Climatic Change (2014) 123:559–569
DOI 10.1007/s10584-013-0961-7

# The impact of technology availability on the timing and costs of emission reductions for achieving long-term climate targets

**Jasper van Vliet · Andries F. Hof · Angelica Mendoza Beltran · Maarten van den Berg · Sebastiaan Deetman · Michel G. J. den Elzen · Paul L. Lucas · Detlef P. van Vuuren**

Received: 30 October 2012 / Accepted: 25 September 2013 / Published online: 18 October 2013

**Abstract** While most long-term mitigation scenario studies build on a broad portfolio of mitigation technologies, there is quite some uncertainty about the availability and reduction potential of these technologies. This study explores the impacts of technology limitations on greenhouse gas emission reductions using the integrated model IMAGE. It shows that the required short-term emission reductions to achieve long-term radiative forcing targets strongly depend on assumptions on the availability and potential of mitigation technologies. Limited availability of mitigation technologies which are relatively important in the long run implies that lower short-term emission levels are required. For instance, limited bio-energy availability reduces the optimal 2020 emission level by more than 4 $GtCO_2eq$ in order to compensate the reduced availability of negative emissions from bioenergy and carbon capture and storage (BECCS) in the long run. On the other hand, reduced mitigation potential of options that are used in 2020 can also lead to a higher optimal level for 2020 emissions. The results also show the critical role of BECCS for achieving low radiative forcing targets in IMAGE. Without these technologies achieving these targets become much more expensive or even infeasible.

## 1 Introduction

In the context of the UN Framework Convention on Climate Change (UNFCCC) most countries have agreed that international climate policy should aim to limit global mean

---

This article is part of the Special Issue on "The EMF27 Study on Global Technology and Climate Policy Strategies" edited by John Weyant, Elmar Kriegler, Geoffrey Blanford, Volker Krey, Jae Edmonds, Keywan Riahi, Richard Richels, and Massimo Tavoni.

**Electronic supplementary material** The online version of this article (doi:10.1007/s10584-013-0961-7) contains supplementary material, which is available to authorized users.

J. van Vliet · A. F. Hof (✉) · A. Mendoza Beltran · M. van den Berg · S. Deetman · M. G. J. den Elzen · P. L. Lucas · D. P. van Vuuren
PBL Netherlands Environmental Assessment Agency, Bilthoven, The Netherlands
e-mail: andries.hof@pbl.nl

D. P. van Vuuren
Department of Geosciences, Utrecht University, Utrecht, The Netherlands

temperature increase to less than 2 °C above pre-industrial levels (UNFCCC 2011). While translating this into near-term policies, policy-makers are confronted with many uncertainties, all kinds of other, related, priorities, and the difficulties in finding a compromise between relevant parties given their different interests. An important difficulty in defining near-term climate policy is that it is directly related to the feasibility of long-term objectives and therefore also long-term uncertainties. This includes, for instance, climate system uncertainties (IPCC 2007), but also uncertainties related to costs, availability, and acceptability of emission reduction technologies in the near and long-term (GEA 2012) and to the rate at which societies are able to introduce policies and adopt them (van Vuuren and Riahi 2011). Policy-makers need to put climate policy in the context of other key policy issues related to energy and land use. These, for instance, include energy security, provision of low-cost energy, and biodiversity protection. These interactions can be illustrated by several recent examples, such as the German government's decision to phase out nuclear power from its power mix in response to the Fukushima reactors incidents in Japan. Similarly, societal acceptance plays a key role in the deployment of carbon capture and storage (CCS) technologies. Decisions on mitigation strategies are thus complex, as policy-makers need to balance short-term targets and costs with long-term climate risks and expectations on technology development and acceptance.

Model-based energy studies can help policy-makers by providing insight into the consequences of technology uncertainty on mitigation costs and reduction potentials (Azar et al. 2010; Clarke et al. 2009; Knopf et al. 2010; Rogelj et al. 2013). The Energy Modeling Forum 27 (EMF27) study provides an important way forward by evaluating the impact of a range of technology portfolios across a large range of models and different climate targets, addressing the research question 'What are the implications of technology availability for reaching long-term environmental goals?' (Kriegler et al. 2013). This study, as part of the EMF27 study, uses the IMAGE modeling framework to focus on the impact of limited energy technology portfolios on the timing and costs of emission reductions. This is especially relevant for decisions on short-term emission targets. The question which short-term emission reductions are required to achieve long-term climate goals were addressed earlier using information on so-called cost-optimal scenarios (e.g. Rogelj et al. 2011; UNEP 2012) which assume full flexibility with respect to timing, sectoral emission reductions and technology choice. Recently more information on non-cost optimal scenarios become available. Some studies have looked at the effect of lower short-term reductions by meeting the reduction proposals of the Copenhagen Accord (van Vliet et al. 2012) and/or limiting specific technologies on the timing of emission reductions (Krey and Riahi 2009; Kriegler et al. in review; Pugh et al. 2011; Riahi et al. 2013; Rogelj et al. 2013; van Vliet et al. 2009). This study focus on limiting technologies, and goes further than existing studies by consistently analyzing an array of technology options and concentration stabilization levels (450, 550 ppm $CO_2$-eq), using the IMAGE model. Within this context, key research questions in this paper are:

- How do limitations on the availability of mitigation technologies affect the timing of emission reductions and the resulting emission levels given a long-term concentration target?
- What are the additional costs of limitations to the use of specific technologies?

This paper first gives a brief overview of the study design and modeling framework. Section 3 discusses the impact of technology limitations on the timing of emission reductions, costs, and associated energy systems. The paper finalizes with discussing the results and conclusions.

## 2 Methods

### 2.1 Study design

The scenarios evaluated in this paper follow the design of the EMF27 study (Kriegler et al. 2013). The core design comprises a matrix with two axes (Table 1). One axis contains three levels of climate ambition: baseline (no climate policy), 3.7 $W/m^2$ not to exceed by 2100 (550 ppm $CO_2$-eq representative) and 2.8 $W/m^2$ by 2100 with overshoot allowed (450 ppm $CO_2$-eq representative). The baseline applied in this analysis is a slightly updated version of the IMAGE scenario used in the OECD Environmental Outlook 2012 (OECD 2012). It represents a business-as-usual scenario based on medium population and income projections. The scenario aims to describe the energy and land-use development during the 21st century without the introduction of new policies to mitigate climate change (van Vuuren et al. 2012). The second axis contains the technology dimension of the study. In the default *Alltech* scenario the full portfolio of technology options is available (see Van Vuuren et al. 2007). This default scenario is compared to technology-limiting scenarios, i.e. a scenario without CCS (*NoCCS*), without nuclear (*NucOff*), with limited availability of bioenergy (*LimBio*), with limited availability of solar and wind (*LimSW*), and, finally, to a scenario with rapid introduction of energy efficiency (*LowEI*). In each of the scenarios in which limitations are put on certain technologies, other technologies can be used more intensively in order to achieve the targets. As shown in Table 1, the *450 ppm NoCCS* and *LimBio* scenarios were not directly feasible in our model framework, given the lack of sufficient alternative mitigation potential. In the latter case, however, the results were so close to a feasible result that they are presented here.

### 2.2 Model framework

For the analysis of the mitigation scenarios we use the Integrated Assessment modeling framework IMAGE[1] 2.4 (Bouwman et al. 2006). The IMAGE framework consists of a set of linked and integrated models that together describe important elements of long-term dynamics of global environmental change, such as air pollution, climate change, and land-use change. The land modules of IMAGE describe the dynamics of agriculture and natural vegetation, including potentials for biofuels under climate change, and the land-use related emissions of greenhouse gases (GHGs). The global energy model included in the IMAGE framework (TIMER) describes the primary and secondary demand and production of energy and the related emissions of GHGs and regional air pollutants (van Vuuren 2007). The model is a simulation model, and different technologies compete for a share in investment based on their relative costs. In total, 10 different primary energy carriers are covered in the model (each of them can be used in various conversion technologies). Energy demand is described by a technology-rich representation for the residential sector and cement and steel production, but by a more aggregated description using more simple activity and price elasticities for all other sectors. The technologies in TIMER are subject to technology development and depletion dynamics determining the long-term costs. For technology

---

[1] The model names are acronyms. IMAGE = Integrated Model to Assess the Global Environment; TIMER = The IMage Energy Regional model; FAIR-SiMCaP = Framework to Assess International Regimes for the differentiation of commitments - Simple Model for Climate Policy Assessment.

**Table 1** Scenario and feasibility overview of the scenarios included in the paper

| Name | Technology assumptions | Feasibility | |
|---|---|---|---|
| | | 450 ppm | 550 ppm |
| Alltech | The model's default assumptions on technology. | Yes | Yes |
| LowEI | Assumptions on end-use technologies leading to a decrease of energy intensity by 25 % in 2050 and 40 % in 2100. | Yes | Yes |
| NoCCS | No Carbon Capture and Sequestration allowed in any sector and region. | No | Yes |
| NucOff | No new nuclear deployment after 2010, phase out of existing stock. | Yes | Yes |
| LimSW | Conservative techno-economic assumptions and penetration of intermittent technologies restricted to 20 %. In the EMF study restrictions are upon Wind&Solar, which in IMAGE means onshore Wind&PV. | Yes | Yes |
| LimBio | Potential for bioenergy limited to 100 Exajoule per year. | Yes[a] | Yes |

[a] Although the LimBio scenario does not completely achieve the 2.8 W/m$^2$ target under the normal restrictions in the model framework, allowing a rapid increase in the near-term carbon price leads to a very similar level of 2.81 W/m$^2$. Therefore, we have decided to include this scenario in this paper

development, either learning curves or exogenous assumptions are used. The SI provides more detail about the model framework.

Within the framework, the FAIR-SiMCaP model is used to design the emission scenarios (den Elzen et al. 2007). This model combines a greenhouse gas abatement cost model with the MAGICC 6 climate model (Meinshausen et al. 2011) to calculate long-term emission pathways. These pathways are determined by minimizing cumulative discounted abatement costs under specific criteria, such as achieving a long-term climate target. The model uses a non-linear optimization algorithm to find an optimal timing and mix of reduction measures across the Kyoto GHGs, using 100 year GWP values as equivalence metric as given in Forster et al. (2007) and a 5 % discount rate (see Van Vliet et al. 2012 for the sensitivity of discount rates on the timing of emission reductions).

Abatement costs in FAIR-SiMCaP are based on the information from the land-use and energy models of IMAGE. For $CO_2$, the energy model is used to construct regional time-dependent price-response curves. Subsequently, the FAIR-SiMCaP model scales the curves that represent early action and delayed response pathways on the basis of the reduction effort in the previous years in order to represent the underlying behavior of the energy model (technology learning and inertia related to capital-turnover rates). The methodology for developing abatement cost curves for non-$CO_2$ GHG emissions are described in Lucas et al. (2007) which take into account the land-use related activity levels, with modifications restricting the speed of implementation of reduction measures as described in van Vliet et al. (2012). Abatement costs in FAIR-SiMCaP equal the area under the aggregated abatement curve across different gases, sources, and regions. For the halogenated gasses (HFCs, PFCs, SF6) marginal abatement cost curves are determined following the methodology described by Harnisch et al. (2009). Halogenated emissions were adapted to better represent the projections as presented by Velders et al. (2009). We only consider carbon prices up to USD[2] 409/t$CO_2$-eq (equal to USD 1500/tC-eq), as the underlying models provide little additional emission reductions above this value.

---

[2] All prices and costs are expressed in 2005 US Dollars.

## 3 Results

In describing the results, we focus on timing of reductions and on mitigation costs. In order to understand the results, we also take a closer look at the deployment of technologies in the different scenarios.

### 3.1 The impact of limited technology on the timing of emission reductions

Table 2 shows $CO_2$-eq emission levels in 2020, 2050, and 2100 under each scenario, for both IMAGE and the range of other models in the EMF-27 study. Considerably more reductions are needed for the 450 than for the 550 ppm $CO_2$-eq target. The *lowEI* scenario has slightly higher 2020 and 2050 emission levels under a 450 ppm target compared to the *Alltech* scenario, as these can be compensated by higher longer-term reductions: the higher flexibility in this scenario as a result of lower baseline emissions leads to a preference for delay due to discounting. For the same reasons, but with an opposite result, the scenario without nuclear leads to slightly lower 2020 and higher long-term emission levels. Restricting the use of renewables, as under the *LimSW* scenario, leads to slightly higher short-term emission levels. Here, the main reason is that the lower deployment of renewables is compensated by higher nuclear deployment in the long run (see Section 3.3). Limiting the use of biofuels has by far the largest effect on timing. In the *LimBio* scenario, there is less potential for bioenergy with carbon capture and sequestration (BECCS), which reduces the potential for negative emissions in the long term (see Van Vuuren et al. 2013). As a result, the model compensates the lack of long-term mitigation potential by higher short-term emission reductions.

**Table 2** $GtCO_2$-eq emissions (including $CO_2$ from land use) over time for all climate scenarios. Ranges for other models are based on the four models (GCAM, MESSAGE, REMIND, WITCH) that report both $CO_2$-equivalent emissions and timing of reductions

| | | 2020 | | 2050 | | 2100 | |
|---|---|---|---|---|---|---|---|
| | | Image | Other models | Image | Other models | Image | Other models |
| 450 | Alltech (default) | 47.6 | [30–50] | 23.5 | [22–27] | −1.0 | [−9–0] |
| | lowEI | 48.3 | [47–48] | 24.9 | [24–33] | −1.8 | [−6–−2] |
| | noCCS | – | [22–35] | – | [14–23] | – | [2–12] |
| | NucOff | 47.1 | [47–49] | 23.3 | [22–25] | 2.5 | [−2–0] |
| | LimSW | 48.5 | [45–48] | 23.8 | [18–24] | −1.4 | [0–3] |
| | LimBio | 43.7 | [24–43] | 23.3 | [17–21] | 11.2 | [4–8] |
| | range | [44–49] | [22–50] | [23–25] | [14–27] | [−1–11] | [−9–12] |
| 550 | Alltech (default) | 52.1 | [31–52] | 37.8 | [26–29] | 13.5 | [15–19] |
| | lowEI | 49.6 | [32–52] | 35.0 | [27–30] | 14.9 | [15–20] |
| | noCCS | 48.4 | [28–49] | 32.7 | [27–31] | 17.0 | [12–20] |
| | NucOff | 52.2 | [30–51] | 35.3 | [27–29] | 17.2 | [15–17] |
| | LimSW | 52.4 | [31–51] | 37.8 | [27–29] | 14.0 | [15–17] |
| | LimBio | 50.2 | [31–50] | 36.4 | [27–29] | 15.5 | [15–19] |
| | range | [48–52] | [28–52] | [33–38] | [26–31] | [14–17] | [15–20] |
| | Baseline | 56.0 | [57–63] | 77.0 | [77–91] | 113.0 | [90–113] |

For achieving the 550 ppm target, there is much more flexibility in the 2020 emission level. Interestingly, the *LowEI* scenario now has an emission level lower than the *Alltech* scenario, as the immediate impact of the reduced baseline emissions dominates over the delay effect. The 550 ppm target gives some insight into the consequences of restricting CCS for timing of emission reductions (this scenario was infeasible for the 450 ppm target). The effect in timing is strong: as CCS is deployed on a large scale in the long run under the default *Alltech* scenario, much lower 2020 emission levels are required in case CCS is not available. The difference is almost 4 $GtCO_2eq$ by 2020. Under the 550 ppm target, limiting bioenergy has a much smaller impact on timing than under the 450 ppm target (given the lower dependence on BECCS).

In general, the IMAGE results for 2020 are at the high end of the range of other models (see Kriegler et al. 2013), indicating the relative importance of short-term inertia in IMAGE compared to other models. Interestingly, the range across the different models is far greater than the range across the different technology scenarios, highlighting the importance of uncertainty caused by model differences. In fact, the large model uncertainty range even obscures the trend in the response to technology limitations for the set of models. Looking at each model individually, however, shows that observations on the impact of different technology assumptions are robust across the models.

## 3.2 The impact of limited technology on the costs of emission reductions

The impact of limited technology availability on mitigation costs are substantial. For instance, the total discounted cumulative costs for achieving the 450 ppm target increase by 18 % if nuclear is excluded and by 70 % under conservative estimates about bioenergy availability, both relative to the *Alltech* scenario (Table 3). The timing of reductions play a key factor here: high carbon prices early in the century in particular lead to higher overall costs (as a result of discounting). For the *NucOff* and *LimSW* scenarios, costs increase particularly in the second half of the century when alternative technology options are increasingly used to compensate for the lower availability of nuclear or renewables. Excluding CCS increases cost by 66 % to achieve the 550 ppm target (for the 450 ppm target, the *NoCCS* scenario is infeasible). For the *lowEI* scenario, a significant costs reduction can be noted given the lower baseline emissions (no costs were assigned to the efficiency improvement in the baseline).

**Table 3** Cumulative discounted mitigation costs for different periods: 2011–2020, 2011–2050, and 2011–2100, in trillion 2005USD, discounted at 5 %

| | | 2020 | 2050 | 2100 |
|---|---|---|---|---|
| 450 | Alltech (default) | 0.21 | 5.7 | 13.5 |
| | lowEI | 0.05 | 2.8 | 7.6 |
| | noCCS | Infeasible | Infeasible | Infeasible |
| | NucOff | 0.28 | 7.3 | 16.0 |
| | LimSW | 0.18 | 5.8 | 13.8 |
| | LimBio | 1.44 | 15.2 | 23.1 |
| 550 | Alltech (default) | 0.07 | 2.2 | 6.3 |
| | lowEI | 0.03 | 1.4 | 3.8 |
| | noCCS | 0.19 | 4.4 | 10.5 |
| | NucOff | 0.07 | 2.8 | 7.7 |
| | LimSW | 0.06 | 2.4 | 6.7 |
| | LimBio | 0.13 | 3.5 | 8.2 |

To assess the interaction between costs, timing of emission reductions, and technology availability, Fig. 1 plots annual undiscounted costs as percentage of GDP against emission level of the different scenarios. This figure clearly shows the lower emission levels and significantly higher costs for the 450 ppm scenarios relative to the 550 ppm scenarios. Again, it is shown that limiting the bioenergy potential has a much larger effect on both costs and emissions under a 450 ppm target than under the 550 ppm target: it shifts the emission pathways to early action and higher costs, similarly as under the *noCCS* scenario. The figure also shows that 2050 is a pivot point between early and late action, especially for the 450 ppm target. Scenarios with lower emission levels in 2020 have higher emission levels at the end of the century (for early action vice versa). In order to achieve the same target, these scenarios show very similar emission levels in 2050.

### 3.3 A closer look at the deployment of technologies

A closer look at the deployment of technologies provides more insight into the role of specific technologies in the different scenarios – and therefore helps to explain the results on timing and costs. Figure 2 presents the contribution of various mitigation measures in the different 450 and 550 ppm technology scenarios. For both climate targets, end-use efficiency improvement represents the most significant contribution to short-term mitigation. In the longer term, the importance of changes in the supply side of energy increases. Again, the figure emphasizes that for a 450 ppm scenario, mitigation measures need to be implemented earlier and usually to a larger extent compared to 550 ppm scenarios (except for wind and PV power where constraints related to intermittency restraints further deployment). Interestingly, in the 550 ppm scenarios, bioenergy is mostly deployed in the transport sector, while other technologies are deployed for electricity generation. In the 450 ppm scenario, the high carbon price induces early use of BECCS. Together with more efficiency, this implies that no further penetration of wind & PV is needed. Next to the deployment over time, the

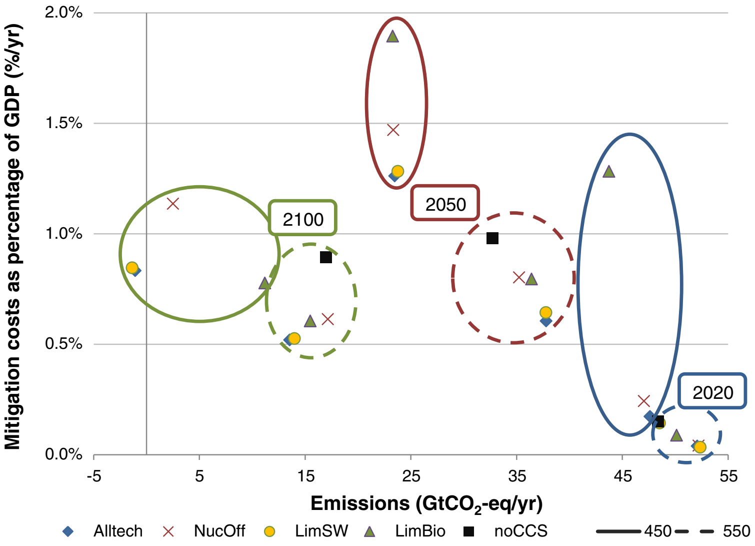

**Fig. 1** Mitigation costs as percentage of GDP against emission levels in 2020, 2050 and 2100, for 450 and 550 scenarios

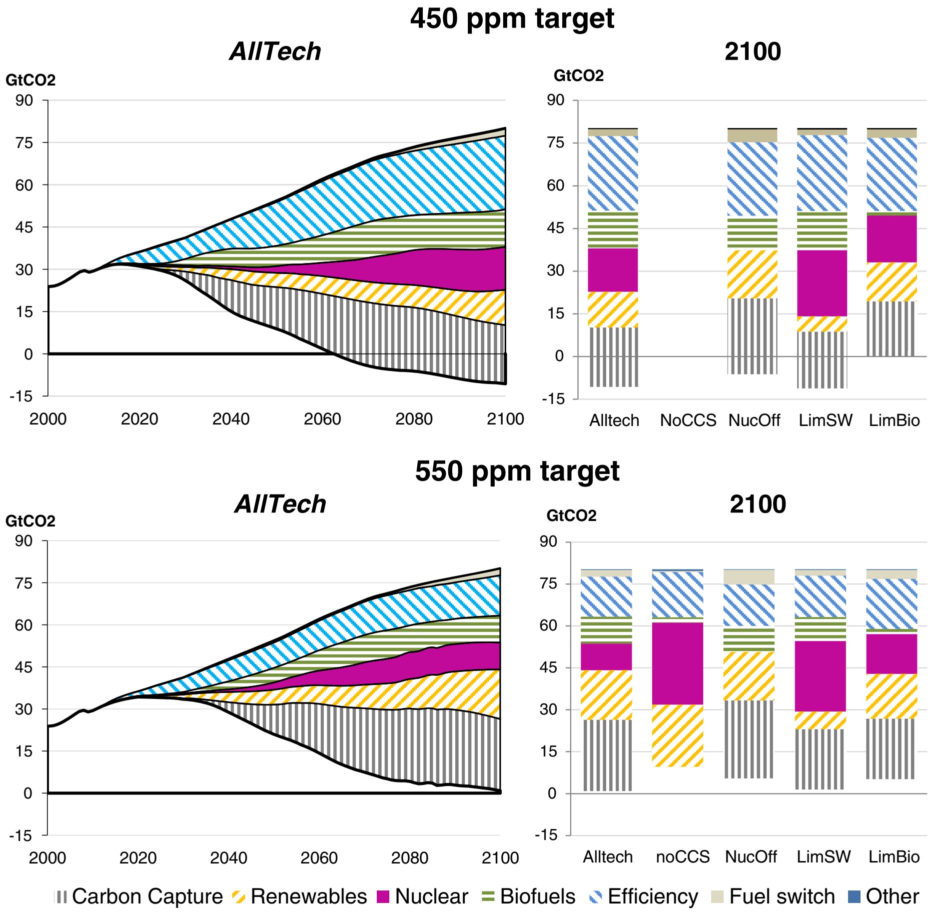

**Fig. 2** Impact of technologies on energy-related CO2 emissions for the 450 and 550 ppm scenario. The shaded areas indicate the emission reductions due to technology mitigation measures. Left hand panels show results over time for the *Alltech* scenario; right-hand panels show results for 2100 for all technology scenarios

right panels show the impact on the mitigation deployment and emission levels in 2100 for each of the technology scenarios.

Figure 3 shows the differences in cumulative contribution to mitigation between 2010 and 2100 by technology. Compensation for excluded technologies takes place mainly by increased use of nuclear, wind and PV power, CCS, fuel switch, or improved energy efficiency measures. The 'compensation' portfolio depends on the excluded technology and its role in the energy system.

In all scenarios, nuclear power plays an important role in compensation for excluding or limiting technologies. In the *NoCCS* and *LimBio* scenarios, improved energy efficiency plays an important part as well in compensation. By far the most compensation is required in the *NoCCS* scenario, which requires increased use of renewables and nuclear power in electricity supply. If nuclear is phased out, this is being compensated by additional use of CCS (and for the 450 ppm target, by a small increase in renewables as well). To summarize, the most important compensation technologies are nuclear, CCS (if nuclear is phased out), and energy efficiency.

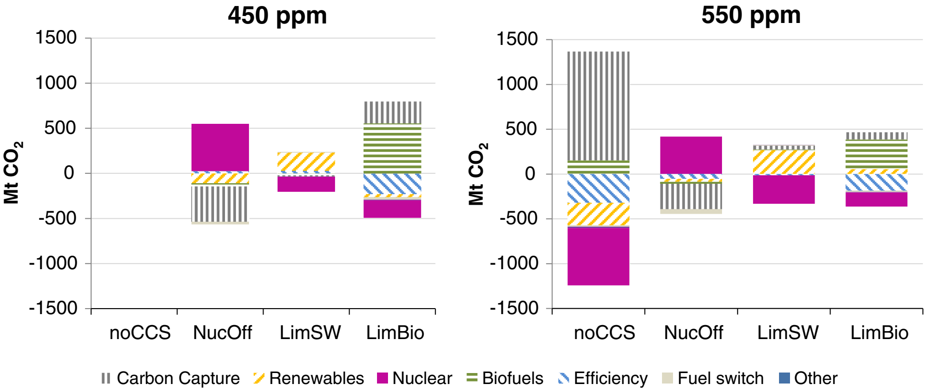

**Fig. 3** Differences in cumulative emissions from 2010 to 2100 by technology; all against the *Alltech* scenario

The relatively small importance of renewables as compensation technology is caused by the rules on the use of intermittent technologies. The rules require the presence of backup capacity. To some degree cost increases play a role as well, such as curtailment of wind and solar power (after 2030) and depletion of favorable sites (especially for wind). It should be noted that there are other mitigation options which are currently not modeled (e.g. concentrated solar power and off-shore wind)—which could clearly influence these conclusions. Moreover, the ability to store power (to overcome restrictions resulting from intermittence and curtailment) could also influence these results.

## 4 Discussion

In our analysis, we report the *NoCCS*, 450 ppm target as being infeasible. Alternatively, one could also reduce the climate ambition until the target becomes feasible. In that case, technology restrictions would be expressed as an increased risk of exceeding the climate target. Such an approach would provide further information on technology restrictions, providing information on the feasibility frontier of each model set-up.

It should be noted that the feasible scenarios presented here may have some different temperature implications despite similar 2100 forcing targets. The relatively early emission reductions of the *LimBio* scenario, for instance, result in a lower probability of exceeding 2 °C than the *Alltech* scenario. In contrast, the relatively high 2100 emission levels in the *LimBio* scenario will lead to a higher chance of exceeding 2 °C after 2100, compared to the other scenarios.

The study shows that if important long-term emission reduction technologies are restricted, optimal mitigation scenarios tend to have lower short-term emissions. Pessimistic long-term expectations about CCS or biomass would therefore imply an increase of the emission gap, defined as the difference between required 2020 emission levels for achieving long-term climate targets and the emission levels resulting from countries' reduction pledges for that year. Also other factors can influence the extent of this gap. For instance, O'Neill et al. (2010), van Vliet et al. (2012), Rogelj et al. (2013), and OECD (2012) analysed the impact of delayed participation or implementation of reduction pledges of the Copenhagen Accord and Cancun Agreements, and show that, albeit at higher costs, scenarios exist that delay emission reductions compared to optimal scenarios.

There are also factors that can influence the timing of emission reductions other than the limited availability of technologies. Although such factors were not studied for this specific scenario design, earlier studies with the IMAGE framework can put the 2020 emission level range as found in this study in perspective. For a 2.9 W/m$^2$ scenario, van Vliet et al. (2012) investigate the impact of a range of discount rates. While the range of emissions in 2050 is small as this year forms a pivotal point between early and late action (as also found in this study), in 2020 emissions can vary by 5 GtCO$_2$-eq. This indicates that the discount rate can play an equally important role in timing as technology limitations. Finally, the way in which targets are defined can also influence the timing of emission reductions. In the current study set up, a target for a single year (2100) was defined. A cumulative emissions target could lead to a different timing of emission reductions.

## 5 Conclusions

*Limitations in long-term technology availability has implications for short-term emission reductions. This is in particular important for the technologies relevant for negative emissions (bioenergy and CCS)* Our study confirms earlier work that limiting technologies relevant for negative emissions implies that higher short-term emission reductions are required to achieve long-term climate targets. For instance, restrictions on bioenergy leads to a reduction in the 2020 cost-optimal emission level for achieving a 450 ppm target of 4 GtCO$_2$-eq compared to the full technology case. However, limiting technologies that usually play an important role in reducing emissions in the near future, such as wind and solar power, can lead to higher short-term emission levels. This means that 2020 emission targets need to be set on the basis of both current and future technology development in terms of costs and potential. Interestingly, restrictions may lead to higher or lower emissions in 2020, depending on the technology and the mitigation target.

*The results show the importance of CCS and bioenergy for meeting long-term climate targets at moderate costs in the IMAGE framework* Limiting bio-energy would increase the costs by 70 % for meeting low concentration targets. Excluding CCS makes these targets even infeasible. Both bio-energy and CCS play a key role in low forcing IMAGE runs, partly due to their importance for BECCS. While limiting bio-energy leads to a significant cost increase, excluding CCS makes low concentration targets even infeasible in IMAGE. The lack of bio-energy is compensated in IMAGE by increasing the use of nuclear and increasing energy efficiency. Excluding nuclear (which is replaced for the largest part by CCS) or limiting wind & PV (which is replaced for the largest part by nuclear) leads to smaller cost increases of 18 % and 2 %, respectively. A more rapid development of energy efficiency in the baseline leads to lower costs in achieving low concentration targets.

## References

Azar C, Lindgren K, Obersteiner M et al (2010) The feasibility of low CO2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). Clim Change 100:195–202

Bouwman AF, Kram T, Klein Goldewijk K (2006) Integrated modelling of global environmental change. An overview of IMAGE 2.4. Netherlands Environmental Assessment Agency, Bilthoven

Clarke L, Edmonds J, Krey V et al (2009) International climate policy architectures: overview of the EMF 22 International Scenarios. Energy Econ 31 (SUPPL 2):S64–S81 den Elzen M, Meinshausen M, van Vuuren D (2007) Multi-gas emission envelopes to meet greenhouse gas concentration targets: costs versus certainty of limiting temperature increase. Glob Environ Change 17:260–280

Forster P, Ramaswamy V, Artaxo P et al (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

GEA (2012) Global energy assessment—toward a sustainable future. Cambridge University Press, Cambridge

Harnisch J, Klaus S, Wartmann S, Rhiemeier JM (2009) Development of F-gas module for TIMER model. ECOFYS, Nuremberg

IPCC (2007) In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Knopf B, Edenhofer O, Flachsland C et al (2010) Managing the low-carbon transition—From model results to policies. Energy J 31:223–245

Krey V, Riahi K (2009) 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:S94–S106

Kriegler E, Tavoni M, Aboumahboub T et al (in review) Can we still meet 2°C with global climate action? The LIMITS study on implications of Durban Action Platform scenarios. Clim Change Econ

Kriegler E, Weyant JP, Blanford GJ et al. (2013) The role of technology for achieving climate policy objectives: overview of the EMF 27 study on technology and climate policy strategies. Clim Change. doi:10.1007/s10584-013-0953-7

Lucas PL, van Vuuren DP, Olivier JGJ, den Elzen MGJ (2007) Long-term reduction potential of non-CO2 greenhouse gases. Environ Sci Policy 10:85–103

Meinshausen M, Raper SCB, Wigley TML (2011) Emulating coupled atmosphere–ocean and carbon cycle models with a simpler model, MAGICC6 - Part 1: model description and calibration. Atmos Chem Phys 11:1417–1456

O'Neill BC, Riahi K, Keppo I (2010) Mitigation implications of midcentury targets that preserve long-term climate policy options. Proc Natl Acad Sci U S A 107:1011–1016

OECD (2012) OECD environmental outlook to 2050. OECD, Paris

Pugh G, Clarke L, Marlay R et al (2011) Energy R&D portfolio analysis based on climate change mitigation. Energy Econ 33:634–643

Riahi K, Kriegler E, Johnson N et al (2013) Locked into Copenhagen Pledges—Implications of short-term emission targets for the cost and feasibility of long-term climate goals. Technological Forecasting and Social Change (in press)

Rogelj J, Hare W, Lowe J et al (2011) Emission pathways consistent with a 2°C global temperature limit. Nature Clim Change 1:413–418

Rogelj J, McCollum DL, O'Neill BC, Riahi K (2013) 2020 emissions levels required to limit warming to below 2°C. Nature Clim Change 3:405–412

UNEP (2012) The emissions gap report 2012. A UNEP Synthesis Report, UNEP

UNFCCC (2011) Report of the Conference of the Parties on its seventeenth session, held in Durban from 28 November to 11 December 2011. Addendum. Part two: Action taken by the Conference of the Parties at its seventeenth session. Decision 2/CP.17: outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention. FCCC/CP/2011/9/Add.1

van Vliet J, den Elzen MGJ, van Vuuren DP (2009) Meeting radiative forcing targets under delayed participation. Energy Econ 31:S152–S162

van Vliet J, van den Berg M, Schaeffer M et al (2012) Copenhagen Accord Pledges imply higher costs for staying below 2°C warming—A letter. Clim Change 113:551–561

van Vuuren DP (2007) Energy systems and climate change. Scenarios for an Uncertain Future, Science, Technology and Society., Utrecht University, Utrecht

van Vuuren DP, Den Elzen MGJ, Lucas PL et al (2007) Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. Clim Change 81:119–159

van Vuuren DP, Kok MTJ, Girod B, Lucas PL, de Vries B (2012) Scenarios in Global Environmental Assessments: key characteristics and lessons for future use. Glob Environ Change 22:884–895

van Vuuren DP, Riahi K (2011) The relationship between short-term emissions and long-term concentration targets. Clim Change 104:793–801

van Vuuren DP, Deetman S, van Vliet J et al (2013) The role of negative CO2 emissions for reaching 2 °C-insights from integrated assessment modeling. Clim Change 118:15–27

Velders GJM, Fahey DW, Daniel JS, McFarland M, Andersen SO (2009) The large contribution of projected HFC emissions to future climate forcing. Proc Natl Acad Sci U S A 106:10949–10954