 period, which increases the likelihood of overshooting the budget and the urgency of reducing GHG emissions after 2030. Furthermore, the larger near-term GHG emissions associated with less stringent policies are generated primarily by additional coal-based electricity generation. Therefore, to be successful in meeting the long-term target despite near-term emissions reductions that are weaker than those implied by cost-optimal mitigation pathways, models must prematurely retire significant coal capacity while rapidly ramping up low-carbon technologies between 2030 and 2050 and remove large quantities of CO_2 from the atmosphere in the latter half of the century. While increased energy efficiency lowers mitigation costs considerably, even with weak near-term policies, it does not substantially reduce the short-term reliance on coal electricity. However, increased energy efficiency does allow the energy system more flexibility in mitigating emissions and, thus, facilitates the post-2030 transition.

1. Introduction

In the last four climate conferences in Copenhagen, Cancún, Durban and Doha, the international community has agreed on the target of limiting the increase in global average temperature to 2 °C above pre-industrial levels, while noting the "significant gap between the aggregate effect of Parties' mitigation pledges […] and aggregate emission pathways consistent with having a likely chance of holding the increase in global average temperature below 2 °C or 1.5 °C" [1,2].

While the discrepancy between mitigation pledges and required near-term emission levels implied by cost-optimal mitigation pathways towards 2 °C is well founded on previous research [3,4], the exact implications of higher-than-optimal emissions in the near term are less well explored. In an effort to inform societies and policy makers of the implications of proposed near-term mitigation pledges, the AMPERE study [5], on which this paper is based, examines the consequences of scenarios with different global emission levels in 2030, which correspond with current 2020 pledges extrapolated to 2030

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[6,7]. Complementing the companion AMPERE papers that focus on mitigation costs and feasibility [5] and technology deployment sensitivities and regional implications [8], this paper explores the implications of different short-term emissions targets for the transformation of the global energy system.

Understanding the differences in energy system transformation pathways helps to explain the economic costs and feasibility of scenarios with higher near-term emissions. Additionally it can indicate how excess costs can be alleviated, but also where real world barriers not included in the models can lead to even higher costs than reported by the models. To examine energy system transformation, we use a set of results from nine global energy-economy models participating in the AMPERE project to explore: 1) path dependency that results from the inertia of energy systems with long-lived infrastructure and 2) the implications of larger near-term emissions for the timing and magnitude of future mitigation. As near-term emissions targets become less stringent (i.e., emissions increase), the deployment of fossil energy infrastructure with long lifetimes, such as coal-fired power plants, is expanded. This additional carbon-intensive infrastructure potentially represents a long-term emissions commitment or carbon lock-in, which can threaten the likelihood of meeting more stringent long-term climate objectives, such as the 2 °C target. Reaching the long-term stabilization target typically requires premature retirement or retrofit with carbon capture and storage (CCS) once the policy regime is strengthened in 2030, without prior anticipation by economic agents. Both of these options result in significant additional system costs, either through the write-off of stranded investments or the installation of CCS infrastructure [9].

Moreover, the rate at which these options can be deployed may be limited by technological limitations, social acceptance, and the ability to ramp-up additional low-carbon energy capacities as a substitute. Thus, this capital inertia causes some degree of path dependency, which limits the degree to which emissions can deviate from their previous trajectory.

In addition, because of the long residence time of CO_2 in the atmosphere, climate stabilization requires the solution of a stock problem. Climate change in a given year is largely determined by the cumulative anthropogenic emissions. Therefore, achieving long-term climate objectives becomes more difficult as 2030 emissions increase as a result of two distinct processes: 1) carbon budget depletion: larger pre-2030 emissions consume a higher share of the allowable CO_2 emissions budget, so that post-2030 emissions must be smaller and 2) carbon lock-in: the larger annual emissions and more carbon- and energy-intensive capital stock in 2030 significantly increases the rate at which the energy system must be transformed and increases the cost of reaching a particular level of emission reductions relative to the previous trajectory.

For the remainder of this paper, we consequently refer to carbon lock-in as the degree to which the configuration of the energy system in 2030 is less than optimal, thus increasing the difficulty of emission reductions achieved post-2030. We do this being well aware that the models are only able to capture the restricted aspect of carbon lock-in associated with physical capital and emissions while institutional and other aspects of this phenomenon [10] are not modeled and hence not the subject of this study. Furthermore, currently existing energy infrastructure also constitutes a considerable emissions commitment and hence carbon lock-in today [11].[1] Our study thus explores how much this lock-in is increased by policies that institute only modest mitigation over the next two decades and what this lock-in implies for the long-term energy system transformation that is required for achieving a low stabilization target.

We present the modeling and scenario framework of this study in Section 2 and discuss the magnitude and composition of the lock-in attained in 2030 in Section 3. Section 4 discusses the long-term budget implications of both the carbon budget depletion and the lock-in from both temporal and sectoral perspectives and Section 5 concludes with a discussion of the results.

2. Study design and methods

This cross-cut analysis is part of the AMPERE model inter-comparison study, which examines mitigation timing and alternative technology futures and is described in detail in the overview article of this special issue [5]. A total of nine energy-economy and integrated assessment models participated in the study (Table 1). To improve comparability of results, model assumptions on regional GDP trajectories and global long-term final energy demand levels were harmonized for the baseline scenarios.

Table 2 provides an overview of the scenarios considered in this paper. They comprise a subset of the scenarios prepared for the AMPERE study [5] and are specifically designed to explore the two phenomena of carbon lock-in and carbon budget depletion explained in Section 1. The baseline scenarios ("Base") represent a future in which the energy system develops without climate policy while the climate mitigation scenarios ("450") must fulfill a constraint on cumulative CO_2 emissions, including land use emissions, from 2000 to 2100 of 1500 Gt CO_2 [5].[2] This is roughly consistent with a limitation of the atmospheric greenhouse gas (GHG) concentration to 450 ppm CO2e in 2100, and implies an about 60–70% likelihood of keeping temperature change relative to pre-industrial levels in 2100 below 2 °C [12]. The analysis presented in this paper considers only scenarios in which the full portfolio of technologies represented in each model is available, both with reference energy intensity (FullTech) and lower energy intensity as a sensitivity analysis (LowEI). For the FullTech scenarios, the observed rate of energy intensity improvement of roughly1.3% per year is assumed to be continued in the future, leading to a

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[1] Here we use the term carbon lock-in to describe how less-than-optimal climate policies result in an energy system configuration that is more emissions-intensive than implied by optimal climate policies. In contrast to Davis et al., we do not quantify the contribution of this excess fossil-based infrastructure to future emissions.

[2] The model with temporal modeling scope until 2050 (DNE21+) has to fulfill a cumulative budget of 1500 Gt CO_2 in the period 2000–2050, which is broadly comparable to the emissions of the other models in that time span (see Section 4.1). For the two models that do not include land-use CO_2 emissions (IMACLIM and POLES), the budget is only 1400 Gt CO_2. Models considering further GHGs beyond CO_2 apply an equivalent price to those emissions, using global warming potentials (GWPs) for the price conversion.

Table 1
Models participating in this study. Premature retirement in REMIND is constrained to max. 4% of total capacity per year, so that full retirement is completed only after 25 years. While the percentage of retired capital thus increases linearly, actual retirement is faster due to the additional effect of normal retirement after the end of the lifetime.

Model name	DNE21+ [23]	GCAM [24]	IMACLIM [25]	IMAGE [26]	MERGE-ETL [27]	MESSAGE [28]	POLES [29]	REMIND [30]	WITCH [31]
Short form	D	G	I	i	M	m	P	R	W
Time horizon	2050	2100	2100	2100	2100	2100	2100	2100	2100
Premature retirement	Yes	Yes	Yes	No	No	Yes	Yes	Yes, 4% p.a.	Yes
Max. primary energy biomass (EJ)	151	880	278	266	189	221	211	306	275

Table 2
Scenarios analyzed in this study. The codes in parentheses will be used throughout this study to refer to the scenarios. The 450-FullTech-LST and 450-FullTech-HST scenarios will be referred to in short as LST and HST respectively.

	No climate policy (Base)	Centennial CO_2 emission budget constraint of 1500 Gt CO_2 (450 ppm CO_2e)		
	Full when-flexibility (OPT)		Low short term target (LST)	High short term target (HST)
Reference energy intensity (FullTech)	Base-FullTech-OPT	450-FullTech-OPT	450-FullTech-LST	450-FullTech-HST
Low energy intensity (LowEI)	Base-LowEI-OPT	450-LowEI-OPT	450-LowEI-LST	450-LowEI-HST

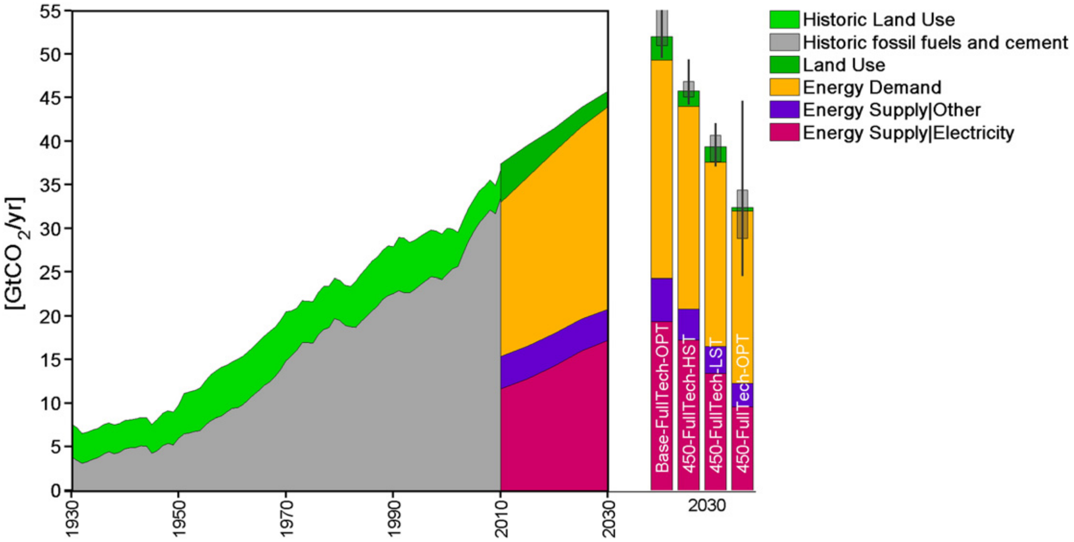

Fig. 1. Historic global CO_2 emissions until 2010 and projected emissions until 2030 for the 450-FullTech-HST scenario based on the REMIND model. The bar plots on the right side indicate projected CO_2 emissions in 2030 by the REMIND model for the four FullTech scenarios. The vertical black lines indicate the full range of total CO2 emissions across the nine models and the grey boxes the interquartile range. Historic data is from Refs. [17,20,21]. Definitions of variables can be found in the AMPERE database and derived variables are defined in the supporting online material

global final energy demand of 910–1000 EJ in 2100 [5]. Higher energy intensity improvement rates of ~1.9% per year are assumed to happen autonomously without additional policies or costs in the LowEI scenarios, resulting in 520–570 EJ final energy demand in 2100. An in-depth analysis of scenarios with limited technological representation is presented in the companion cross-cut paper [8].

To study carbon lock-in, we consider scenarios with prescribed (typically sub-optimal) short-term mitigation targets in 2030, along with scenarios with full when-flexibility and an optimal distribution of emission reductions over time. The scenarios with prescribed 2030 targets were constructed as two-stage scenarios in models with perfect foresight, so that they run in myopic mode until 2030 with no anticipation of the post-2030 policy signal before 2030[3] (see Bosetti et al. [13] and Richels et al. [14] for a discussion with the opposite cases of anticipated policy changes). Specifically, the model considers

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[3] The short-term targets are specified as annual emission levels in 2030. The scenarios assume a smooth development of climate policies with comparable ambition levels before 2030. For models with perfect foresight, myopic behavior was mimicked by using a two-phase approach. In the first stage, a perfect foresight scenario is run with a long-term ambition level – generally considerably lower than in the 450 policy scenarios – that allows the model to hit the near-term target in 2030. This first run is used to fix the solution through 2030, and then another perfect foresight scenario is run with the long-term budget target. The exact implementation has been the choice of the individual modeling teams, as long as it was made sure that the model has limited foresight when planning prior to 2030.

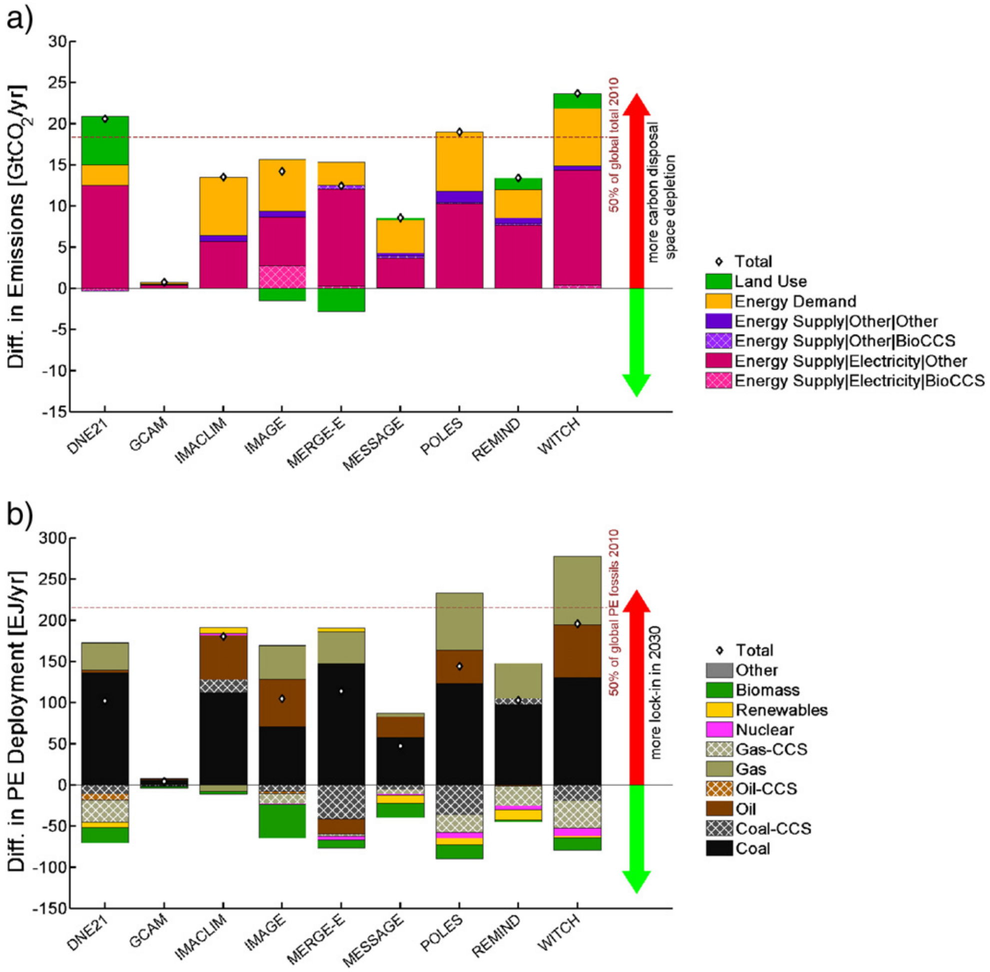

Fig. 2. Differences in a) CO_2 emissions by sources, and b) primary energy types between 450-FullTech-HST and 450-FullTech-OPT in 2030. Dashed lines indicate reference values in 2010 [22]

two short-term targets: high (“HST”) and low (“LST”). In the HST scenarios, the target for total Kyoto gas emissions in 2030 is 60.8 Gt CO_2e and in the LST scenarios the target is 52.8 Gt CO_2e in 2030.[4] As seen in Fig. 1, the HST scenarios imply weaker-than-optimal mitigation efforts and hence policies until 2030. Therefore we refer to the HST scenarios as weak policy scenarios in relation to the OPT scenarios. However, the weak designation should only be understood in a relative sense and does not imply any absolute valuation of the considered policy targets.

The short-term targets were developed by extrapolating the 2020 pledges under the UNFCCC to 2030 and reflect likely emissions outcomes for stringent fulfillment of those pledges (LST) and a more lenient case (HST) where only unconditional pledges are fulfilled [5]. For most models, the two targets lie within the range spanned by the baseline scenario on the high end and the optimal 450 scenario on the low end, although there is an overlap between optimal scenarios and those with low short term targets (see bars on the right side of Fig. 1). The left side of Fig. 1 compares the trajectory of historic CO_2 emissions with the trajectory projected until 2030 by REMIND for the 450-FullTech-HST scenario. Although the HST scenario represents the highest 2030 CO_2 emissions of any of the 450 ppm mitigation scenarios and, thus, the most carbon budget depletion and lock-in, it still implies significantly lower emission growth rates than those observed in the last decade. The LST scenario represents an intermediate level of carbon lock-in and roughly implies a return to current emission levels by 2030. Finally, in the first best climate policy scenario (450-FullTech-OPT), 2030 emissions are considerably lower than those in 2010 for the majority of models. The difference in emissions between the HST and the 450-OPT scenario is roughly 15 Gt CO_2 for most models, or close to 50% of total 2010 emissions.

3. Energy System in 2030: Which sectors contribute most to carbon lock-in?

This section evaluates carbon lock-in and its main contributors for scenarios with sub-optimal short-term emission targets (LST and HST). Specifically, the sectors

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[4] Models that cover only industrial and energy related CO_2 emissions (IMACLIM and POLES) must comply with targets for fossil fuels and industry CO_2 emissions of 44.2 and 37.3 Gt CO_2 in the HST and LST scenarios, respectively.

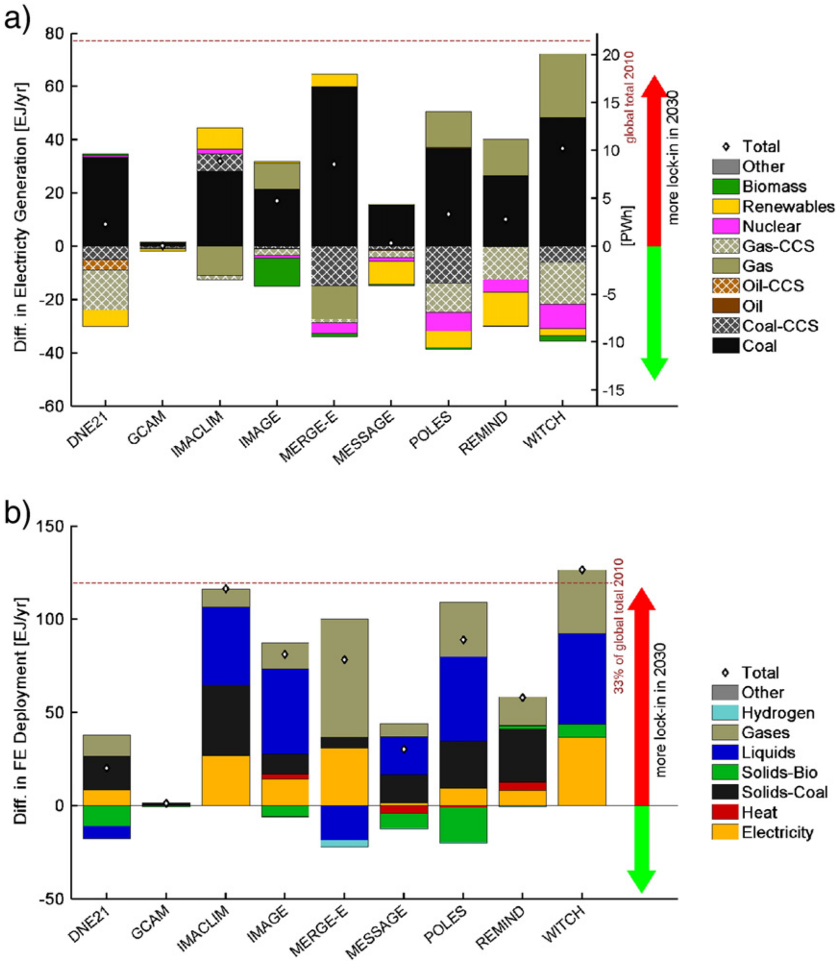

Fig. 3. Differences in a) electricity generation, and b) final energy by carrier between 450-FullTech-HST and 450-FullTech-OPT in 2030. Dashed lines indicate reference values in 2010 [22]

that contribute most to carbon lock-in are identified by calculating the difference in energy system deployment and CO_2 emissions relative to 450-OPT scenarios for each sector in 2030, which is when the near-term target is specified and the myopic period ends.

While total 2030 emissions are exogenously prescribed via the short-term target definitions in the HST and LST scenarios, the sectoral composition of the emissions is an endogenous model outcome. By contrast, 2030 emissions in the OPT scenarios are determined endogenously in each model. Consequently, the overall size and composition of the CO_2 emissions gap between the HST and 450-OPT scenarios shown in Fig. 2a vary across models. While GCAM identifies a very small gap of less than 1 Gt CO_2, the range across the rest of the models is 8–24 Gt CO_2,[5] which is comparable to 21–65% of total global CO_2 emissions in 2010. Most models indicate that more than half of the foregone emissions abatement is attributed to the electricity supply. Generally, the second largest contribution comes from additional demand-side emissions from the consumption of combustible fuels.

As expected, the less ambitious emission reductions in the HST scenario are caused by greater deployment of fossil primary energy without carbon capture and sequestration (CCS) relative to the OPT scenario (Fig. 2b). The increase in fossil primary energy demand amounts to 90–270 EJ, which compares to 431 EJ of fossil energy use observed in 2010. Within the group of fossil fuels, coal exhibits the largest increase in deployment. Furthermore, we observe less deployment of low-carbon energy sources and a substantial net increase of primary energy of 50–200 EJ.

Increased fossil fuel use is also evident in the electricity sector where significantly more electricity is generated using coal and gas plants without CCS in the HST scenario (Fig. 3a). Coal-based electricity generation increases up to 17 PWh or 60 EJ, compared to total global electricity generation of 21 PWh or 77 EJ in 2010. In addition, low-carbon generation technologies, such as coal and gas with CCS, nuclear, biomass and other renewables, are deployed at lower levels. Consequently, the

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[5] The high short term target does not make a substantial difference for the GCAM model, as this model projects a high overshoot of the long-term target and subsequent carbon dioxide removal (CDR) from the atmosphere, even under full when-flexibility. Other models do not have the possibility for such high amounts of CDR, mainly because of limits on the production of biomass, but also because of limits on the geological sequestration of carbon dioxide, or the absence of bioplastics sequestration.

price of electricity is smaller in the HST scenario until 2030, resulting in a greater net demand for electricity. The increase in electricity generation with fossil fuels generates much of the surplus emissions until 2030 and the underinvestment into low-carbon options leads to higher ramp-up rate requirements for these options after 2030, particularly in the two subsequent decades [8].

Regarding differences in final energy use by carrier, it is noteworthy to observe that electricity makes up only a small portion of the additional final energy use relative to the OPT scenario (Fig. 3b). The HST scenario tends to yield lower price-induced energy efficiency improvements until 2030, resulting in a difference in total final energy use compared to OPT of up to one third of 2010 total final energy use.

Figs. 2 and 3 suggest that the difference in emissions abatement in the year 2030 between the HST and OPT scenario is primarily the result of two processes: 1) end-use efficiency improvements are higher in the OPT scenarios than in the HST scenarios and in most models the difference is evenly distributed across the different end-use fuel types; and 2) the carbon intensity of electricity supply is much further reduced in the OPT scenario than in the HST scenario, whereas the carbon intensity of non-electric final energy supply is not significantly lowered in comparison to the baseline even in the OPT scenario (Fig. 4). This pattern reflects the greater difficulty and cost of emissions reductions in non-electric energy supply [15,16] and the comparatively low marginal abatement costs for many efficiency measures and the substitution of coal-based electricity generation with low-carbon alternatives.

The substitution of low-carbon alternatives for coal is comparatively cheap because new generation capacities must be built anyway, given the projected rise in electricity demand across the world. In the optimal policy scenario, all models foresee stagnation or even a net decline in installed capacity for coal-based electricity generation without CCS in 2030 relative to 2010. By contrast, the HST scenario implies a net increase of these capacities in most models (Fig. 5a). Even if the total capacity stagnates for the next two decades, significant new capacity will still be required to replace retired facilities. Since coal power plants are characterized by long technical lifetimes, typically ranging from 30 to 50 years, any new capacity built over the next two decades will contribute to significant lock-in of carbon intensive generation. In the HST climate mitigation scenarios in which the electricity sector must rapidly decarbonize after 2030, most models, must prematurely retire and thus strand large amounts of this coal capacity (Fig. 5b). Johnson et al. [9] discusses the costs and implications of stranded coal capacity given various near-term emissions targets.

In the LowEI scenarios, total installed coal capacities under short-term targets are very similar to those found in the reference energy intensity (FullTech) scenarios even though overall final energy demand is much smaller (Fig. 5a). This means that the end-use efficiency improvements, which are assumed to happen autonomously (i.e. without any costs involved), in these scenarios, reduce the urgency of transitioning to low-carbon electricity generation. Consequently, the carbon intensity of electricity is higher in the LowEI HST and LST scenarios than in the corresponding FullTech scenarios (Fig. 4a). While in general it is a trivial result that with fixed emission targets, scenarios with less energy demand yield higher carbon intensities, it is noteworthy that coal-based electricity generation, which involves very long-lived capital stocks, is nearly identical in the LowEI and FullTech scenarios.

The main insight from the analysis in this section is that the majority of foregone abatement options in the LST and HST scenarios are reductions in coal-based electricity production. As the corresponding production capacities represent long-lived capital assets, the expansion of coal constitutes a considerable lock-in of carbon-intensive technologies. Meanwhile, reduced investment in low-carbon technologies means that the share of these technologies remains low in 2030. In combination, these developments pose a considerable challenge for the rapid transition to low-carbon energy that is required in the following decades to limit warming to 2 °C.

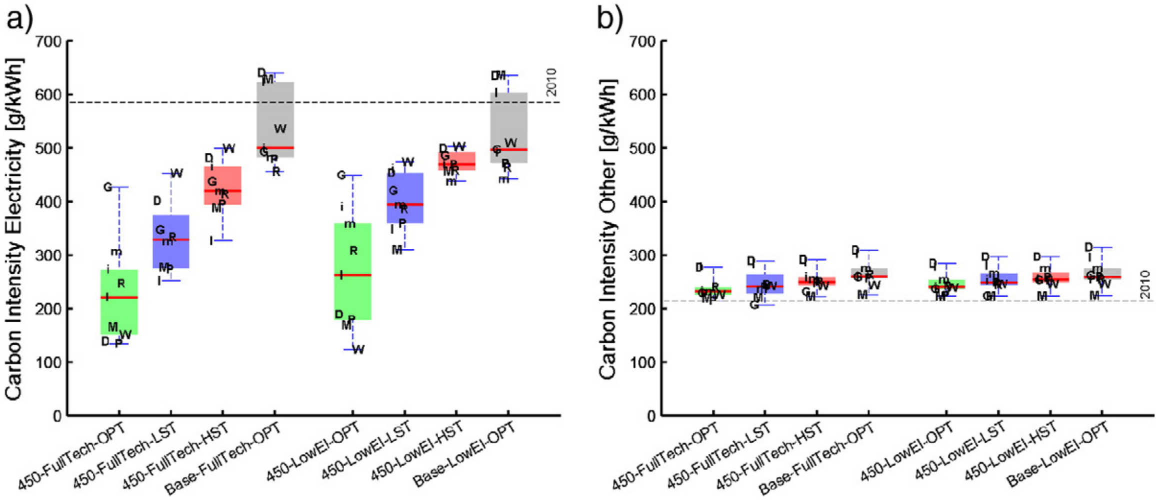

Fig. 4. Carbon intensity of secondary energy electricity (left panel) and final energy without electricity (right panel) in 2030 for all eight scenarios. The red lines mark the median level across all models, the colored boxes indicate the interquartile ranges and the whiskers indicate the full model ranges. The letters indicate the values associated with each model (see Table 1 for full model names). The dashed horizontal line marks the 2010 historic value [22].

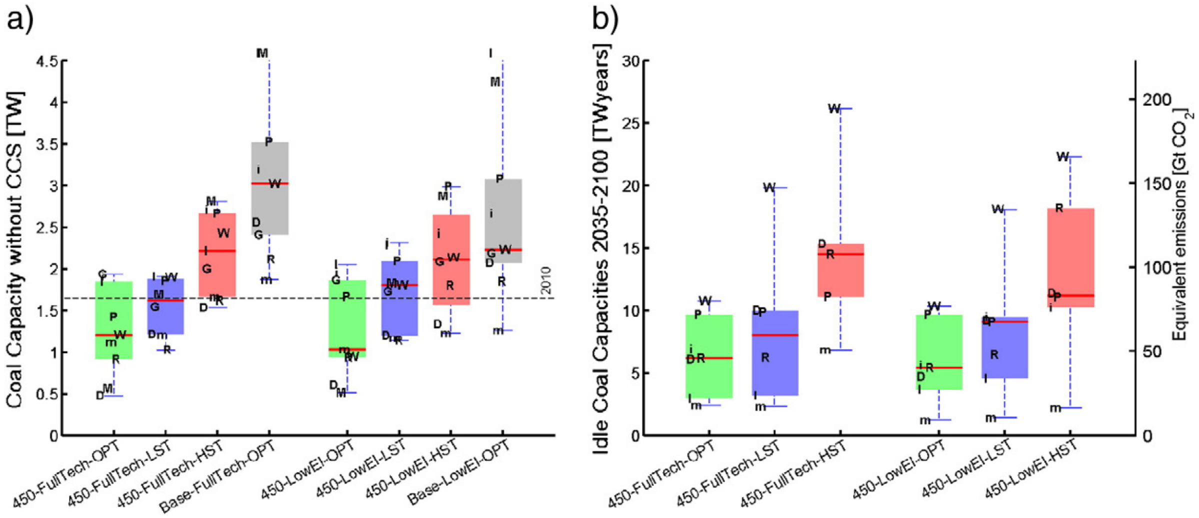

Fig. 5. Total installed capacity for coal-based electricity generation without CCS in 2030 (left) and stranded capacity of coal electricity without CCS measured in cumulative unused capacities from 2035 to 2100 and expressed both in TW_{years} and Gt CO_2 (secondary *y*-axis, right). For the calculation of equivalent emissions we assume a constant emission factor of 850 g/kWh. The red lines mark the median level across all models, the colored boxes indicate the interquartile ranges and the whiskers indicate the full model ranges. The letters indicate the values associated with each model (see Table 1 for full model names). The dashed horizontal line marks the 2010 historic value [22].

4. The effects of short-term emission targets on long-term emission patterns

This section discusses the temporal and sectoral allocations of the allowable CO_2 budget in scenarios with optimal versus weak near-term policies and describes the differences in these allocations among models.

4.1. Exhausting the emissions budget

Achieving stringent long-term climate protection targets requires that cumulative emissions of CO_2 are strictly limited. In the 450 ppm scenarios considered in this study, less than 1200 Gt CO_2 can still be emitted between 2010 and 2100, as more than 300 Gt have been emitted from 2000 to 2009 [17]. For comparison, more than 1600 Gt CO_2 of anthropogenic emissions have been emitted in the 90 years between 1920 and 2009. Even under the assumption of immediate action as in the 450-OPT scenario, more than half of the 2010–2100 budget will be consumed within the next two decades, which leaves only 400–550 Gt CO_2 for the period from 2030 to 2100 (Fig. 6). As emissions until 2030 are even larger in the HST scenario, the budget for the remaining seven decades of the 21st century would be reduced to 320–410 Gt CO_2, thus increasing the challenge significantly.

The magnitude of the challenge becomes evident when one examines the cumulative emissions in 2050 for both scenarios. In the 450-OPT scenario, roughly half the models already exhibit an overshoot over the allowable CO_2 emissions budget in 2050, making the achievement of the long-term budget dependent on successful removal of considerable amounts of CO_2 in the second half of the century. For all but one model, cumulative emissions until 2050 are considerably larger in the HST scenario, which increases the need for carbon dioxide removal (CDR) from the atmosphere and thus increases the risk of failing to meet the long-term target, as reflected in the infeasibility of this scenario in two of the nine models.[6] In the HST scenario, the models with time horizons to 2100 cluster into two distinct groups based on how much they overshoot the long-term budget in 2050.[7] Four models (GCAM, MESSAGE, MERGE-ETL and REMIND) substantially overshoot the budget by more than 200 Gt CO_2 in 2050, while two models (POLES and WITCH) are roughly at the maximum budget level in 2050 and overshoot the budget only modestly in later decades.[8] This grouping coincides with the tentative model classification scheme described by Kriegler et al. [18], as all models belonging to the "high response" group show a high overshoot.[9] Models in these groups generally are more sensitive to carbon prices, reduce carbon intensity more quickly than energy intensity and can more rapidly transform the energy system.

4.2. Sectoral and temporal composition of the CO_2 emissions budget in scenarios with optimal and weak near-term policies

From the analysis of emissions budgets it becomes clear that the differences between mitigation pathways with weak near-term action and optimal pathways can be characterized in terms of three distinct temporal phases: (i) a carbon lock-in phase during the weak policy regime from 2010 to 2030; (ii) a catch-up phase from 2030 until about 2050 characterized by very high decarbonization rates; and (iii) a compensation

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[6] See Ref. [5] for discussion of the infeasibility concept and the risk for infeasibility of the scenarios.

[7] The model with time horizons until 2050 (DNE21+) must by scenario design meet the budget level in 2050 and, thus, cannot overshoot the budget.

[8] Although IMAGE and IMACLIM are also part of this project, they both found the 450-FullTech-HST scenario to be infeasible.

[9] The IMAGE model is the only exception since it is in the "high response" group, but infeasible for the 450-FullTech-HST scenario. IMAGE is one of two models participating in this study with no possibility for early retirement of existing capacities, which explains the infeasibility.

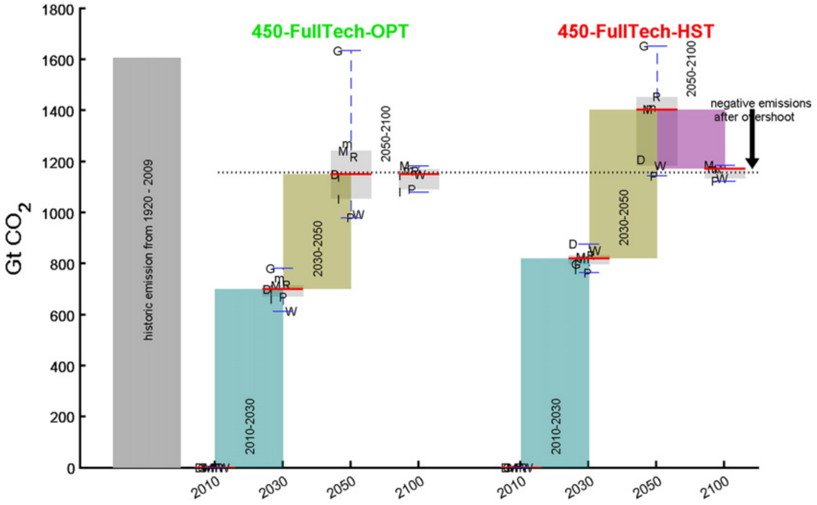

Fig. 6. Medians of cumulative CO_2 emissions after 2010 (red lines) across models together with interquartile ranges (grey boxes) and full model ranges (whiskers) for four points in time and two scenarios. The colored boxes illustrate the differences between medians from one time step to the next (please note that they do not represent the medians across models of the emission budgets in those periods). The dark grey box on the left side represents total CO_2 emissions from fossil fuels, industry and land-use from 1920 to 2009 [17,20,21]. The dotted horizontal line marks the 2100 emissions budget target and the letters indicate the values associated with each model (see Table 1 for full model names).

phase after 2050, during which excess emissions in the first half of the century are compensated by emission levels below those observed in the OPT scenario. Differences in the temporal allocation of emissions also influence their sectoral allocation and can be related to the three temporal phases. Currently nearly half of global CO_2 emissions from the energy sector originate from transformation processes on the supply side of the energy system, mainly electricity generation (Fig. 1). Previous studies on ambitious mitigation have pointed out that supply side emissions are more easily mitigated so that the supply share of emissions decreases in mitigation scenarios [15,16] and can even turn negative. In scenarios with weak near-term policy (HST and LST), the share of emissions from the supply side does not decrease much by 2030 (Fig. 1), and thus, much of the excess emissions in comparison to optimal near-term scenarios (OPT) during the 2010–2030 period comes from the supply side (Fig. 7).

During the 2030–2050 period, the change in emissions between the OPT and HST scenarios is not consistent among models. While some models (WITCH, MERGE-ETL, and DNE21+) achieve lower emissions, at least in some sectors, in the HST scenario, other models (REMIND, POLES, and MESSAGE) have excess emissions in all sectors in the 2030–2050 period that are similar to those in the 2010–2030 period (Fig. 7).[10] For DNE21+, this is directly linked to its 2050 time horizon and the scenario definition, which mandates the same cumulative emissions over the 2010–2050 period in both the OPT and HST scenarios.

For models with time horizons to 2100, the amount of CO_2 emitted during the 2030–2050 period in the weak policy scenarios can be explained by two factors: 1) path dependency during the transition to a more stringent climate policy regime, and 2) the long-term emissions abatement potential. Models with strong path dependency are less flexible in the rate of emission reductions achieved in the short-term. Both factors are influenced by energy system characteristics on both the supply and demand sides (see Table 1). On the demand side, a model's path dependency is determined by a model's short-term price elasticity of energy service demand and the ability to ramp-up low-carbon demand technologies (e.g., biofuels, solar heating and electro mobility). On the supply side, a model's ability to reduce emissions is constrained by the ramp-up potential of low-carbon supply options like nuclear, bioenergy, wind and solar [8] and the ability to prematurely retire carbon-intensive fossil-based generation capacity. Similarly, the long-term emissions abatement potential is determined by assumptions about sectoral energy demands and their long-term efficiency potentials, low-carbon energy supply options, and the availability of technologies to remove CO_2 from the atmosphere, such as bioenergy with carbon capture and storage (BioCCS).

Models with high path dependency and/or high long-term mitigation potential tend to have higher 2030–2050 emissions, while models with lower long-term mitigation potentials need to perform deeper emission reductions in the 2030–2050 period. Since carbon prices reflect the marginal costs of mitigation in each time period, the prices in 2050 can serve as proxies for the difficulty and/or necessity of mitigating CO_2 from 2030 to 2050. As the short-term 2030 target increases, the need for mitigation generally increases for the 2030–2050 period and, thus, the 2050 carbon price also increases (Fig. 8). However, there is significant variation in the carbon price among the models with two distinct clusters evident in the HST

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[10] GCAM results for the 450-FullTech-OPT and 450-FullTech-HST scenarios are almost identical (see footnote 4). Furthermore, IMAGE and IMACLIM are not considered since the 450-FullTech-HST scenario was found infeasible in both models. See Ref. [5] for discussion of the infeasibility concept.

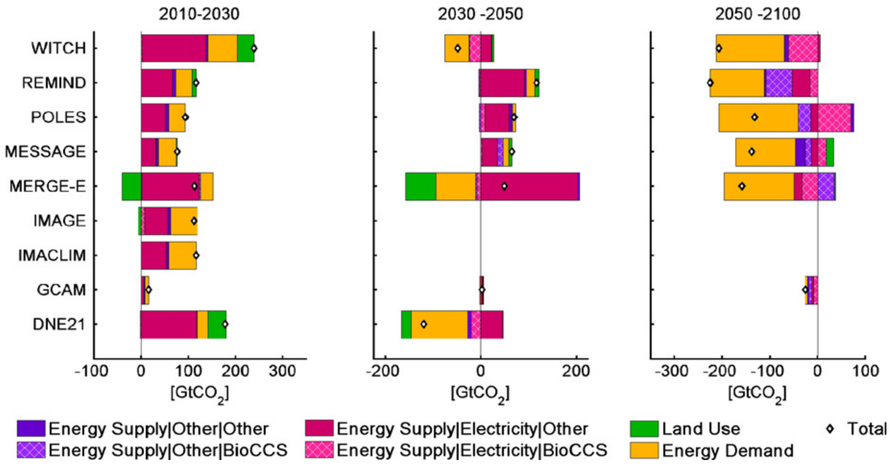

Fig. 7. Differences in cumulative sectoral CO_2 emissions between the 450-FullTech-OPT and 450-FullTech-HST scenarios for all models and three time periods: 2010–2030, 2030–2050 and 2050–2100

scenario: those with relatively high carbon prices and those with low prices. The models with high absolute carbon prices in 2050 include MERGE-ETL, WITCH and POLES. The high prices suggest that the energy systems in these models are pushed close to the limits of their mitigation potentials. However, the reasons why these models are pushed to their mitigation limits by 2050 differ.

For MERGE-ETL, the model has difficulty reducing emissions in this period, particularly in the electricity sector where no premature retirement of built capacities is possible. As a result, the model significantly overshoots the long-term budget in 2050 and compensates with net negative emissions in the latter half of the century (Fig. 6 and Fig. A1 in the supplementary online material). By contrast, POLES and WITCH cannot achieve large net negative emissions in the long-term and, thus, cannot significantly overshoot the long-term budget in 2050 and still meet the long-term target (Fig. 6 and Fig. A1). As a result, these models must put much more effort into decreasing emissions in the 2030–2050 period, resulting in more mitigation and a larger increase in carbon prices. The models with more modest carbon prices include MESSAGE, REMIND, and GCAM. These models include a large variety of low-carbon energy supply options and achieve large net negative emissions in the latter half of the century and, thus, they can significantly overshoot the long-term budget in 2050 (Fig. A1).[11]

In the second half of the century, all models that found the HST scenario feasible achieve either net negative or zero cumulative emissions during this period using primarily biomass with CCS (BioCCS) (Fig. A1). Furthermore, in the HST scenario, all models, except GCAM,[12] reduce cumulative emissions by an additional100–250 Gt CO_2 relative to the OPT scenario to compensate for excess emissions up to 2050 (Fig. 7). Most of the additional reduction comes from the demand sector, with relatively smaller contributions from the decrease of positive supply emissions and increase of negative supply emissions associated with BioCCS. This finding suggests that most of the BioCCS potential is utilized in both the OPT and HST scenarios so the additional emissions reductions required in the HST scenario largely come from reduced energy demand. Two models (WITCH and POLES) have quite substantial cumulative positive supply side emissions of 150–230 Gt CO_2 in the 450-OPT scenario that decrease by less than 15% despite the roughly doubled CO_2 price in the HST scenario (Fig. A1). This finding suggests that WITCH and POLES cannot decarbonize the energy supply as much as other models. Consequently, despite significant CO_2 removal potential, negative emissions are only sufficient to balance positive emissions and large net negative emissions are not achieved by these models.

In summary, this section indicates that if models are to achieve the long-term climate target in the HST scenario, they must have either the ability to achieve large net negative emissions in the latter half of the century or the ability to rapidly transition to low-carbon energy technologies and achieve net zero emissions in the latter half of the century. In scenarios with lower energy intensity (LowEI) these requirements are less severe as the lower baseline final energy demand provides the models with more flexibility and less urgency in addressing long-term mitigation. This means that not only can investments in low carbon technologies be stretched out over longer periods of time, but also the phase-out of carbon-intensive technologies can be more gradual. For example, less coal-based electricity generation capacity is stranded in the LowEI scenarios (Fig. 5b). As a result, the mitigation costs and carbon prices in LowEI scenarios are much lower than in scenarios with reference energy intensity (Fig. 8). For all models with time horizons until 2100, it is less expensive to achieve the cumulative budget with low energy intensity after two decades of weak climate policy (450-LowEI-HST) than it is in the scenario with immediate mitigation and reference energy intensity (450-FullTech-OPT).

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[11] Note that the models with the largest net emissions during the 2030–2050 period (and thus those with the largest overshoots) are also the models that have the greatest potential for net negative emissions in the latter half of the century (Fig. 6 and Fig. A1).

[12] There is very little difference between the emissions trajectories for the 450-FullTech-OPT and 450-FullTech-HST scenarios in GCAM (see footnote 4).

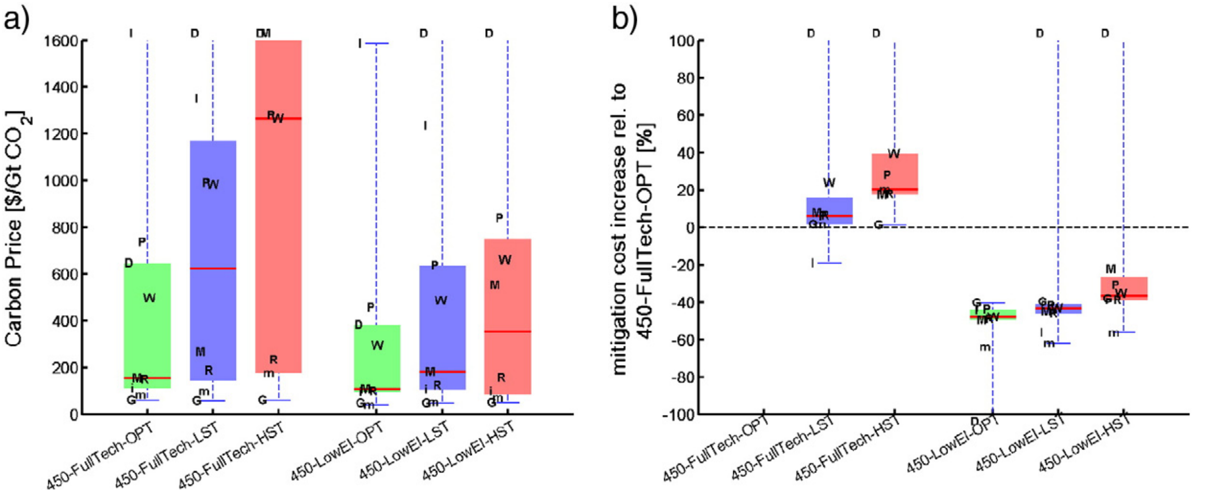

Fig. 8. Carbon prices in 2050 (left) and increase in mitigation cost relative to 450-FullTech-OPT scenario (right). Note that the temporal profile of tax paths differs across models. The letters indicate the values associated with each model (see Table 1 for full model names).

This is especially noteworthy, as the carbon lock-in in 2030 is very similar in the low and reference energy intensity scenarios in 2030 (Section 3 and especially Fig. 5a).

5. Discussion

This study provides several policy-relevant insights into the implications of weak near-term policies on the achievability of long-term climate targets, such as the 2 °C target. Under these policies, all models indicate that most of the foregone near-term abatement results from increases in coal-fired electricity generation. Consequently, if global warming is to be limited to 2 °C in 2100, the models indicate that huge quantities of installed coal capacity will need to be prematurely retired between 2030 and 2050. Such a vast global write-off of capital would be unprecedented in scale. Even though early retirement avoids extra emissions of up to 200 Gt CO_2, weak policy scenarios essentially guarantee that the long-term cumulative budget will be exceeded around 2050. Therefore, another insight is the necessity of achieving significant negative emissions in the second half of the century using biomass with CCS and terrestrial sequestration. As near-term emissions targets become less stringent (i.e., as action is delayed), the magnitude of required negative emissions increases, which poses a larger risk of failure in meeting long-term climate objectives.

The results also imply that concerted efforts to improve energy efficiency will not prevent lock-in of coal-based electricity capacity, at least if weak near-term polices are implemented as emission targets. Rather, low energy demand coupled with emission targets reduces pressure to decrease carbon intensity on the supply side and, thus, allows the share of fossil energy to increase in the near-term. However, in the longer term, this reduced pressure is also beneficial because it increases the flexibility of the energy system in making a transition that is consistent with a 2 °C target. Furthermore, the additional flexibility and reduced investment on the supply side reduce carbon prices and mitigation costs, which improve the economic feasibility of achieving the climate objective.

The comparison of model results also suggests that further research is needed to explore the uncertainties regarding key assumptions in the models. In particular, while all results are subject to the general limitations of long-term energy-economic modeling, it is noteworthy that the feasibilities and costs of sub-optimal near-term policy scenarios are strongly dependent on assumptions regarding the availability and cost of carbon dioxide removal in the second half of the century [8]. In addition, assumptions regarding premature retirement and the availability and relative costs of electricity supply technologies influence the ability of models to swiftly decarbonize the electricity sector and cope with large write-offs of stranded capital in the resource extraction (see also Ref. [19]) and fossil fuel sectors. Furthermore, most models do not account for potential political and other non-economic barriers to both stranding significant electricity capacity and rapidly ramping up low-carbon technologies. Thus, the models may overestimate how rapidly an energy system transition can occur. For this reason, further research is needed to explore the risks and uncertainties associated with achieving rapid energy system transformations and large net negative emissions.

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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.2013.10.001.

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