Technological Forecasting & Social Change 90 (2015) 73–88

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

# The impact of near-term climate policy choices on technology and emission transition pathways

Jiyong Eom [a,*], Jae Edmonds [b], Volker Krey [c], Nils Johnson [c], Thomas Longden [d], Gunnar Luderer [e], Keywan Riahi [c], Detlef P. Van Vuuren [f,g]

[a] Graduate School of Management of Technology, Sogang University, Mapo-gu, Seoul 121-742, Republic of Korea
[b] Pacific Northwest National Laboratory, Joint Global Change Research Institute, College Park, MD 20740, USA
[c] International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361 Laxenburg, Austria
[d] Fondazione ENI Enrico Mattei and Euro-Mediterranean Centre for Climate Change, Venice, Italy
[e] Potsdam Institute for Climate Impact Research, Telegraphenberg A31, D-14473 Potsdam, Germany
[f] PBL Netherlands Environmental Assessment Agency, PO Box 303, 3720 AH Bilthoven, The Netherlands
[g] Utrecht University, Copernicus Institute for Sustainable Development, Utrecht, The Netherlands

ARTICLE INFO

*Article history:*
Received 1 February 2013
Received in revised form 23 September 2013
Accepted 24 September 2013
Available online 8 November 2013

*Keywords:*
Near-term climate policy
Technology deployment
Emission pathway
Technology upscaling

ABSTRACT

This paper explores the implications of delays (to 2030) in implementing optimal policies for long-term transition pathways to limit climate forcing to 450 ppm $CO_2$e on the basis of the AMPERE Work Package 2 model comparison study.
The paper highlights the critical importance of the period 2030–2050 for ambitious mitigation strategies. In this period, the most rapid shift to low greenhouse gas emitting technology occurs. In the delayed response emission mitigation scenarios, an even faster transition rate in this period is required to compensate for the additional emissions before 2030. Our physical deployment measures indicate that the availability of CCS technology could play a critical role in facilitating the attainment of ambitious mitigation goals. Without CCS, deployment of other mitigation technologies would become extremely high in the 2030–2050 period. Yet the presence of CCS greatly alleviates the challenges to the transition particularly after the delayed climate policies, lowering the risk that the long-term goal becomes unattainable.
The results also highlight the important role of bioenergy with $CO_2$ capture and storage (BECCS), which facilitates energy production with negative carbon emissions. If BECCS is available, transition pathways exceed the emission budget in the mid-term, removing the excess with BECCS in the long term. Excluding either BE or CCS from the technology portfolio implies that emission reductions need to take place much earlier.


## 1. Introduction

Technological implications of climate change mitigation policies have been an important area of research for the integrated assessment modeling (IAM) community. Previous studies focused on the role of technology, particularly the influence of technology availability on the cost of climate change mitigation policies [1–5]. A few model inter-comparison studies, such as ADAM [6], RECIPE [7], and EMF27 [8], also explored the role of technology across a wide suite of IAMs, based on a coordinated set of technology assumptions. They examined the nature of energy system transformation under climate change mitigation policies and the influence of technology availability on mitigation costs and on the feasibility of meeting ambitious climate goals.

The IAM studies agree that technology is indeed one of the key components of climate change mitigation and directly affects the attainability of low climate stabilization [6–8]. They suggest that more and better performance of the technology options available for mitigation leads to lower cost of mitigation and a higher likelihood of achieving

* Corresponding author.
*E-mail address:* eomjiyong@sogang.ac.kr (J. Eom).

0040-1625/$ – see front matter 
http://dx.doi.org/10.1016/j.techfore.2013.09.017

ambitious climate targets. It has also been shown that limiting climate change will undoubtedly require major changes to the global energy system, which takes the form of extensive deployment of new and existing low-carbon technologies [1,7–9]. Thus the availability of technology has the effect of shaping the optimal time path of emission mitigation, that is, the relative degree of near-term and longer-term emission reductions, which in turn influences the cost of achieving the climate targets [4,8].

Technological aspects of long-term mitigation policies are receiving renewed attention as current national emission reduction pledges are not consistent with the reductions required to meet the 2 °C target in a cost-minimizing way [10]. Although previous studies have shown that a delay in climate policy can result in substantial increases in mitigation costs and even infeasibilities [7,11–16], there exists no single model inter-comparison study that systematically explores the role of technology under weak near-term climate policies that are consistent with what is currently being discussed in the international climate policy arena.

This study employs AMPERE WP2 scenarios to explore this research gap [17]. Nine different IAMs with varying representation of the energy–economy–climate system and unique strengths participated in this study. All models use coordinated assumptions about technology availability and harmonized near- and long-term emission budgets and population and economic developments to allow for a comprehensive, relatively robust characterization of the role of technology in achieving meaningful climate stabilization in the long term under weak near-term policies. We hypothesize that weaker-than-optimal near-term actions imply that subsequent emission mitigation and energy system transformations will be forced to accelerate in subsequent years with the responsiveness depending on the available emission mitigation technology options.

The objective of this study is to investigate what near-term climate policies may imply for technology deployment and longer-term emission pathways that achieve the 450 ppm $CO_2$e target[1] in 2100 under alternative technology availability setups. The three sets of research questions include:

1. How do less-than-optimal near-term emission mitigation policies affect mid-term and long-term emission mitigation requirements to achieve an end-of-century goal? How are the resulting pathways affected by technology availability? We will examine whether these variables become particularly sensitive when specific technologies are excluded and whether there is a critical set of technologies required to achieve the long-term stabilization goal.
2. What are the physical requirements of the transitions described in questions 1? For example, what are the land requirements; how many power plants need to be built; and what is the rate of capacity expansion? Are such transformations constrained by resource limits and how do they compare to historical technology deployment rates?
3. How do specific IAM characteristics affect the above questions? We will attempt to explain the results by identifying specific technologies on which different IAMs rely for mitigation and the abilities of the IAMs to do large technology upscaling or early retirement.

The paper is organized as follows. Section 2 provides a brief background on the study design and scenario set-up. Section 3 explores long-term $CO_2$ emission pathways toward the 450 ppm $CO_2$e target after the period of optimal or delayed mitigation actions under various technology availability scenarios. Section 4 then examines the transformation of the energy system with a particular emphasis on the characteristics of technology deployment. Section 4.1 then discusses the physical implications of such technology deployment, and Section 4.2 offers conclusions.

## 2. Study design and scenario set-up

In this study, we employ a subset of AMPERE WP2 scenarios that is generally consistent with a concentration target of 450 ppm $CO_2$e (2.6 W/m$^2$) in 2100, corresponding to a cumulative emission budget over the period 2000 to 2100 of 1500 Gt$CO_2$.[2] We combine this with two alternative near-term climate policies through 2030 and five technology sensitivity experiments.

The two near-term climate policies are:

1. Optimal short-term emissions (*OPT*) and
2. Emissions limited to 60.8 Gt$CO_2$e per year in 2030 (*HST*[3]).

Note that the OPT pathways are model-specific and that the HST scenarios are calculated in terms of Kyoto greenhouse gases [17].[4] After the year 2030, models have full

[1] The 450 ppm $CO_2$e target is broadly consistent with limiting long-term temperature change below 2 °C compared to pre-industrial levels [44], which is called for by the UN Framework Convention on Climate Change [45] and also regarded as a reasonable benchmark to avoid dangerous climate change [46]. This is apparently an aspirational target as a globally appropriate agreement with binding emission constraints to achieve the target is not likely to be reached anytime soon. To allow for various analyses related to mitigation costs and feasibility of achieving long-term targets, the AMPERE exercise also includes scenarios achieving 550 ppm $CO_2$e, which represents lower climate ambition [17]. In this paper, however, we chose to focus on the cases with the aspirational but meaningful target to highlight the influence of near-term mitigation action on required long-term emission mitigation and energy-system transformation, which tend to amplify as the target gets more stringent.

[2] The use of a cumulative $CO_2$ emission budget reduces the uncertainty that would be introduced if each modeling team were to employ its own simple climate model and facilitates participation by groups that do not have in-house atmosphere–climate models.

[3] HST indicates "high short-term target," which is the low-ambition extrapolation of global greenhouse gas emissions levels from the pledges by 2020 under the 2010 Cancún Agreements [47].

[4] To meet aspirational warming goals, we need deep emission reductions not only of Kyoto greenhouse gases—$CO_2$, $CH_4$, $N_2O$, $SF_6$, HFCs, and PFCs—but also of some non-Kyoto air pollutants—black carbon aerosols and tropospheric ozone precursors. Reducing black carbon emissions in particular, which could also be achieved from local air-quality measures, would help decrease short-term net radiative forcing and thus result in lower global warming for a few decades [49]. In the AMPERE exercise, however, we do not examine the issue of accelerated action on air pollutants as a major near-term strategy of achieving the long-term 450 ppm $CO_2$e stabilization target. One important consideration for this was that only five models out of the nine participating models represent full greenhouse gases and radiative agents, although eight models represent full Kyoto gases. So, we set the high short-term target of 60.8 Gt$CO_2$e for those eight models with full Kyoto gases. For the other two models, POLES and IMACLIM, that represent only fossil and industrial $CO_2$ emissions, the target has been set to 44.2 Gt$CO_2$ in 2030.

**Table 1**
Scenarios covered in this study and feasibilities ("NR" indicates not-reported scenarios, "INF" indicates infeasible scenarios, and "F" indicates feasible and reported scenarios).

| | DNE21+ | GCAM | IMACLIM | IMAGE | MERGE-ETL | MESSAGE | POLES | REMIND | WITCH | F and INF (count) |
|---|---|---|---|---|---|---|---|---|---|---|
| FullTech-OPT | F | F | F | F | F | F | F | F | F | 9/0 |
| NucOff-OPT | F | F | F | F | F | F | F | F | F | 9/0 |
| LimSW-OPT | NR | F | NR | F | F | F | F | F | NR | 6/0 |
| LimBio-OPT | NR | F | NR | INF | F | F | F | F | NR | 5/1 |
| NoCCS-OPT | F | F | NR | INF | F | F | INF | F | INF | 5/3 |
| FullTech-HST | F | F | INF | INF | F | F | F | F | F | 7/2 |
| NucOff-HST | F | F | INF | INF | INF | F | F | F | F | 6/3 |
| LimSW-HST | NR | F | INF | INF | F | F | F | F | NR | 5/2 |
| LimBio-HST | NR | F | INF | INF | INF | INF | F | F | NR | 3/4 |
| NoCCS-HST | F | F | INF | INF | INF | INF | INF | INF | INF | 2/7 |

flexibility to mitigate emissions in a cost-effective manner so as to achieve the cumulative emission budget.

Each of the above policy scenarios is examined in light of five alternative technology performance-availability assumptions [17]:

1) *FullTech*: all (model-specific) technologies are available and can be fully deployed;
2) *NucOff*: nuclear power is phased out[5];
3) *LimSW*: limited progress in solar and wind power technology improvement;
4) *LimBio*: limited bioenergy supply availability; and
5) *NoCCS*: $CO_2$ capture and storage technology is not allowed to deploy.

The combination of the two near-term targets and the five technology exclusion cases gives 10 possible scenarios for each IAM.[6]

For this model comparison, nine IAMs have participated: DNE21+ [18], GCAM [19–21,22], IMACLIM [23,24], IMAGE [15,25], MERGE-ETL [26,27], MESSAGE [28], POLES [29], REMIND [30,31], and WITCH [32,33]. MERGE-ETL, MESSAGE, REMIND, and WITCH are inter-temporal general equilibrium models, IMACLIM is a recursive-dynamic general equilibrium model, and DNE21+, GCAM, and POLES are recursive-dynamic partial equilibrium models. All of the IAMs run through 2100, except for DNE21+, which extends to 2050. Aside from the solution approaches, the IAMs strongly differ in many other aspects. For instance, not all of the participating IAMs incorporate all greenhouse gas emissions from fossil fuel and industrial (FF&I) uses and land use changes. Specifically, IMACLIM and POLES cover FF&I $CO_2$ emissions only. The models also differ widely in the representation and substitutability of technologies, which influences their ability to quickly transform the energy system and meet long-term low stabilization targets. The diagnostic study in this issue [34] evaluates the IAMs in terms of emission responses to harmonized carbon prices, reliance on carbon intensity reduction relative to energy intensity reduction, and the rate of energy system transformation. A more detailed description of the individual IAMs is given in the overview paper of this issue [17].

[5] The NucOff scenario reflects a phase out of nuclear occurring after 2010 and incorporates plants that are under construction (but not planned or proposed). Other technologies remain available as in FullTech.

[6] Alternative energy efficiency scenarios are explored in the context of carbon lock-ins in this issue [39].

Note that not all IAMs reported all ten of the possible scenarios (Table 1). The failure of the IAMs to report scenarios is attributable to a wide range of factors, ranging from technically not being able to find a solution, to having found a solution but with the carbon price being "too high," to simply not attempting to run the scenario. As such, individual modeling teams were required to report the feasibilities of the scenarios that they were asked to run, by indicating "NR" (not run) for the not-attempted scenarios, "INF" (infeasible) for the scenarios that failed to solve or generated an excessively high carbon price, and "F" (feasible) for all other scenarios. 57 feasible scenarios out of 90 possible scenarios were reported and used for the analysis. Note that the number of IAMs that find a scenario feasible varies widely among technology availability assumptions, so that conclusions drawn from direct comparison across alternative technology availability cases in this study may be subject to sample selection bias. We will refer to Table 1 to discuss feasibilities in various scenarios.

## 3. $CO_2$ emission pathways toward 450 ppm $CO_2$e

Achieving 450 ppm $CO_2$e stabilization in 2100 requires major changes in the global energy system. The character of the transformation pathway reflects near-term climate policy assumptions as well as the long-term goal [17]. To the extent that the HST pathway undertakes less near-term emission mitigation than the OPT pathway, it reduces the remaining allowable emission budget.

### *3.1. Transition pathways with optimal near-term policies (OPT)*

In the FullTech cases, bioenergy (BE) with $CO_2$ capture and storage (CCS) technology is available for all IAMs. The BE and CCS (BECCS) technology combination facilitates energy production with net $CO_2$ removal from the atmosphere. This in turn means that a fixed budget can be met through "overshoot" pathways, in which the long-term target is temporarily exceeded but eventually reduced to target levels through BECCS.

In the FullTech-OPT scenarios, nearly all IAMs report negative net global emissions by 2070 (Fig. 1). Negative emissions mostly come from BECCS and also terrestrial sequestration through land-use change such as afforestation and soil carbon enhancement. By 2050, emissions have been reduced to a small fraction of reference levels.

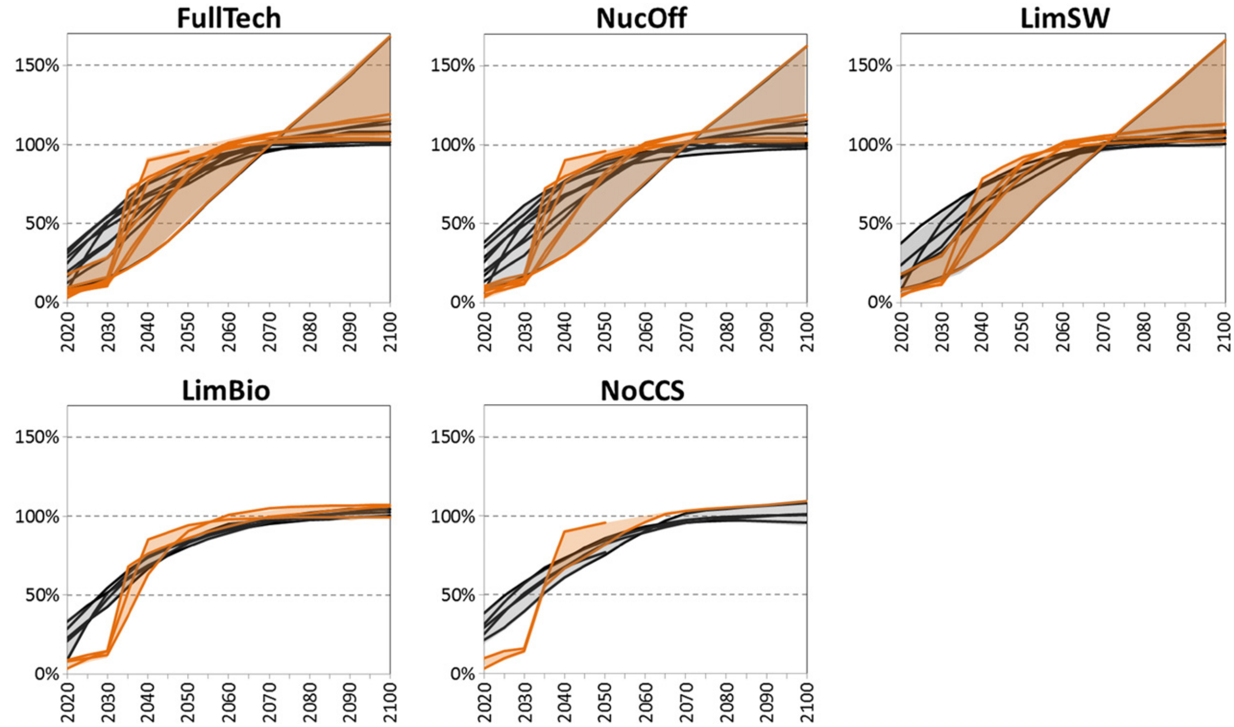


**Fig. 1.** Mitigation of $CO_2$ emissions relative to the baseline emissions. Gray funnel indicates the range of feasible OPT scenarios, and orange funnel indicates the range of feasible HST scenarios. Values greater than 100% indicate negative net global $CO_2$ emissions.

All modeling teams have BECCS as a technology option, and all report deployment of the technology in the OPT-FullTech scenario, though the extent to which it is deployed varies across models. Some IAMs, such as GCAM, REMIND, and MESSAGE, report negative global emissions facilitated by BECCS deployment (Fig. 1). Others, for example POLES, deploy BECCS, but net global emissions remain positive. In GCAM, BECCS is supplemented by terrestrial carbon sequestration, which in turn is facilitated by carbon prices which shift relative food prices resulting in dietary shifts away from carbon-intensive activities, such as cattle, and toward forests, soil carbon enhancement and bioenergy production [35].

Limiting nuclear power or non-bioenergy renewables with cost-effective near-term mitigation paths (the OPT policy scenarios: NucOff-OPT or LimSW-OPT) does *not* change the basic behavior of deep emission cuts in the long run through negative emissions (Fig. 1).[7] This is because these technologies are only used for electricity production, for which other low-carbon options are readily available [8]. Note that the NucOff and LimSW cases lead to greater percentage reductions in the near-term and smaller percentage reductions in the long term relative to the full technology availability case. This is because, with those technologies excluded, the baseline scenarios present greater emissions that accrue mostly in the long term, while the stabilization scenarios lead to slightly greater emission reductions in the near term and slightly less negative emissions in the long term. However, overall differences in emission mitigation are small relative to scenarios in which BECCS is unavailable.

Limiting BECCS in the OPT scenarios (NoCCS-OPT or LimBio-OPT) has the effect of greatly reducing timing flexibility in mitigation (Fig. 1). We find that emission mitigation is shifted toward the present from the future, since the option to "overshoot" the cumulative target and make up for it with negative emissions late in the century is no longer available. By contrast, the presence of the long-term negative emission opportunity from BECCS technologies shifts emission mitigation to the future from the present.

Nonetheless, several scenarios still report negative global emissions even in the OPT scenario without CCS (NoCCS-OPT). This result is possible with terrestrial sequestration (DNE21+, GCAM, and MESSAGE) and, to a lesser extent, the use of biological material in long-lived products (GCAM). We also find that, compared with the case where BECCS is fully available, mitigation pathways show smaller variance across the models, although we begin to see fewer models reporting scenarios—IMAGE becomes infeasible in LimBio and NoCCS, and POLES and WITCH become infeasible in the NoCCS scenario (Table 1).[8]

[7] BECCS technology is available in scenarios that limit nuclear power (NucOff) or limit non-biomass renewable energy forms (LimSW).

[8] Three models, DNE21+, IMACLIM, and WITCH, did not attempt to run either of these scenarios.

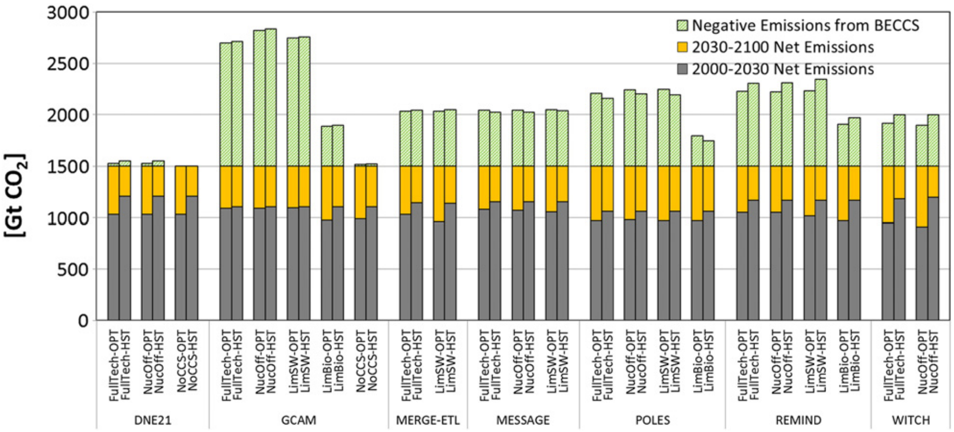


**Fig. 2.** 2000–2030 consumption of the 1500 $GtCO_2$ budget (gray), remaining post-2030 $CO_2$ budget (red), and budget expansion due to negative emission (green) in the OPT and HST policy cases.

### *3.2. Transition pathways with less-than-optimal near-term policies (HST)*

Two-thirds or more of the 1500 $GtCO_2$ budget is consumed in the 30 years between 2000 and 2030, and the remainder in the subsequent 70 years (Fig. 2). The HST policy cases all set an emission level of 60.8 $GtCO_2e$ in 2030[9] [17], which corresponds to the low-ambition extrapolation of the emission pledges by 2020 under the 2010 Cancún Agreements. As this level is greater than any model reported for an OPT scenario, emission mitigation in the HST scenarios is less than optimal. As a consequence, models are forced to accelerate emission mitigation in the years 2030–2050 (Figs. 1 and 3) and/or deploy negative emission technology more aggressively (for example, DNE21+, GCAM, MERGE-ETL, REMIND, and WITCH) (Fig. 2). The accelerated post-2030 transformation in the energy system into low carbon technologies, as highlighted in Fig. 3, invokes reductions in aggregate energy demand and increases in mitigation costs.[10]

The degree to which the HST policy is suboptimal varies across models. For GCAM, the difference is relatively small (Fig. 2). In optimal mitigation pathway scenarios, GCAM undertakes a large part of emission mitigation in the latter half of the century through BECCS. As a result, GCAM significantly overshoots the long-term budget during the century. For all other IAMs, particularly for WITCH and DNE21+, a larger portion of the post-2030 emission budget is consumed due to the HST policy as it would be optimal for them to conduct serious emission mitigation earlier, given that they cannot significantly overshoot the long-term target during the century while still meeting the long-term target. The extreme case is IMACLIM, where all HST scenarios become infeasible.

The ability to produce negative emissions has an important role to play in HST scenarios in several models. For GCAM and REMIND, in particular, the proportion of the post-2030 budgets that are consumed as a consequence of the HST policy becomes particularly high when BECCS is limited (LimBio-HST or NoCCS-HST) (Fig. 2). Also, HST scenarios are associated with higher costs particularly when BECCS is limited (see [17] for the discussion on mitigation costs).

The extent of the technology portfolio was also important in finding transition pathways. Seven of the nine modeling teams reported the ability to meet the cumulative emission budget under the HST constraint if all technology options, including BECCS, were available. Limiting technology availability increased the number of models that reported the case to be "infeasible" (Table 1). When CCS was unavailable, only two modeling teams—DNE21+ and GCAM—reported transition pathways: both of them instead reported large-scale terrestrial sequestration, which presents negative emissions.[11]

The important implication is that significant delay in emission mitigation actions leads to negative emissions using BECCS and/or terrestrial sequestration becoming a requirement rather than a choice. Another important insight is that as we delay more, the scale of required negative emissions increases, posing a greater risk of failing to achieve the long-term climate goal.

### *3.3. Regional roles in transition pathways*

Regional composition of $CO_2$ emissions for each of the reported scenarios is shown in Fig. 4.[12] ASIA (China, India, Southeast Asia, and Korea) accounts for the largest share of emissions across all models, followed by the OECD90. The rest of the world (ROW) accounts for the smallest share. While regional shares wax and wane across models and scenarios, variation is relatively modest. This is likely due to the assumption that all global regions initiate emission mitigation simultaneously, face a common price of carbon even in the near-term, and generally

[9] For POLES and IMACLIM, which have only fossil and industrial $CO_2$ emissions, the HST target has been set to 44.2 $GtCO_2$ in 2030.

[10] The overview paper [17] points out that mitigation costs increase for the HST scenarios, relative to their OPT counterparts. These effects are exaggerated when BECCS is limited.

[11] Although CCS was unavailable terrestrial sequestration was available in both DNE21+ and GCAM, and GCAM also reported negative fossil fuel and industrial emissions associated with the use of bioenergy in long-lived materials, e.g. plastics.

[12] The results of AMPERE exercise are shown at regional aggregations of the world's five macro regions (OECD90, REF, ASIA, MAF, and LAM). The definition of the regions is available at https://secure.iiasa.ac.at/web-apps/ene/AMPEREDB/.

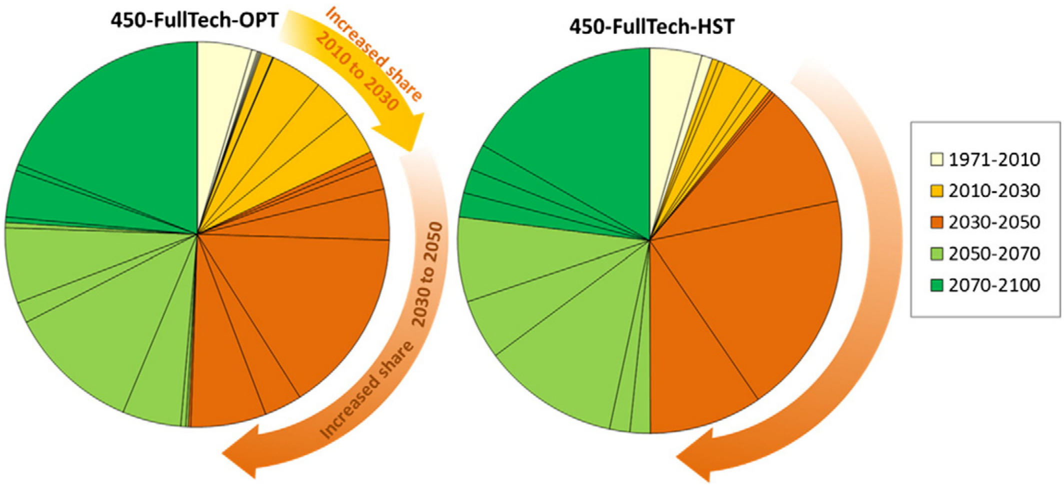


**Fig. 3.** The shares of non-emitting primary energy supply that occurs for sequential periods beginning in 2010 for the OPT and HST policy in the FullTech scenarios: Colored areas display the median of reporting models. Individual model shares by period are indicated by black lines showing variation across individual models. The largest increase in the share of non-emitting primary energy occurs between 2030 and 2050, though the transformation continues throughout the 21st century.

have access to the same technology options. The assumption of the same near-term carbon price across regions distinguishes this review from those that specify varying regional prices—such as AMPERE Work Package 3 [36], LIMITS [37], and RoSE [38]. The HST policy results in higher cumulative emissions in ASIA compared with the OPT case for DNE21+, POLES, and REMIND, likely due to the relatively high near-term emissions per unit of energy in ASIA. The trend is, however, reversed for WITCH.

## 4. Technology deployment toward 450 ppm $CO_2$e

A detailed look at technology deployment to meet the 1500 $GtCO_2$ 21st century emission budget reveals four clear findings:

- *There is no "Silver Bullet."*[13] No single technology delivers the emission mitigation required to transform the energy system from its reference pathway to one limiting cumulative emissions to 1500 $GtCO_2$ in the 21st century;
- There are *multiple possible technology portfolios* that can transform the energy system from its reference pathway to one limiting cumulative emissions to 1500 $GtCO_2$ in the 21st century;
- The period *2030 to 2050 is critical* for mitigation technology deployment; and
- Foregoing or limiting mitigation technology options increases reliance on the remaining technologies in the transformation technology portfolio.

The remainder of this section elaborates these findings one by one.

### 4.1. Full technology deployment

The comparison of the IAMs resoundingly suggests that there is no "Silver Bullet" to the achievement of 450 ppm $CO_2$e, independent of the stringency of near-term actions (Fig. 5).[14] A broad range of supply- and demand-side responses is required to make a major emission reduction, and their relative contributions vary among IAMs and over time.

The mitigation responses can be grouped into three inter-related categories. The first response category, which is the utmost concern of this paper, is the upscaling of low-carbon technologies, such as, wind, solar, nuclear, bioenergy, and CCS technologies including BECCS. While the IAMs deploy all emission mitigation technologies to some degree if available, they do differ in the relative contributions to emissions (Fig. 5). GCAM responds by deploying BECCS in a large scale mostly after 2050, though BECCS remains a part of an emission mitigation technology portfolio. The expansion of solar power is pronounced in MERGE-ETL and MESSAGE even as early as in the 2030–2050 period, and REMIND has its rapid expansion seen only after 2050. The second option is the premature retirement of emitting sources, particularly coal-fired power plants. All IAMs but IMAGE allow for such premature retirement (see Bertram et al. [39] in this issue), and the option is exercised to a varying

[13] A "Silver Bullet" technology is one which alone is sufficient to achieve emission mitigation goals at little or no cost.

[14] Note that none of the IAMs have taken into account the complete list of all potential silver bullets that are currently discussed. This is not only because the development of such technologies is highly uncertain—thus different models would have very different prospects—but also because the AMPERE study, as a scenario exercise, intends to examine the interaction between the availability of major technology options that are shared among the IAMs and near-term policy actions, not to explore the entire space of possible technology developments, which would in itself be an interesting avenue for future research. In this regard, the no-silver-bullet argument may be augmented with the assertion that even silver bullets were to emerge they are very hard to guarantee, so that portfolio approach would be needed anyway to hedge against the technological risks.

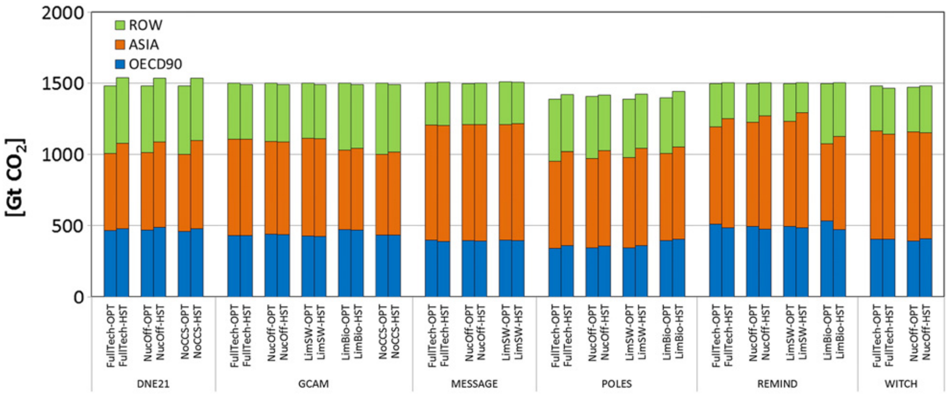


**Fig. 4.** Regional composition of emissions 2000 to 2100 for OECD90, ASIA, and the rest of the world (ROW).

degree among the IAMs especially between 2030 and 2050 (Fig. 5). Although implementing various types of retirement policies is a necessary step toward long-term energy system transformation that is consistent with the 2 °C target, in practice, stranded capital assets and regional politics may pose significant challenges. The last option, which is co-determined by the availability and economics of the first two responses, is the reduction in energy demand. IMACLIM and, to a lesser extent, WITCH have net energy reductions during 2030–2050 as non-bioenergy renewables do not become viable options until then, that is, as a significant transformation of the energy sector is limited. The model diagnostic study of this issue [40] points out that IMACLIM and WITCH exhibit less reliance on carbon intensity reductions relative to energy intensity reductions for their mitigation strategies. Our results also confirm that the relative contributions from these supply- and demand-side mitigation responses, particularly in the 2030 to 2050 time frame, are influenced by the level of near-term climate actions.

### 4.2. Technology deployment between 2030 and 2050

The 20 years between 2030 and 2050 are a period of intensive transformation in energy systems to meet the 1500 $GtCO_2$ 21st century emission budget for both the OPT and HST

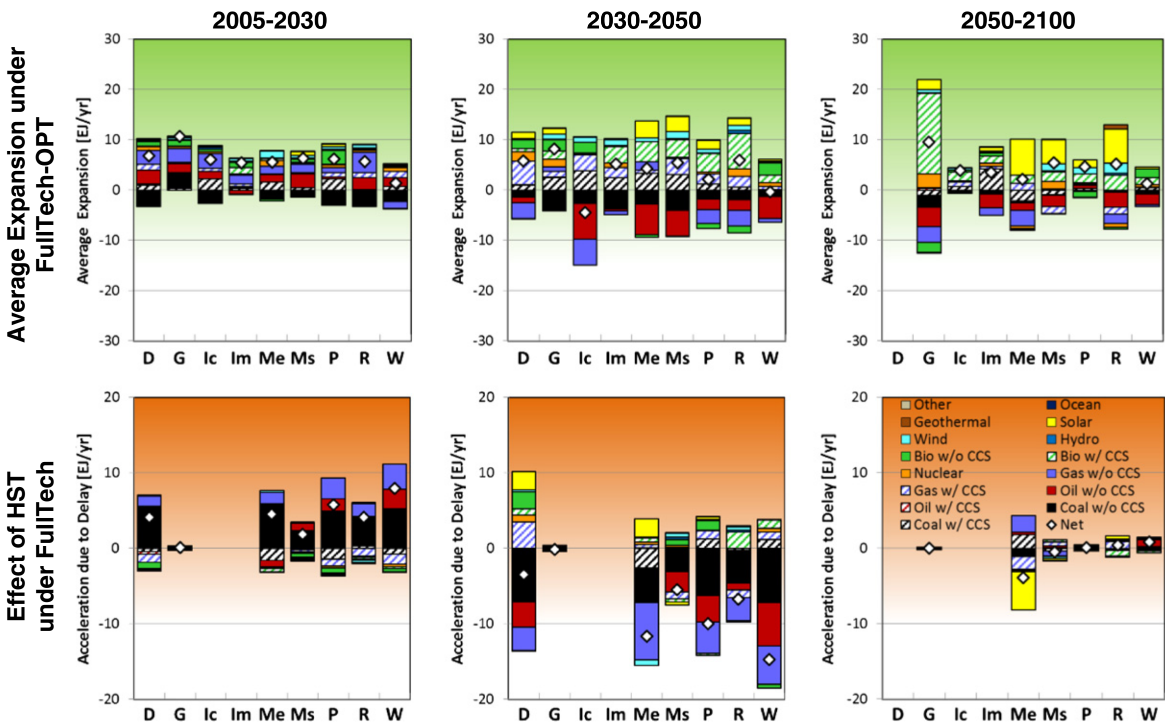


**Fig. 5.** The rate of deployment in global primary energy under FullTech-OPT (top row) and excess deployment under HST relative to the FullTech-OPT case (bottom row) in the 2005-to-2030 (first column), 2030-to-2050 (second column), and 2050-to-2100 time frames (third column).

policy scenarios (Figs. 3 and 5).[15] During this period, the pace of phasing out fossil capacities gets faster as existing capital stock retires earlier than scheduled (except for IMAGE), while at the same time many of the low-carbon technologies with decreasing costs become viable options, both promoted by rising carbon tax imposed on emitting sources. For example, BECCS technologies, when available, are aggressively deployed, and even natural gas and oil technologies start to phase out in many of the IAMs between 2030 and 2050. The exception is GCAM, which presents the greatest deployment of BECCS only after 2050. Remember that DNE21 + runs only through 2050.

The period between 2030 and 2050 is particularly important for the HST policy regimes. This 20-year period in the HST policy case requires accelerated system transformation to compensate for the suboptimal emission mitigation between 2010 and 2030, a period characterized by large-scale deployment of emitting sources and little deployment of CCS technologies (Figs. 3 and 5). All IAMs indicate that most of the additional emissions in the 2010–2030 period are produced by coal combustion, almost entirely by coal-fired power plants.

The additional emission reductions between 2030 and 2050 come from all of the mitigation responses discussed above: faster expansion in low-carbon technologies (bioenergy with and without CCS and, to a lesser extent, solar, wind, and nuclear power), faster retirement of emitting sources after 2030, and associated greater reductions in energy demand. The results indicate that if any of these responses are severely constrained in certain IAMs, their scenarios are likely to be infeasible. For example, IMAGE and IMACLIM have infeasibility even in the full technology availability case because the former does not have the ability to rapidly retire fossil capacities and the latter is already pushed to its limits to fossil capacity retirement (and associated reductions in energy demand). Johnson et al. [41] of this issue discusses the relationship between near-term climate policy and stranded coal capacity in the case of MESSAGE-MACRO scenarios. Note that nearly all of the additional low-carbon technology deployment and fossil capacity retirement are made before 2050 for all feasible models, so that HST has no noticeable effect on post-2050 deployment. This explains why post-2050 emission pathways are similar for both OPT and HST scenarios (Fig. 1). We discuss physical deployment rates of low-carbon technologies in Section 4.1.

The accelerated 2030–2050 transformation in the HST policy case necessarily involves extra costs. It leads to major reductions in energy demand relative to the optimal case (OPT) (Fig. 5). The decreased energy demand can be translated into additional losses of consumption or increased mitigation costs, and as the post-2030 losses more than offset the near-term consumption gains in the non-ideal mitigation pathways, it eventually leads to increased total policy costs in net present value terms (see [17] for the discussion of policy costs) and infeasibilities in the cases of IMACLIM and IMAGE.

### 4.3. The effect of technology limitations

Losing a technology option in the optimal policy case (OPT) causes other available mitigation technologies to expand earlier at a larger scale and/or fossil capacities to phase out more rapidly, and weak near-term actions (HST) require such technological responses to be implemented at an even larger scale in the 2030–2050 period (see Figs. S1–S4 in the online supporting materials). When BECCS is limited, a particularly rapid catch-up transformation occurs. In principle, the relative contributions of mitigation responses in the individual IAMs depend on assumed technology performance and cost, the degree to which technologies can substitute for each other in the model, the timing of the phase out of fossil capacities, and assumed or model-determined limits to the speed at which new plant and equipment can deploy.

We consider limits on four technologies: (1) Nuclear power (2) variable renewable electricity supply (wind and solar power) (3) Bioenergy and (4) CCS. Each of these mitigation technologies plays a different role in the energy system. The first two technologies play an important role in providing power generation. Bioenergy can be used either as a renewable source of fuels, including transportation fuels, a feedstock for power generation, and in combination with CCS, a means by which carbon can be removed from the atmosphere. CCS can be used in combination with any large emission source, including power stations and industrial facilities, including cement manufacturing. Thus, limitations on each of these will have different repercussions for the overall emission mitigation technology portfolio.

#### 4.3.1. Nuclear phase out

The effect of no new construction of nuclear power plants (NucOff-OPT) is relatively minor before 2030 because their expansion is modest when the nuclear option is available (Fig. 5). Furthermore, a large proportion of current plants and those currently under construction will continue to operate until then (Fig. S1). The effect on energy demand is fairly limited as CCS-based fossil energy and renewables, which would be anyway deployed at a large scale after 2030, expand a little faster to compensate for the gradual decommissioning of nuclear power plants. Also, weak near-term policies (NucOff-HST) do not make its post-2030 technology deployment particularly different from the full technology availability case (FullTech-HST).

#### 4.3.2. Renewable energy limits

In the limited renewable scenario (LimSW-OPT), the major impacts on the deployment of renewables are seen only after 2030, the period when renewables are to compete with other low-carbon technologies (Fig. S2). MERGE-ETL, MESSAGE, and REMIND show demand reductions after 2050, the period when

[15] Our separation of the century-scale time frames—pre-2030, 2030–2050, and post-2050—originates both from the design of AMPERE WP2 study and from our findings about technology deployment. First, according to the protocol of AMPERE WP2 study, during the first stage up to 2030, global emissions follow a trajectory toward the fixed year-2030 target. As a result, the amount of cumulative emissions and the associated emission mitigation burden during the next stages will critically depend on the first stage emission pathway to 2030. This distinct set-up helps explicitly assess the implications that near-term policy actions have for the attainability of long-term climate goals and attendant technology upscaling requirement after 2030. Second, the separation before and after the year 2050 is from our observation that, for the HST policy regimes, nearly all of the catch-up deployment is made between 2030 and 2050 (see Figs. 3 and 5). Therefore, if we had an alternative separation of the time frames, we might have not been able to elicit robust findings related to technology deployment and emission pathways after delayed policy actions, which is the main focus of this study.

**Table 2**
Median upscaling rates of nuclear, solar, and wind power between 2030 and 2050 (full ranges are indicated by the numbers within the brackets).

| Region | Tech | Short-term target (sample) | Nuclear power 2030–2050 | | Solar power 2030–2050 | | Wind power 2030–2050 | |
|---|---|---|---|---|---|---|---|---|
| | | | ΔGW | Δ plants per year | ΔGW | Deployment rate relative to 2011 | ΔGW | Deployment rate relative to 2011 |
| World | FullTech | OPT (9) | 511 [−37, 1357] | 17 | 3455 [86, 6962] | 53 | 1397 [449, 3032] | 6 |
| | | HST (7) | 885 [191, 1995] | 29 | 3329 [975, 18013] | 51 | 1182 [245, 4081] | 5 |
| | NucOff | OPT (9) | −177 [−286, −20] | −6 | 3510 [77, 12759] | 54 | 1308 [818, 3886] | 5 |
| | | HST (6) | −164 [−286, −122] | −5 | 4623 [1970, 34176] | 71 | 1822 [1274, 5351] | 8 |
| | LimSW | OPT (6) | 269 [33, 1318] | 9 | 142 [−12, 4312] | 2 | 534 [386, 2290] | 2 |
| | | HST (5) | 387 [−86, 1290] | 13 | 360 [14, 5969] | 6 | 280 [−681, 2507] | 1 |
| | LimBio | OPT (5) | 343 [−93, 1920] | 11 | 4226 [3132, 8275] | 65 | 1530 [1494, 4150] | 6 |
| | | HST (3) | 545 [462, 2544] | 18 | 8504 [3840, 8902] | 131 | 2172 [2128, 7328] | 9 |
| | NoCCS | OPT (5) | 1064 [−49, 2691] | 35 | 5255 [3418, 18204] | 81 | 1112 [1072, 4801] | 5 |
| | | HST (2) | 3205 [2694, 3716] | 107 | 23547 [5555, 41539] | 362 | 3214 [2368, 4059] | 14 |
| OECD90 | FullTech | OPT (9) | 70 [−203, 419] | 2 | 785 [3, 1374] | 12 | 243 [189, 1125] | 1 |
| | | HST (7) | 102 [−106, 798] | 3 | 853 [124, 6476] | 13 | 200 [89, 1378] | 1 |
| | NucOff | OPT (9) | −118 [−237, −17] | −4 | 765 [3, 3466] | 12 | 317 [231, 1089] | 1 |
| | | HST (6) | −117 [−237, −89] | −4 | 984 [186, 11120] | 15 | 559 [315, 1611] | 2 |
| | LimSW | OPT (6) | −28 [−212, 253] | −1 | −7 [−64, 888] | 0 | 135 [−21, 906] | 1 |
| | | HST (5) | −43 [−118, 256] | −1 | 6 [−59, 1059] | 0 | 120 [−313, 651] | 1 |
| | LimBio | OPT (5) | 80 [−173, 325] | 3 | 1262 [184, 2185] | 19 | 207 [104, 1367] | 1 |
| | | HST (3) | 130 [−17, 504] | 4 | 1383 [245, 2312] | 21 | 486 [306, 2587] | 2 |
| | NoCCS | OPT (5) | 133 [−137, 605] | 4 | 1617 [316, 9632] | 25 | 123 [110, 1600] | 1 |
| | | HST (2) | 950 [805, 1095] | 32 | 7745 [428, 15061] | 119 | 704 [349, 1060] | 3 |
| ASIA | FullTech | OPT (8) | 497 [−24, 118] | 17 | 1394 [16, 3712] | 21 | 363 [139, 1194] | 2 |
| | | HST (6) | 601 [158, 1055] | 20 | 1794 [769, 8327] | 28 | 368 [271, 1706] | 2 |
| | NucOff | OPT (8) | −18 [−38, −1] | −1 | 1562 [13, 7483] | 24 | 498 [226, 1945] | 2 |
| | | HST (6) | −18 [−38, −13] | −1 | 2586 [1258, 18889] | 40 | 550 [482, 2669] | 2 |
| | LimSW | OPT (5) | 398 [128, 1033] | 13 | 203 [0, 2242] | 3 | 248 [30, 1154] | 1 |
| | | HST (4) | 401 [197, 744] | 13 | 671 [72, 3254] | 10 | 128 [−26, 1212] | 1 |
| | LimBio | OPT (4) | 681 [125, 1126] | 23 | 2940 [2052, 4016] | 45 | 573 [303, 1554] | 2 |
| | | HST (3) | 316 [254, 1427] | 11 | 4496 [2517, 4590] | 69 | 888 [637, 3120] | 4 |
| | NoCCS | OPT (4) | 792 [753, 1523] | 26 | 3693 [2361, 6296] | 57 | 395 [210, 1776] | 2 |
| | | HST (2) | 1512 [1028, 1996] | 50 | 8342 [3400, 13285] | 128 | 618 [412, 823] | 3 |
| ROW | FullTech | OPT (9) | 87 [−27, 268] | 3 | 818 [14, 3064] | 13 | 629 [8, 1327] | 3 |
| | | HST (7) | 144 [−4, 336] | 5 | 1021 [47, 3211] | 16 | 503 [80, 997] | 2 |
| | NucOff | OPT (9) | −21 [−48, −2] | −1 | 865 [13, 2589] | 13 | 644 [162, 1143] | 3 |
| | | HST (6) | −21 [−42, 18] | −1 | 1038 [88, 4167] | 16 | 755 [213, 1070] | 3 |
| | LimSW | OPT (6) | 111 [−21, 287] | 4 | 42 [−1, 1182] | 1 | 363 [227, 694] | 2 |
| | | HST (5) | 74 [−12, 290] | 2 | 91 [10, 1656] | 1 | 157 [0, 644] | 1 |
| | LimBio | OPT (5) | 42 [−4, 470] | 1 | 2074 [887, 2961] | 32 | 985 [801, 1323] | 4 |
| | | HST (3) | 162 [161, 614] | 5 | 2094 [1078, 2531] | 32 | 1230 [754, 1621] | 5 |
| | NoCCS | OPT (5) | 179 [88, 638] | 6 | 2276 [1277, 2608] | 35 | 904 [500, 1425] | 4 |
| | | HST (2) | 743 [571, 916] | 25 | 7460 [1728, 13192] | 115 | 1892 [1197, 2587] | 8 |

renewables were to become the major mitigation technology, although they do not agree whether energy demand will exhibit the same behavior even before 2050. Note that energy system transformation in GCAM is not very sensitive to the future of renewables because of much larger emission mitigation potential from BECCS. The post-2030 technology deployment after weak near-term actions (LimSW-HST) is not very different from the full technology availability case (FullTech-HST).

#### 4.3.3. Bioenergy limits

In the limited bioenergy scenario (LimBio-OPT), however, all feasible models have immediate reductions in energy demand relative to the full technology availability case (Fig. S3). This is because they are required to cut emission earlier as the negative emission option (BECCS) cannot be exercised in a large scale (Fig. 1). Limiting bioenergy is costly also because bioenergy is the most important source of non-electric low-carbon energy [8]. The rapid near-term emission reductions are achieved mainly by more rapid phase-out of conventional fossil energy and earlier deployment of CCS-based fossil energy, and after 2030, solar and nuclear power is put in to the system more rapidly. Also importantly, the weak near-term actions with limited bioenergy supplies (LimSW-HST) make post-2030 technology deployment even more pronounced—more rapid phase-out of emitting sources and earlier deployment of renewables—than the full technology availability scenario (FullTech-HST).

#### 4.3.4. CCS ban

The no CCS scenario (NoCCS-OPT) presents the greatest departure from the behavior observed in the other technology scenarios (Fig. S4). Emission reductions till 2030 are achieved by slower build-up of emitting sources and earlier deployment of bioenergy (w/o CCS) and solar power, collectively resulting in immediate reductions in energy demand, which is more pronounced than in the limited bioenergy case where the negative emission option (BECCS) is suppressed because of reduced feedstock availability but CCS technologies remain available. Moreover, the 2030–2050 transition without CCS requires tremendously rapid deployment of low carbon technologies (bioenergy w/o CCS, nuclear, and solar). In this case, we move much more quickly toward low carbon sources because of the complete absence of CCS (both BECCS and FECCS), which is one of the most flexible de-carbonization options. Not unexpectedly, the weak near-term actions without CCS (NoCCS-HST) only amplify these effects, spanning mostly in the short 2030–2050 period. The catch-up transformation is characterized by remarkably faster retirement in emitting sources and a larger scale deployment of bioenergy (w/o CCS), renewables, and nuclear power, which necessarily leads to major reductions in energy demand even after 2030. The 2030–2050 transition without CCS is less likely to succeed as indicated by only two IAMs (DNE21+ and GCAM) with a relatively large potential for technological responses remaining feasible, suggesting that the risk of failing to achieve the long-term climate goal will increase substantially especially when strong policy actions are delayed without having CCS available in the future. These two modeling teams also reported higher transition costs—for DNE21+, total energy system costs increased 940% relative to the optimal near-term action case (NoCCS-OPT).

## 5. Physical deployment in the 2030 to 2050 period: OPT and HST

In preceding sections we discussed the speed of the energy system transformation during the period 2030 to 2050. This 20-year period is critical to limiting cumulative emissions to 1500 $GtCO_2$ over the 21st century. The scale of the energy system transition is large in physical terms as well as relative terms. In this section, we focus on low-carbon energy sources, such as nuclear, solar, wind, bioenergy, and CCS, as the deployment of these technologies may pose particularly big challenges in terms of resource requirements and investment needs. Table 2 summarizes the scale of the transition for nuclear, solar and wind deployments.

### 5.1. Nuclear power

In the OPT-FullTech scenario, the median of 340 1.5GWe nuclear power plants would need to be built in the 20 years between 2030 and 2050 (Table 2). In the NoCCS-HST scenario, however, that number jumps to 2140 1.5GWe plants[16] or at an average rate of 107 new plants coming on line per year for feasible models, a number roughly comparable to the entire 2010 United States fleet of nuclear power plants.

As long as CCS remains available, the myopic near-term policy (HST) would lead to a faster expansion of nuclear power, reaching up to the median of 580 1.5GWe plants globally over the 20-year period or at an average rate of about 29 new plants per year. Yet, this annual rate of upscaling is not unprecedented and was observed in the mid-1980s [42]. One interesting finding is that the models are generally more optimistic about the future of nuclear power in ASIA than in other global regions (Fig. S5) as its high population growth, rapid economic development, and a lack of cheap technology alternatives all make nuclear power as a promising option. This suggests that losing the option of nuclear power would require faster expansion in other low-carbon technologies for ASIA, as supported by the region's large increase of solar and wind power capacity in the no-new-nuclear case compared to the full technology availability case (Fig. S5).

Without CCS, however, the median upscaling of nuclear power plants ranges from about 700 to 2140 1.5GWe plants globally over the 20-year period or at an average rate of 35 to 107 new plants per year, depending on the level of near-term actions (Table 2). In particular, ASIA would have to upscale its nuclear capacity with about 26 plants per year even in the optimal case and about 50 plants per year in the HST policy case. This is a substantial departure from the region's recent past, but may not be unreasonable. For example, as of January 2013, China and India have planned 51 and 18 plants and proposed 120 and 39 plants, respectively,[17] even without any major mitigation policies. However, the transformation in OECD90 is likely to be difficult with the HST policy if without CCS, as it would require an annual net build-up of 32 plants. Given that many of nuclear power plants operating in OECD90 will start to retire (there are only 5 plants under construction and 33 plants planned), the post-2030 upscaling of nuclear capacity would be challenging.

### 5.2. Solar power

In the case of solar power, achieving the low stabilization target after the myopic near-term actions implies up to 4 times faster expansion between 2030 and 2050 than the optimal policy case. This catch-up transformation is non-trivial, demanding the median scale-up of about 50–360 times of year-2011 global solar capacity over the 20-year period with the fastest increase when a no-CCS world is doing less than optimal in the near term (NoCCS-HST). This rate of upscaling requires 0.6–4.5% of the size of current crop lands in such a short period of time,[18] which is a major shift even aside from system integration and siting issues. However, the optimal near-term policies require much slower upscaling over the same period, ranging between 50 and 80 times of year-2011 global solar capacity with technology exclusion giving greater increases. At the regional level, the most rapid build-up of solar power takes place in ASIA and, to a lesser extent, in ROW. The HST policy makes the split across the regions even more pronounced with the annual percentage expansion rate of ASIA and ROW reaching up to 30% (Fig. S5).

[16] Note that the number is the mean of the two models that remain feasible under NoCCS-HST (GCAM and DNE21+). Even though both GCAM and DNE21+ tend to have relatively rapid nuclear power deployment among all feasible models (e.g., in the FullTech-OPT case, GCAM and DNE21+ projected 750 plants and 1330 plants, respectively in comparison of the model median of 340 plants), the NoCCS-HST scenario still presents major increases of the deployment of nuclear power plants for them.

[17] World Nuclear Power Reactors & Uranium Requirements from World Nuclear Association: http://www.world-nuclear.org/info/reactors.html.

[18] The total global land area of 1.3 thousand $km^2$ has been assumed for year-2011 solar power based on CSP land requirement of about 2 $km^2$ for a 100MWe plant [49].

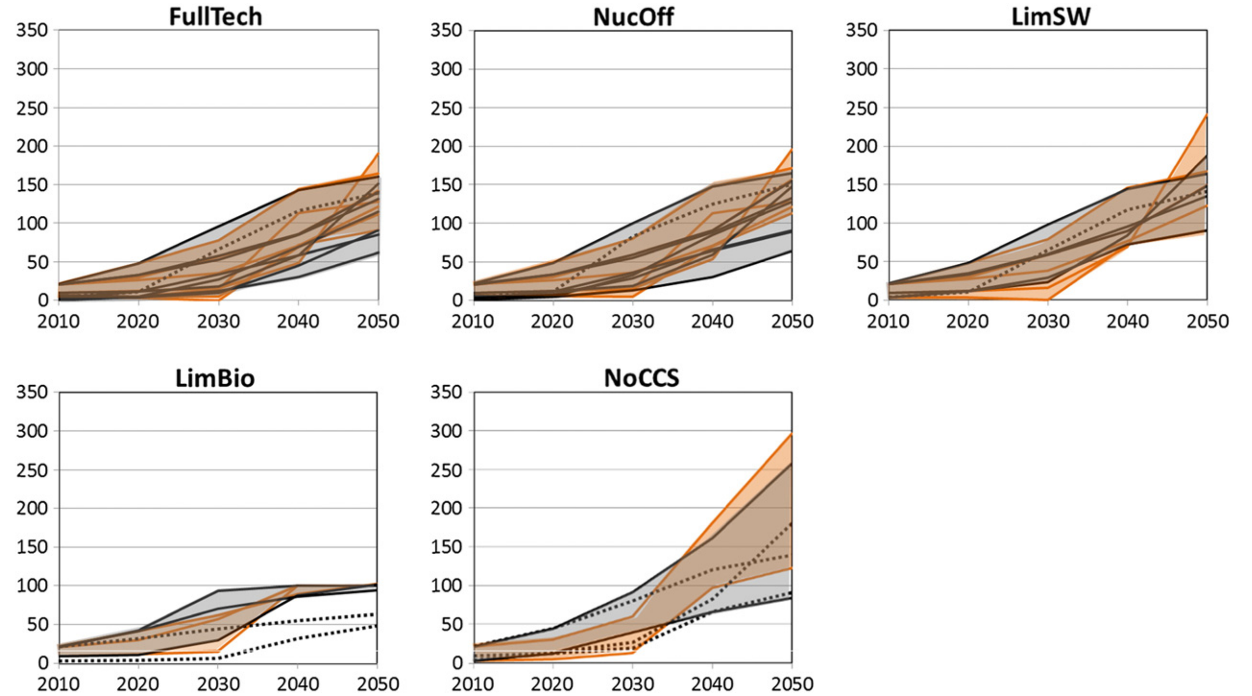


**Fig. 6.** Global bioenergy production [EJ/year] as represented by feasible OPT scenarios (gray funnel) and feasible HST scenarios (orange funnel): Dotted lines represent scenarios that are feasible only in the OPT case, but not in the HST case.

## 5.3. Wind power

The extent of upscaling is less pronounced in the case of wind power than in the solar power case, in part due to the higher starting value for wind, although the myopic near-term policy may still claim 5–14 times of year-2011 global wind capacity for the 2030–2050 transformation (Table 2). The weak near-term actions, except for the case with limited BECCS, do not necessarily lead to particularly faster upscaling for wind power than the optimal case. And technology exclusion does not so much affect the rate of upscaling, which is also different from the solar power case. It seems that wind power is the last technology option to be exercised as a technology substitute. Yet, the HST upscaling of wind power requires as much as

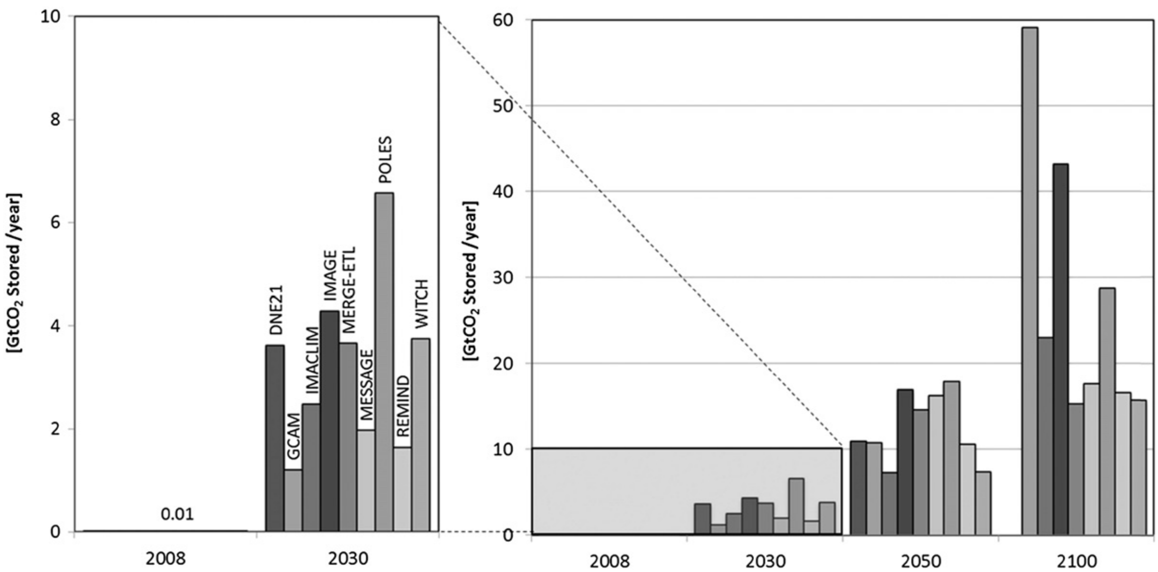


**Fig. 7.** Annual rate of geological carbon sequestration [$GtCO_2$/year] under FullTech-OPT.

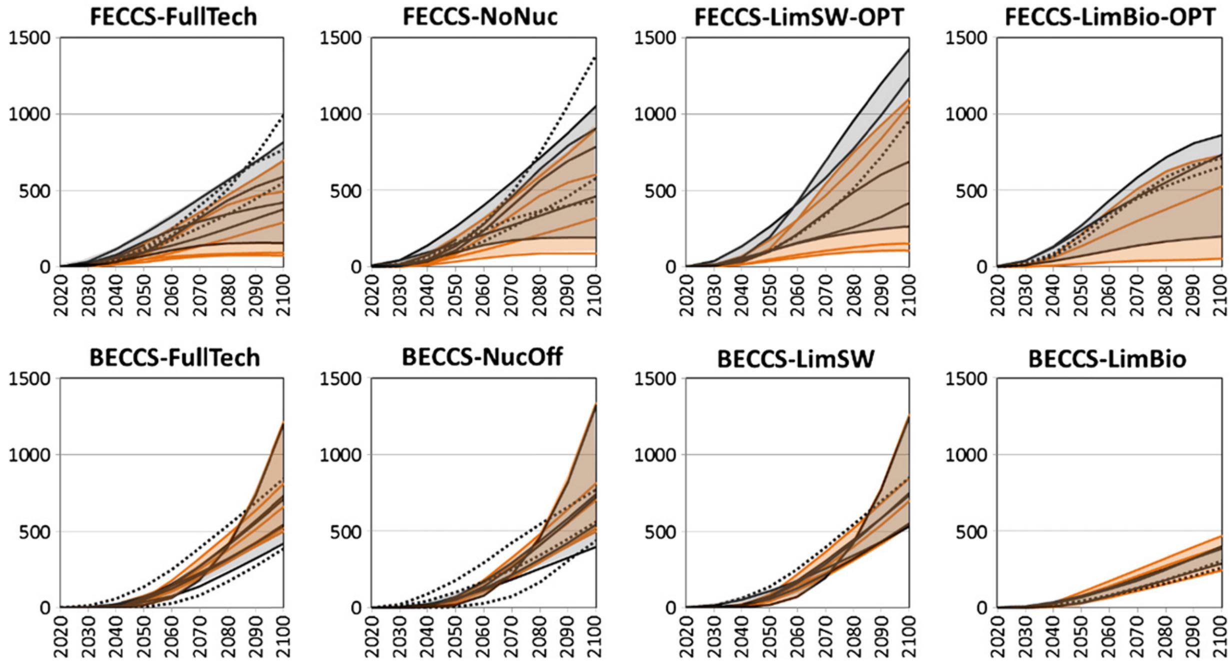


**Fig. 8.** Cumulative $CO_2$ storage [$GtCO_2$] from fossil energy CCS (upper) and bioenergy CCS (lower): Gray funnel indicates the range of feasible OPT scenarios, and orange funnel indicates the range of feasible HST scenarios. Dotted lines represent scenarios that are feasible only in the OPT case, but not in the HST case.

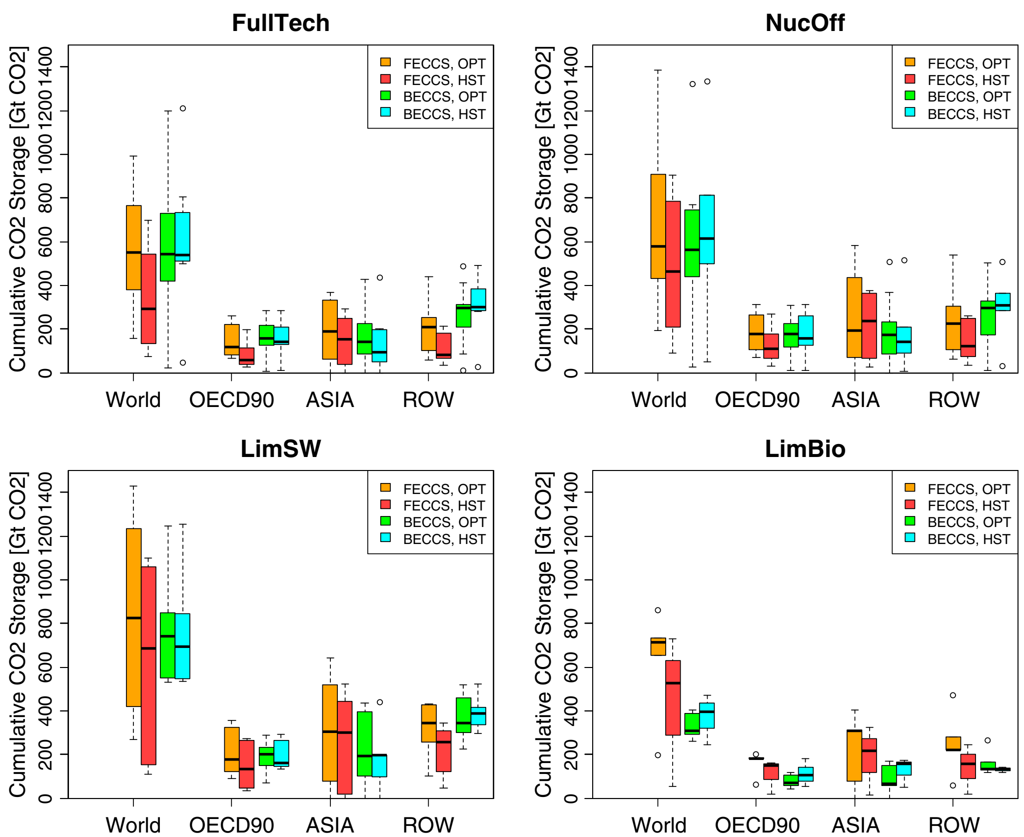


**Fig. 9.** Year-2100 cumulative storage of fossil energy CCS (FECCS) and bioenergy CCS (BECCS) in $GtCO_2$ in various technology availability scenarios.

2.3–6.4% of the size of current crop lands over the 20-year period.[19] At the regional level, the IAMs are generally more optimistic about wind power expansion in ROW (Africa, Middle East, Latin America, and Eastern Europe), than in other global regions. Without CCS, ROW exhibits particularly fast wind upscaling, requiring about 8 times upscaling of the current wind capacity in the 2030–2050 period. The region's annual percentage expansion rate is up to about 30%, which is high but not unprecedented—this rate of wind power deployment was seen globally in the late 1990s, albeit with a smaller base [43]. This suggests that, for ROW, CCS may be the major post-2030 mitigation strategy in the myopic policy action case, so that losing this important option requires disproportionately faster expansion in other low carbon sources such as nuclear and wind in particular (Fig. S5).

### 5.4. Commercial biomass

Achieving the 450 ppm $CO_2$e target in 2100 without limited bioenergy production may cause the demand for commercial biomass to increase rapidly by 2050 relative to its current level (Fig. 6), which would necessitate substantial increases in lands for bioenergy crops. Without CCS (NoCCS-OPT), in particular, bioenergy crop lands reach about half the size of current crop lands by 2050 (5130 thousand $km^2$ compared to 10,430 thousand $km^2$) in the case of GCAM. This considerable land expansion in the no CCS case is due to the call to do more near-term emission reductions that are made possible by faster upscaling of biomass production (Fig. S4). In the other technology exclusion scenarios and the full technology availability scenario, however, upscaling in commercial biomass production by 2050 will be in many cases less than seven times of the current production. This would require much less land for bioenergy crops (2670 thousand $km^2$ in GCAM) compared to the case without CCS, resulting in less damages to ecosystem.

The myopic near-term policy may require even faster expansion in bioenergy production right after the policy regime is strengthened, possibly doubling the rate of post-2030 expansion if CCS is not available (Fig. 6). In GCAM without CCS, the size of bioenergy crop lands increases five times between 2030 and 2050 after the myopic actions (NoCCS-HST), compared to the 2.5 times increase over the same period in the optimal policy counterpart (NoCCS-OPT). Note that a direct comparison across technology availability scenarios may suffer from the varying number of feasible IAMs. For example, both in the full technology availability case (FullTech-HST) and in the limited renewable energy case (LimSW-HST), MERGE-ETL exhibits the lowest biomass production of all IAMs by 2050, although it does not report any other HST scenarios. Nevertheless, the rapid post-2030 upscaling in biomass production and its land use requirements would have the effect of raising the rental rate on land and thus crop prices due to increased land use competition, damaging the global poor and posing substantial social challenges.

[19] The total global land area of 47.6 thousand $km^2$ has been assumed for year-2011 wind power based on wind power spacing of 0.25 $km^2$ per a 1MWe plant, which is the low end of the range that is often assumed in the literature [50].

### 5.5. $CO_2$ capture and storage (CCS)

Achieving the 450 ppm $CO_2$e stabilization requires not only the rapid expansion of low-carbon technologies but also a substantial growth of geological carbon sequestration through CCS (Fig. 7). The magnitude of the scale-up challenges for CCS grows with time. The required upscaling between 2008 and 2030 is indeed remarkable as CCS must increase by about 3 orders of magnitude from the current experimental CCS facilities that store a total of 5Mt$CO_2$ per year. Yet, post-2030 upscaling in CCS is also extraordinary in terms of the growth in scale—models project $CO_2$ storage rates of about half to double of current global $CO_2$ emissions from fossil fuel and industry by 2100.

The results indicate that achieving the 450 ppm $CO_2$e stabilization through CCS requires a large share of BECCS as large as the demand for conventional fossil energy based CCS (FECCS) (except for the limited bioenergy case) (Figs. 8 and 9). This is because all IAMs treat BECCS, if available, as a major mitigation option to achieve such an aggressive stabilization target, offering flexibility in emission trajectories and helping reduce policy costs. The IAMs also agree that, among the global regions, ROW relies on BECCS the most, suggesting that limiting BECCS might lead to a costly transformation particularly for ROW. This is consistent with the region's high sensitivity of wind and solar upscaling to the availability of BECCS (Fig. S5).

Interestingly, the myopic near-term actions shift the allocation between the total demands for FECCS and BECCS both globally and regionally, resulting in less FECCS and more BECCS (Figs. 8 and 9). On the one hand, we have lower demand for FECCS due to the delayed introduction of FECCS, which later competes with renewable energy (including BECCS) that becomes less expensive. On the other hand, they tend to have higher demand for BECCS—greater negative emissions—as the post-2030 catch-up is not sufficient enough to get the emissions back on track.

Nevertheless, carbon storage resource itself is not likely to limit the transformation even in the case where nuclear or renewables are limited. Total global demand for CCS (FECCS and BECCS combined) is far below the total CCS "Effective Storage Capacity" estimate of 13,500 Gt$CO_2$ and even below the "Practical Storage Capacity" estimate of 3900 Gt$CO_2$ (with the land-based capacity of about 3100 Gt$CO_2$) [43]. Yet, it does not necessarily imply that attendant CCS infrastructure will be easy to establish. Social acceptance may also be another important barrier to overcome as in the case of nuclear power.

## 6. Conclusions and discussion

The AMPERE Work Package 2 model inter-comparison study, which engaged nine participating integrated assessment modeling teams, explored the implications of less-than-optimal near-term emission mitigation for mid- and long-term transition pathways, which limit climate forcing to 450 ppm $CO_2$e in 2100, and interactions with technology availability.

### 6.1. Findings

This study reaffirms two important findings. We found no "Silver-Bullet" technology whose deployment accounted for all emission mitigation and, thus, eliminated the need for other emission mitigation technologies. We also found that multiple technology transition pathway portfolios could be used to achieve the long term goal of low climate forcing.

The long-term goal, 450 ppm $CO_2$e, was implemented as a cumulative net emission limit of 1500 $GtCO_2$ between 2000 and 2100. However, no limit was set on either annual or cumulative emissions prior to the year 2100. That is, "overshoot" scenarios were allowed. Modeling teams reported negative net global $CO_2$ emissions when BECCS was available. When BECCS was available, models used this option to exceed the 1500 $GtCO_2$ budget in the mid-term removing the excess with BECCS in the long term. Excluding either bioenergy or CCS limited the role of negative emissions and strongly shifted emission mitigation toward the near-term. The foregone long-term negative emission option greatly increased the risk of failing to achieve the long-term climate goal, particularly when combined with delayed near-term policy actions.

The study highlighted the critical importance of the period between 2030 and 2050, in which the largest percentage shift from emitting to non-emitting technology occurs. Less-than-optimal emission mitigation in the period 2010 to 2030 simply increases the challenge in the next 20 years, requiring even more rapid shifts toward non-emitting energy technologies. We found that on average 70% of the 1500 $GtCO_2$ 21st century emission budget was used by the year 2030 and that the remainder of the budget was allocated in the remaining 70 years. The absence of a "Silver-Bullet" technology in achieving the long-term climate goal points to the fact that a broad range of responses will collectively make a major difference, suggesting that global energy R&D programs need to take a portfolio approach with an emphasis on overall performance of emission mitigation.

Against a background of less-than-optimal near-term emission mitigation policies, technology deployment in the 2030 to 2050 time frame was greatly accelerated with nearly all of the catch-up deployment made during this period. We calculate physical deployment measures during this period and show that, in some instances, when the use of CCS is banned, deployment rates become extremely high if the long-term goal is to be achieved. With the use of CCS banned, 2140 1.5GWe nuclear power plants would need to be built in the 20 years between 2030 and 2050. Expansion rates for other technologies are similarly pronounced. Global land devoted to bioenergy production, for example, could be as much as half the size of current crop lands by 2050 when CCS was banned.

Renewable energy upscaling rates are also rapid. The median 2030–2050 upscaling of solar power could be 50 to 360 times the year-2011 capacity level (5–14 times for wind power). Although this result is sensitive to near-term policy commitments, the highest rate of upscaling always occurs in the case without CCS. Land requirements for the 2030–2050 solar power upscaling could amount to 0.6–4.5% of the size of current crop lands (2.3–6.4% for wind power), which is not trivial.

Expansion rates for CCS deployment, once made available, were similarly dramatic. Models reported $CO_2$ capture and storage rates of more than tens of billion tons of $CO_2$ per year by the century-end from its current level of a few million tons of $CO_2$ per year. Nevertheless, total demand for CCS would remain well below the "Practical Storage Capacity" estimate of potential geological $CO_2$ repositories and would greatly alleviate the challenges to mid- and long-term transitions to limit climate forcing.

Like any other model comparison studies, the findings from this research may be subject to limitations associated with structural diversity among the participating IAMs. Most importantly, they exhibit different reliance on various mitigation responses—the upscaling of low-carbon technologies, the premature retirement of emitting sources, and the associated reduction in energy demand—which led to some models suggesting relatively easy technology-based solutions but others suggesting failure to achieve the long-term climate goal after the delayed policy actions. While not investigated in this study, our results would be sensitive to the degree to which installed coal capacity can be prematurely retired between 2030 and 2050 which varies among the IAMs (see [39] in this issue). Further research is needed to systematically explore the interaction between various mitigation responses.

### 6.2. Future directions

While the AMPERE model comparison project has added substantially to our understanding of the interactions between technology and policy in limiting climate change, much remains to be learned. Three potentially important extensions of this work are:

- *Consideration of a broader range of mitigation policies*—in this study we assume that all of the world's nations act in unison using a common policy instrument, the common carbon tax. The degree of coordination assumed here is highly unlikely. Exploring combinations of delay in global and regional participation is needed.
- *Consideration of policy instruments in addition to the carbon tax*—for example, the European Union policy architecture uses multiple instruments in combination. The research questions include what such policies might imply for the cost and effectiveness of achieving low stabilization (see for example [36]).
- *Consideration of demand-side technologies*—in this study we focused on the implications for the deployment of various supply-side technologies. The required expansion in low-carbon end-use technology alternatives, such as electric and hybrid cars, electric heat pumps, and hydrogen-based technologies, might be equally challenging, and the rate would be affected by the availability of major de-carbonization options to the power and hydrogen system, most importantly, CCS.

## Acknowledgment

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 265139 (AMPERE). Eom and Edmonds also wish to express appreciation to the Integrated Assessment Research Program in the Office of Science of the U.S. Department of Energy (DOE SC-IARP) for partially funding this research. Pacific Northwest National

Laboratory is operated by Battelle for the U.S. Department of Energy under contract DE-AC05-76RL01830. Eom's research is also supported by the Sogang University Research Grant of 201310010. The views and opinions expressed in this paper are those of the authors alone.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.techfore.2013.09.017.

## References

[1] L. Clarke, J. Edmonds, H. Jacoby, H. Pitcher, J. Reilly, R. Richels, Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations, U.S. Climate Change Science Program, 2007.
[2] R.G. Richels, G.J. Blanford, The value of technological advance in decarbonizing the U.S. economy, Energy Econ. 30 (2008) 2930–2946.
[3] V. Krey, K. Riahi, Implications of delayed participation and technology failure for the feasibility, costs, and likelihood of staying below temperature targets—greenhouse gas mitigation scenarios for the 21st century, Energy Econ. 31 (2009) S94–S106.
[4] P. Kyle, L. Clarke, G. Pugh, M. Wise, K. Calvin, J. Edmonds, et al., The value of advanced technology in meeting 2050 greenhouse gas emissions targets in the United States, Energy Econ. 31 (2012) S254–S267.
[5] V. Bosetti, C. Carraro, M. Tavoni, Climate policy after 2012, CESifo Econ. Stud. 55 (2009) 235–254.
[6] O. Edenhofer, B. Knopf, T. Barker, L. Baumstark, E. Bellevrat, B. Chateau, et al., The economics of low stabilization: model comparison of mitigation strategies and costs, ADAM Project Energy J. 31 (2010) 11–48.
[7] G. Luderer, V. Bosetti, M. Jakob, M. Leimbach, J.C. Steckel, H. Waisman, et al., The economics of decarbonizing the energy system—results and insights from the RECIPE model intercomparison, RECIPE Project Clim. Chang. 114 (2011) 9–37.
[8] V. Krey, G. Luderer, L. Clarke, E. Kriegler, Getting from here to there – energy technology transformation pathways in the EMF-27 scenarios, Clim. Chang. (2013), http://dx.doi.org/10.1007/s10584-013-0947-5(in press).
[9] M. Tavoni, E. Cian, G. Luderer, J.C. Steckel, H. Waisman, The value of technology and of its evolution towards a low carbon economy, RECIPE Project Clim. Chang. 114 (2011) 39–57.
[10] UNEP, The Emissions Gap Report, 2010.
[11] J. Edmonds, L. Clarke, J. Lurz, M. Wise, Stabilizing $CO_2$ concentrations with incomplete international cooperation, Clim. Pol. 8 (2008) 355–376.
[12] I. Keppo, S. Rao, International climate regimes: effects of delayed participation, MESSAGE Technol. Forecast. Soc. Chang. 74 (2007) 962–979.
[13] L. Clarke, J. Edmonds, V. Krey, R. Richels, S. Rose, M. Tavoni, International climate policy architectures: overview of the EMF 22 international scenarios, EMF22 Project Energy Econ. 31 (2009) S64–S81.
[14] V. Bosetti, C. Carraro, A. Sgobbi, M. Tavoni, Delayed action and uncertain stabilisation targets. How much will the delay cost? Clim. Chang. 96 (2009) 299–312.
[15] J. van Vliet, M.G.J. den Elzen, D.P. van Vuuren, Meeting radiative forcing targets under delayed participation, IMAGE Energy Econ. 31 (2009) S152–S162.
[16] M. Jakob, G. Luderer, J. Steckel, M. Tavoni, S. Monjon, Time to act now? Assessing the costs of delaying climate measures and benefits of early action, RECIPE Project Clim. Chang. 114 (2011) 79–99.
[17] K. Riahi, E. Kriegler, N. Johnson, C. Bertram, M. den Elzen, J. Eom, et al., Locked into Copenhagen Pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals, Technol. Forecast. Soc. Chang. 90 (2015) 8–23(this issue).
[18] K. Akimoto, T. Tomoda, Assessment of global warming mitigation options with integrated assessment model DNE21, Energy Econ. 26 (2004) 635–653.
[19] J. Edmonds, J. Reilly, Global Energy: Assessing the Future, Oxford University Press, Oxford, New York, 1985.
[20] L. Clarke, J. Edmonds, H. Jacoby, H. Pitcher, J. Reilly, R. Richels, CCSP synthesis and assessment product 2.1, Part A: Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations2006.
[21] J. Eom, R. Moss, K. Calvin, B. Bond-Lamberty, L. Clarke, J. Dooley, et al., Scenarios of future socio-economics, energy, land use and radiative forcing, Engineering Response to Global Climate Change, Lewis, 2013.
[22] S. Kim, J. Edmonds, J. Lurz, S. Smith, M. Wise, The ObjECTS framework for integrated assessment: hybrid modeling of transportation, Energy J. 27 (2006) 63–91.
[23] H. Waisman, C. Guivarch, F. Grazi, J.C. Hourcade, The IMACLIM-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight, Clim. Chang. 114 (2012) 101–120.
[24] O. Sassi, R. Crassous, H. Waisman, C. Guivarch, D. Belle, M. Cedex, IMACLIM-R : a modelling framework to simulate sustainable development pathways, Int. J. Glob. Environ. Issues. 10 (2010) 5–24.
[25] A.F. Bouwman, T. Kram, K.K. Goldewijk, Integrated modelling of global environmental change: An Overview of IMAGE 2.4, n.d.
[26] S. Kypreos, Modeling experience curves in MERGE (model for evaluating regional and global effects), Energy 30 (2005) 2721–2737.
[27] S. Kypreos, O. Bahn, A MERGE model with endogenous technological progress, Environ. Model. Assess. 8 (2003) 249–259.
[28] S. Messner, M. Strubegger, User's Guide for MESSAGE III, 2001.
[29] European Commission, POLES 2.2, European Commission, 1996.
[30] M. Leimbach, N. Bauer, L. Baumstark, Technological change and international trade—insights from REMIND-R, Energy J. 31 (2010) 109–136.
[31] M. Leimbach, N. Bauer, L. Baumstark, O. Edenhofer, Mitigation costs in a globalized world: climate policy analysis with REMIND-R, Environ. Model. Assess. 15 (2009) 155–173.
[32] E. De Cian, V. Bosetti, M. Tavoni, Technology innovation and diffusion in "less than ideal" climate policies: an assessment with the WITCH model, Clim. Chang. 114 (2011) 121–143.
[33] V. Bosetti, E. Massetti, M. Tavoni, The WITCH Model: Structure, Baseline, Solutions, 2007.
[34] E. Kriegler, N. Petermann, J. Schwanitz, Diagnosing integrated assessment model behavior, Technol. Forecast. Soc. Chang. (2013) 1–25.
[35] M. Wise, K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, et al., Implications of limiting $CO_2$ concentrations for land use and energy, Science 324 (2009) 1183–1186.
[36] E. Kriegler, K. Riahi, N. Bauer, J. Schwanitz, V. Bosetti, A. Marcucci, et al., The difficult road to global cooperation on climate change: the AMPERE study on staged accession scenarios for climate policy, Technol. Forecast. Soc. Chang. (2013).
[37] E. Kriegler, M. Tavoni, T. Aboumahboub, G. Luderer, K. Calvin, G. DeMaere, et al., Can we still meet 2 °C with global climate action? The LIMITS study on implications of Durban Action Platform scenarios, LIMITS Project Clim. Change Econ. (2013)(Submitted for publication).
[38] G. Luderer, C. Bertram, K. Calvin, E. De Cian, E. Kriegler, Implications of weak near-term climate policies on long-term climate mitigation pathways, Clim. Chang. (2013), http://dx.doi.org/10.1007/s10584-013-0899-9(in press).
[39] C. Bertram, N. Johnson, G. Luderer, K. Riahi, M. Isaac, J. Eom, Carbon lock-in through capital stock inertia associated with weak near-term climate policies, Clim. Chang. 90 (2015) 62–72(this issue).
[40] E. Kriegler, N. Petermann, V. Krey, V. Schwanitz, G. Luderer, S. Ashina, et al., Diagnostic indicators for integrated assessment models of climate policies, Technol. Forecast. Soc. Chang. 90 (2015) 45–61(this issue).
[41] N. Johnson, V. Krey, D. Mccollum, S. Rao, K. Riahi, Stranded on a low-carbon planet: implications of climate policy for the phase-out of coal-based power plants, Technol. Forecast. Soc. Chang. (2013).
[42] C. Wilson, a. Grubler, N. Bauer, V. Krey, K. Riahi, Future capacity growth of energy technologies: are scenarios consistent with historical evidence? Clim. Chang. 118 (2013) 381–395.
[43] J. Dooley, Estimating the supply and demand for deep geologic $CO_2$ storage capacity over the course of the 21st century: a meta-analysis of the literature, Energy Procedia 37 (2013) 5141–5150.
[44] M. Meinshausen, S.J. Smith, K. Calvin, J.S. Daniel, M.L.T. Kainuma, J. Lamarque, The RCP greenhouse gas concentrations and their extensions from 1765 to 2300, Clim. Chang. 109 (2011) 213–241.
[45] UNFCCC, Decisions adopted by the conference of the parties, Report of the Conference of the Parties on its Seventeenth Session, Held in Durban from 28 November to 11 December 2011, 2011.
[46] H.J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley, G. Yohe, Avoiding Dangerous Climate Change, Cambridge University Press, 2006.
[47] M. den Elzen, M. Roelfsema, A. Hof, H. Bottcher, G. Grassi, Analysing the Emissions GAP Between Pledged Emissions Reductions Under the Cancun Agreements and the 2C Climate Target, 2012.
[48] B. Hare, M. Schaeffer, M. Rocha, J. Rogelj, N. Hohne, K. Blok, et al., Closing the 2020 emissions gap, Issues, Options and Strategies 2012.
[49] IPCC: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, Prepared by Working Group III of the Intergovernmental Panel on Climate Change, in: O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (Eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2011, 1075 pp.

**Jiyong Eom** is an assistant professor in the Graduate School of technology Management at Sogang University in Korea. He was a staff scientist at the Pacific Northwest National Laboratory's Joint Global Change Research Institute when the first draft of this paper was submitted. His principal research focuses on integrated assessment of global environmental problems and energy and environmental policy analysis.

**Jae Edmonds** is a chief scientist and Battelle Fellow at the Pacific Northwest National Laboratory's Joint Global Change Research Institute. His principal research focus is the role of energy technology in addressing climate change.

**Volker Krey** is the deputy program leader of the Energy Program at the International Institute for Applied Systems Analysis (IIASA), Austria. His scientific interests focus on the integrated assessment of climate change and the energy challenges.

**Nils Johnson** is a research scholar at the International Institute for Applied Systems Analysis (IIASA) in Austria.

**Thomas Longden** is a researcher at Fondazione Eni Enrico Mattei (FEEM) and the Euro-Mediterranean Centre for Climate Change (CMCC) in Italy.

**Gunnar Luderer** is a senior researcher at the Potsdam Institute for Climate Impact Research (PIK, Germany). He is head of the Global Energy Systems group at PIK.

**Keywan Riahi** is leading the Energy Program at the International Institute for Applied Systems Analysis (IIASA, Austria). In addition he holds a part-time position as Visiting Professor at the Graz University of Technology, Austria.

**Detlef P. van Vuuren** is a senior researcher at PBL Netherlands Environmental Assessment Agency—working on integrated assessment of global environmental problems. He is also a professor at the Copernicus Institute for Sustainable Development at Utrecht University.