Environmental Research Letters

PAPER

Carbon budgets and energy transition pathways

Detlef P van Vuuren, Heleen van Soest, Keywan Riahi, Leon Clarke, Volker Krey, Elmar Kriegler, Joeri Rogelj, Michiel Schaeffer and Massimo Tavoni

1 PBL Netherlands Environmental Assessment Agency, The Hague/Bilthoven, The Netherlands
2 Utrecht University, Copernicus institute for sustainable development, Utrecht, The Netherlands
3 International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria
4 PNNL, Pacific Northwest National Laboratory, Washington DC, USA
5 PIK, Potsdam Institute for Climate Impact Research, Potsdam, Germany
6 ETH Zurich, Zürich, Switzerland
7 Climate Analytics, Berlin, Germany
8 Environmental Systems Analysis Group, Wageningen University and Research Centre, PO Box 47, 6700 AA Wageningen, The Netherlands
9 Fondazione Eni Enrico Mattei (FEEM) and Centro Euromediterraneo sui Cambiamenti Climatici (CMCC), Milan, Italy
10 Politecnico di Milano, Department of Management, Economics and Industrial Engineering, Milan, Italy

E-mail: Detlef.vanvuuren@pbl.nl

Keywords: carbon budget, mitigation strategy, climate policy, integrated assessment

Supplementary material for this article is available online

Abstract

Scenarios from integrated assessment models can provide insights into how carbon budgets relate to other policy-relevant indicators by including information on how fast and by how much emissions can be reduced. Such indicators include the peak year of global emissions, the decarbonisation rate and the deployment of low-carbon technology. Here, we show typical values for these indicators for different carbon budgets, using the recently compiled IPCC scenario database, and discuss how these vary as a function of non-CO2 forcing, energy use and policy delay. For carbon budgets of 2000 GtCO2 and less over the 2010–2100 period, supply of low carbon technologies needs to be scaled up massively from today’s levels, unless energy use is relatively low. For the subgroup of scenarios with a budget below 1000 GtCO2 (consistent with >66% chance of limiting global warming to below 2 °C relative to preindustrial levels), the 2050 contribution of low-carbon technologies is generally around 50%–75%, compared to less than 20% today (range refers to the 10–90th interval of available data).

1. Introduction

Several publications have recently highlighted the relationship between cumulative CO2 emissions and long-term temperature change (Allen et al 2009, Matthews et al 2009, Meinshausen et al 2009, Zickfeld et al 2009, IPCC 2013, Friedlingstein et al 2014). This relationship emerges as a result of the dominant contribution of CO2 to total anthropogenic warming and the long atmospheric lifetime of CO2. The policy implication of this relationship is that it is possible to derive so-called ‘carbon budgets’ that are associated with achieving certain climate targets with a certain probability (Knutti and Rogelj 2015). The strength of such budgets is that they clearly convey the messages that (1) long-term temperature change does not depend on CO2 emissions at a specific moment in time, but on the accumulated CO2 emissions over a long time period, (2) that therefore, near-term CO2 emissions are important as they, too, exhaust the available budget, and (3) finally, that for any stabilisation target, CO2 emissions will need to be phased out eventually (Anderson et al 2008, Matthews and Caldeira, 2008, IPCC 2013, Knutti and Rogelj 2015). There is, however, still flexibility in the timing of CO2 emissions contributing to the budget, particularly when including the option of negative emissions (Obersteiner et al 2001, van Vuuren et al 2007, Azar et al 2010, Tavoni and Socolow 2013).

In defining emission pathways consistent with specific carbon budgets it is important to realise that these would require major changes in current energy and land-use systems (Clarke et al 2014, Kriegler et al 2014, Tavoni et al 2015). Such transitions will be
constrained by socio-economic and technological inertia, manifested, among other things, in capital turnover rates, substitution dynamics, and limitations in implementation potential. This means that there are constraints on the possible pathways that are consistent with specific carbon budgets. Scenarios from integrated assessment models (IAMs) can provide insight into such transition pathways, capturing some of the relevant dynamics (Luderer et al 2013, van Vuuren and Stehfest 2013, Rogelj et al 2013b, Riahi et al 2015, Tavoni et al 2015). For the recent IPCC Fifth Assessment Report (AR5), a large set of IAM-based scenarios has been compiled, based on different models and derived for different types of targets, including forcing targets, carbon budget constraints, emission targets and prescribed carbon taxes (Clarke et al 2014). The characteristics of these scenarios have been assessed in the IPCC AR5 report.

Given the recent focus on carbon budgets, there is a need for insights into the implications of various carbon budgets, something that can be provided by the IAM-based scenarios. Going significantly beyond earlier assessments, in this paper we use the scenario database to directly explore how different carbon budgets relate to emissions pathways and, subsequently, energy system requirements. We do so by plotting information against a continuous CO2 budget axis, in contrast to the more aggregated representation for scenario categories often used earlier (e.g. Clarke et al 2014). The figures shown here provide more insights into the underlying information (e.g. variance) than the aggregated statistics. We specifically look into the implications of different budgets for (1) emission reductions over time, (2) the contribution of CO2 and non-CO2 greenhouse gases, and (3) the scale of the key energy-system transformations underlying these reductions. This provides the possibility to relate CO2 budgets to policy actions by looking into the continuous relationship between those two aspects. As explained in the section on methods, for each scenario climate information is available in the database based on runs of a probabilistic version of the climate model MAGICC (Meinshausen et al 2009, 2011).

2. Methods

The analysis represented here relies on the IPCC AR5 scenario database that contains IAM-based scenarios published in the scientific literature period 2007–2013 (Clarke et al 2014). The database was used in chapter 6 of the WG3 contribution to IPCC’s Fifth Assessment Report and is available at https://secure.iiasa.ac.at/web-apps/ene/AR5DB/. It was compiled by means of an open call to modelling teams to submit scenarios to the AR5 database. The database includes information on the emissions, energy, land-use, technology and costs characteristics of these scenarios (Krey et al 2014). About 1200 scenarios were submitted, including baseline (no new climate policy), optimal policy and other mitigation scenarios. The baseline scenarios, although arguably not very realistic, represent a useful (counterfactual) point of reference for analysis in many studies. The optimal policy scenarios provide insight into least-costs strategies assuming that policies can be introduced in all sectors and regions from a base year onwards. Other mitigation scenarios include various constraints such as the policy delays associated with currently proposed climate policies, as pledged for 2020 and 2030 (Krey et al 2014). In the analysis here, we used those scenarios in the database that included information on 21st-century CO2 emissions (we used the same method as used in AR5 to add a default pathway for land-use related CO2 emissions in case only energy-related emissions were reported). Because the database was compiled to support AR5 analysis, it contains scenarios published from 2007 onwards, thus including scenarios that assume stringent policies could still be introduced from around 2010 onwards. Other authors have pointed out before that this may lead to possible bias in the results (allowing for a too optimistic view of the feasibility of ambitious climate targets) (Anderson 2015). In particular, this involved the question whether many models already have a peak in emissions in 2010, as in reality global CO2 emissions increased by around 8.5% in the 2010–2015 period (Le Quéré et al 2015). However, the far majority of scenarios have been reported in 10 year steps, meaning that 2020 emissions could still be below the 2010 level without ruling out a 2015 peak. Therefore, we added two additional constraints to only remove those scenarios from the analysis that are clearly inconsistent with historically observed trends. First, all scenarios with 2010 emissions outside the 37.4 ± 3.8 GtCO2 estimated by IPCC AR5 were excluded (Edenhofer et al 2014). Second, all scenarios with 2020 emissions more than 25% below 2010 level were excluded. This level is based on a maximum reduction rate of 7% starting from the 2015 emission level (the 7% rate is based on the maximum reduction rates after 2020 and the mean of scenarios showing the most rapid reduction in the 2030–2050 period in Riahi et al 2015). Finally, in order to identify whether scenarios that assume an emission peak already in 2015 behave differently, an additional scenario category was added within the optimal scenario group. This additional category shows 2020 emissions below the observed 2015 level (i.e. 8.5% above 2010). In total, 106 scenarios were removed on the basis of these additional constraints.

For those scenarios in the database that contained sufficient information, the carbon-cycle and climate model MAGICC (Meinshausen et al 2011) was used by the authors of the IPCC report to add a consistent set of forcing and climate data (and include it in the database). MAGICC is calibrated against more complex atmosphere–ocean general circulation models and it
has been shown to be consistent with the latest complex climate models in terms of mean climate outcomes (including the carbon budget) and, to some degree, also the uncertainty ranges (Rogelj et al 2014, Schaeffer et al 2015). This implies that the database can provide a link between carbon budgets and a range of important scenario attributes, including energy system parameters and emissions and climate system parameters.

While IAM scenarios provide an important source of information, it is clear that models do not capture all aspects of mitigation strategies. Moreover, the analysis of such models is bounded by assumptions for key uncertainties such as technology change, energy prices and social acceptance of new technologies (Clarke et al 2014, Grubb et al 2014, Kriegler et al 2015a). In general, IAMs focus on identifying low-costs scenarios under clearly specified limitations (e.g. the participation of regions in international climate policy), assuming (fully) functioning markets. The model results are generally meant to be indicative of possible developments given current insights on technology development. It is not easy to assess the implications of the simplifications included in the models. While the assumption of well-functioning carbon markets may imply that models are likely to underestimate costs, the recent rapid development in costs of renewables could also mean that in the long-term, costs could be lower than suggested by the models.

Overall, several studies have shown general trends of model output in terms of use of specific technologies (mostly the focus of this article) to be roughly consistent with historical trends (Wilson et al 2013) (van Sluisveld et al 2015). An other important point is that models mostly focus on technological and economic factors, which means that results say little about political or social feasibility (e.g. regarding the acceptance of carbon-capture-and-storage, CCS). Real-world strategies that deliberately depend on more expensive mitigation options (e.g. the rapid expansion of PV in Germany a few years ago), for instance for political reasons, tend to be underrepresented.

In the discussion section, more attention is paid to some key characteristics of IAMs and the implications for our findings.

Two assumptions that play a key role in the overall characteristics of mitigation strategies of IAMs include the timing of climate policy in different regions and sectors and the inclusion of negative emission technologies, which will be shown in this paper. Regarding timing of policies, the AR5 database includes 'optimal scenarios' (which have no further constraints on mitigation technology, timing, or participation) and scenarios that have assumed technology restrictions or delays in policy implementation. If relevant, the scenarios that assume delay have been shown separately in this paper. Similarly, scenarios that show net negative emissions in the second half of the century have been distinguished from scenarios that do not have net negative emissions.
3. Results

3.1. IAM information on carbon budgets

Figure 1 shows—consistent with the carbon budget literature—that, for the scenarios included in the database, there is a very strong relationship between cumulative CO$_2$ emissions and temperature and forcing outcomes. The almost linear relationship between cumulative CO$_2$ and temperature is uncertain in two ways: first, there is an uncertainty in the slope of the relationship, caused by the uncertainty in the climate system response, and second, there is a scenario uncertainty, shown as a variation around the central relationship, caused by differences in the timing of emission reductions and the reduction in non-CO$_2$ climate forcers (see also Rogelj et al 2015b). The impact of scenario uncertainty is shown by the spread of the individual dots (figure 1(b)), while the two outer lines additionally include the impact of climate system uncertainty. As a result, a range of different climate outcomes is associated with a specific carbon budget. For instance, a carbon budget of around 2500 GtCO$_2$ over the period 2010–2100 may lead to a temperature increase that ranges from 2.4 °C to 2.8 °C compared to pre-industrial level as a result of scenario uncertainty (10th–90th percentile), and 1.7 °C–3.8 °C compared to pre-industrial level if climate response uncertainty is also included. In the IPCC report, the scenarios were categorized on the basis of projected (median) 2100 forcing levels. Throughout this paper, we instead relate policy relevant indicators to a continuous range of cumulative CO$_2$ emissions. Similar relationships as shown in figure 1 can be drawn for different indicators such as peak temperature. While 2100 temperature correlates well with 21st-century budgets, for stringent scenarios, peak temperature correlates better with the cumulative CO$_2$ emissions until the peak (see SI). Depending on the type of impacts, it might be more relevant to look at peak temperature or at (long-term) transient temperature.

The vertical bars illustratively couple the results to cumulative CO$_2$ emissions associated with keeping temperature likely (i.e. >66% chance) below different temperature levels. These vertical bars are also used in subsequent graphs in this article to relate policy-relevant indicators to the climate outcomes. The estimated carbon budgets are based on the 67th percentile temperature outcome which have been approximated by taking the average of the temperature projections for the 50th and 84th percentile for each scenario that was assessed by MAGICC as part of the AR5 Scenario database. For each IPCC AR5 WGIII scenario category, the median 67th percentile temperature outcome was computed over all scenarios, and a piecewise linear line was used to interpolate between these median points. Finally, the width of the illustrative shadings in figures 1–6 (see also supplementary table S1) was computed by determining the intersection of the piecewise linear line with specific temperature levels, like 1.5 °C, 2 °C, 2.5 °C, or 3 °C relative to pre-industrial values.

3.2. Timing of emission reductions

Figure 2 shows the available scenarios as a function of time. For the baseline scenarios, emissions typically increase rapidly until 2050, followed by a slower increase after 2050 (purple lines). For carbon budgets of less than 2500 GtCO$_2$, global carbon emission profiles peak during the 21st century, followed by a distinct decline. For emission budgets of less than 1500 GtCO$_2$, an early emission peak needs to be followed by rapid reductions, mostly resulting in net negative emissions by the end of the century. As discussed by Kriegler et al (2015b), the year emissions peak in scenarios strongly depends on scenario assumptions (see figures 2(c) and (d)). While part of the scenario literature looks into cost-optimal trajectories towards long-term climate goals (i.e. based on minimised discounted costs over the century), other scenarios deliberately account for policy delay (i.e. less mitigation action is undertaken in the near term, in line with existing policies, while still aiming for the same long-term global climate objective). The two categories are shown separately in figures 2(c) and (d). The reduction before 2050 strongly depends on the use of negative emissions technologies in the second half of the century. This is shown in figure 3. For CO$_2$ budgets around 1000 GtCO$_2$ over the 2010–2100 period (which are consistent with a >66% probability of limiting warming to below 2 °C by 2100), most cost-optimal scenarios have negative emissions post-2050. At the same time, they still peak almost immediately (and thus at current emission levels), in order to avoid very expensive rapid reduction rates later on. For higher cumulative CO$_2$ emission levels, emissions can peak at a later point in time. For instance, under scenarios with a CO$_2$ budget of 1025–1775 GtCO$_2$ (around 50%–66% probability of limiting global warming to below 2 °C) emissions peak before 2030. In terms of peak year and level, the differences between cumulative CO$_2$ budgets up to around 2000 GtCO$_2$ are relatively small; emissions peak before 2040—with a median emission level (across all budgets below 2000 GtCO$_2$) that is under 20% above year-2010 emissions. Several multi-model studies have looked into the question how long-term targets could still be reached starting from currently formulated climate policies (pledges) in combination with corresponding policy projections for 2030 (Riahi et al 2015, Tavoni et al 2015, Kriegler et al 2015b). These so-called delay scenarios show a later and higher peak at the global level, compensating the additional emissions by quicker emissions reductions after 2030 and more negative emissions after 2050 (figure 2). Also Peters et al (2015) showed that currently formulated policies are inconsistent with an early action emission profile.
The annual emission reduction rate between 2010 and 2050 increases with decreasing cumulative CO2 emissions (figure 3). Earlier work already showed that average annual emission reduction rates over the full 2010–2050 period do not differ greatly between cost-optimal and delay scenarios, as delay scenarios (developed using models that allow for negative emissions) already catch up with the optimal ones in terms of emission level by 2050 (Riahi et al 2015), and compensate for the higher cumulative emissions after 2050. Emission reductions increase steeply for low carbon budgets, but, this critically depends on post-2050 reduction rates and non-CO2 emission reductions, as will be discussed further. For CO2 budgets of below 1025 GtCO2, annual emission reductions over the 2010–2050 period are around 2%–6% (computed as compound annual growth rates; range refers to 10–90th percentile). In terms of the decarbonisation rate, i.e. the improvement of the CO2/GDP ratio over time, the range is between 4.3% and 8.5% per year (figure 3(c)). For comparison, historically, global decarbonisation rates have been mostly around 1%–2% per year (van Vuuren et al 2015). Figures 3(a)–(c) also illustrate the influence of the possible negative emissions in the second half of the century, by using a different colour for the scenarios that achieve net negative cumulative emissions over the 2080–2100 period. For low carbon budgets the scenarios with negative emissions (blue) are clearly more frequent than those without (red). There is also some difference in the emission reduction rates (negative emission scenarios show typically lower reduction rates over the full period up to 2050 for a specific carbon budget than those without). At the same time, however, there is a much stronger impact on 2030 emission reduction rates (not shown). The finding that short-term

Figure 2. Profiles for CO2, (panel (a)) and CO2eq emissions (based on SAR GWP100 as included in the AR5 database, panel (b)) for all scenarios in each of the categories defined in figure 1 (10th–90th percentile), as well as the emission profiles of the RCPs (van Vuuren et al 2011). Panel (c) shows the year of the peak in CO2 emissions, distinguishing optimal and delay scenarios, while panel (d) shows the peak height compared to 2010 emissions. Coloured bands show ranges of cumulative CO2 emissions consistent with various levels of global-mean temperature increase in 2100, see figure 1 and methods.
emission reductions consistent with long-term climate targets are dependent on assumptions on long-term mitigation potential (van Vuuren and Riahi 2011, Rogelj et al 2013a), is of key importance for international climate negotiations that discuss near-term emission targets.

Finally, scenarios with smaller carbon budgets on average have somewhat higher energy intensity improvements (figure 3(d)), which increase from 1% to 2.5% for high cumulative emissions (budgets above 3500 GtCO$_2$) consistent with the baseline scenario, to between 1.5% and 3% for cumulative emissions below 1775 GtCO$_2$ (comparable to rates achieved in OECD countries during the 1980s). The increase in improvements for energy intensity is clearly less pronounced than for the decarbonisation rate and shows considerable overlap between low and high carbon budgets indicating the importance of fuel substitution (to low carbon fuels) and CCS in low emissions scenarios.

3.3. Non-CO$_2$ emissions and forcing

A key factor responsible for the spread in 21st-century CO$_2$ budgets and temperature levels is the forcing of non-CO$_2$ gases (figure 4(b)). Figure 4(a) indicates that there is a weak correlation between non-CO$_2$ and CO$_2$ forcing ($r^2$ of 0.39 for a linear regression over the whole range), but no correlation at low forcing levels ($r^2$ of virtually zero for forcing of $<4$ W m$^{-2}$). The weak correlation arises as a result of common sources of CO$_2$ and other (non-CO$_2$) Kyoto gases (e.g. coal and natural gas use) and the multigas policy approach assumed in IAMs calculations (consistent with current policies). The relationship, however, is weak as (1) CO$_2$ emission reductions are also associated with reductions in SO$_2$ emissions (which offset part of the
CO$_2$ warming), and (2) in nearly all models, the mitigation potential for CH$_4$ and N$_2$O emission reductions is limited and implemented already at moderate carbon prices (up to USD 100/tCO$_2$-eq). Remaining non-CO$_2$ emissions include, for instance, methane emissions from free roaming cows and emissions associated with the use of nitrogen fertilizers (Smith et al 2014, Gernaat et al 2015). As a result, similar minimum forcing levels for non-CO$_2$ gases are reached both under average and stringent mitigation scenarios. This leads to the increasing share of non-CO$_2$ forcing at more stringent targets (limitations in non-CO$_2$ reductions in combination with negative emissions slowly reduce the relative contribution of CO$_2$ forcing towards the end of the century).

3.4. Energy-system transitions

Staying within low-carbon budgets requires an enormous scale up of the contribution of low-carbon emission technologies (figure 5). Low-carbon emissions technologies are here defined as fossil fuels with CCS, renewable energy, bio-energy (including bio-energy with CCS), and nuclear power, consistent with how they are dealt with in most underlying models. For some of these technologies, there is a strong debate on the effective reduction level for CO$_2$ emissions. First of all, capture rates in CCS are not likely to be 100% effective and leakage may occur from storage sites. Second, several bio-energy application chains lead to greenhouse gas emissions, with current literature providing a wide range of possible values (Smith et al 2014). It should be noted that the scenarios use mostly second-generation biofuels and bio-energy as feedstock in electricity production. Most models do account for some emissions for these technologies, but lower than for conventional use of fossil fuels. In presenting the results we distinguish between baseline scenarios, cost-optimal scenarios, and delay scenarios. In 2010, the contribution of bio-energy, renewable energy and nuclear power was around 14% of world energy use, if we include traditional bio-energy (firewood, charcoal, manure and crop residues). Most scenarios expect the use of traditional bio-energy to be reduced over time. This notwithstanding, under scenarios with low carbon budgets the total contribution of low-carbon emission technologies increases rapidly. In the results for 2030, there is a significant difference between scenarios that assume a delay and those that assume immediate (cost-optimal) emission reductions. This difference, however, has disappeared by 2050. The contribution of low-carbon energy technologies in cost-optimal scenarios with cumulative CO$_2$ emissions from 2010 to 2100 smaller than 1775 GtCO$_2$ increases to around 100–300 EJ yr$^{-1}$ by 2030 (20%–50% of primary energy use) and to 200–550 EJ yr$^{-1}$ by 2050 (40%–80% of primary energy use). This implies a scale up by a factor of two to four, between 2010 and 2030, and a further doubling between 2030 and 2050. We have made a distinction between optimal scenarios with and without an emission peak in 2015. While some differences are visible between the categories for 2030 for decarbonisation rates and technology deployment levels, no differences can be found for 2050 (figure 6). In the delay scenarios, the scale up in 2030 is less than in the optimal scenarios, but as a result, an even more rapid deployment is needed between 2030 and 2050 to reach similar deployment levels by 2050 to those in the cost-optimal cases (Riahi et al 2015). For higher carbon budgets, the share of low-carbon emission energy remains typically at 2010 level (see figure).
The required scale up depends critically on the volume of energy consumption as shown in figures 5(e) and (f). This is most noticeable for 2050, where the deployment level of low carbon technologies shows a clear gradient under different energy consumption levels; low energy demand levels (e.g. below 400–500 EJ yr⁻¹) lead to considerably less low carbon technology deployment than high energy demand levels. In other words, energy conservation can significantly reduce the demand for low carbon technologies (Riahi et al 2012).

In figure 6, we further differentiate the information in terms of different energy technologies, i.e. biomass, non-biomass renewables and fossil fuels with CCS. Again, a distinction is made between delay and cost-optimal scenarios. The share of both bio-energy and non-biomass renewables strongly increases for low cumulative CO₂ emissions, especially in 2050, but also under cost-optimal scenarios in 2030. Total bio-energy use in the cost-optimal response for low CO₂ budgets (<1775 GtCO₂) in the scenarios increases to 40–120 EJ by 2030 (or 5%–23% of primary energy, 10th–90th percentile, median of 75 EJ yr⁻¹) and to 75–200 EJ by 2050 (10%–35% of primary energy, median of 140 EJ yr⁻¹). For less stringent budgets, the bio-energy use contribution can be less both in 2030

---

**Figure 5.** Low-carbon emissions energy use in 2030 and 2050 (primary energy). Panels show (a) and (b) absolute values and (c) and (d) % of total primary energy use for different scenarios categories. Lines indicate the best fit correlation (3rd degree polynomial) for respectively optimal (blue) and delay scenarios (red), while the dashed lines indicate the 10th–90th percentile for all categories. Panels (e) and (f) show absolute deployment level as function of different levels of energy demand. For coloured bands see figure 1 and methods. Goodness of fit for all regressions is provided in supplementary table S2.
and 2050. Clearly, there has been considerable debate on the land-use impacts of bio-energy production in relation to food production, and biodiversity protection and even the consequences for indirect emissions (see earlier remarks). In some of the IAM models these factors are accounted for, but this should be seen in the context of considerable scientific uncertainties (Searchinger et al. 2008, Popp et al. 2014). The recent IPCC report estimated that most likely 100 EJ yr\(^{-1}\) could be produced sustainably in 2050, while a high estimate could go up to around 300 EJ. The contribution of all other renewables by 2030 is considerably less than bio-energy. For low carbon budgets, however, their deployment catches up by 2050—indicating a massive scale up over the whole period. The range of deployment for each low carbon technology is very large, as a result of the possibility of substitution. The same trends are observed for fossil fuels with CCS. Here, the spread is even larger, ranging from no CCS application to deployment levels similar to those of bio-energy or other renewables by 2050. Scenarios with no CCS deployment are the result of specific studies in which CCS deployment is not allowed. Another distinction is that CCS deployment is only observed for the lowest categories—while CCS is hardly used for high carbon budgets (in contrast to the other technologies).

4. Discussion and conclusions

Our analysis depends on IAM scenarios published in the literature over the 2007–2013 period and submitted to the AR5 scenario database. Several limitations are therefore related to potential sampling bias in the scenario set of this database. First of all, our results clearly depend on the subjective assumptions made by researchers publishing IAM model results about future factors that are inherently uncertain. In that context, while models provide (based on these assumptions) information on technological and economic factors that characterize decarbonisation scenarios and the possibility to implement them, they provide little information on socio-political factors that are essential for feasibility in the real world (e.g. the acceptance of large scale CCS use). Another key assumption is development of fossil fuel prices. IAM

---

**Figure 6.** Share of biomass, non-biomass renewable energy and CCS in total primary energy (distinguishing cost-optimal, delay and baseline scenarios). For coloured bands see figure 1 and methods. Goodness of fit characteristics of all regressions are provided in supplementary table S2.
models mostly focus on long-term trends and many of the models contained in the analysis published in the 2007–2013 period did not use the high fossil fuel prices observed at that time. Similarly, the question whether current low oil prices would influence the results would require an assessment of whether oil prices are expected to remain low over a long period of time. For many models, fossil fuel prices are endogenously calculated and the fossil fuel prices are in fact relatively low in most mitigation scenarios anyway. Results presented here can therefore be expected to be reasonably robust in the light of the recent oil price development. Second, research projects recently have put more emphasis on stringent climate targets than on weak climate targets. As a result—a relatively large share of scenarios is found with cumulative CO₂ emissions of the order of 800–2000 GtCO₂. Third, while several research projects have looked into delay scenarios for stringent targets, very few studies looked into delay scenarios for less stringent targets (an exception is (O’Neill et al 2010)). Fourth, some research projects and models have contributed more to the database than others, possibly influencing the results with respect to the primary energy mix. For this reason, we looked into the position of those models that have submitted most scenarios to the database in figure 5 (see appendix) and found that indeed some models have a preference for specific technologies. This emphasises the importance of a multi-model approach, including a much wider range for outcomes of individual technologies than provided by single models. Interestingly, no specific model bias can be found for the sum of all low-carbon technologies. Finally, virtually none of the scenarios submitted to the database return warming to below 1.5 °C by 2100 with a likelihood of more than 50%, although a study published more recently provides an overview of such scenarios (Rogelj et al 2015a). Overall, however, we consider the conclusions in terms of aggregated characteristics such as decarbonisation rates, the contribution of different gases and the up-scaling of non-CO₂ emitting technologies to be relatively robust against possible biases in method (given the focus on the role of policy-delay and negative emissions). This is, among others, due to the large number of different models represented in the database. Outcomes for specific technologies, however, may depend on common assumptions across the IAM community (e.g. most models assume that CCS technology can be developed at large scale). An important limitation is that the database approach cannot easily handle information on scenarios that were not feasible in a specific model (e.g. due to limited mitigation potential). This problem was noted before in a critical review of the AR4 analysis (Tavoni and Tol 2010). Individual model studies can correct for this by carefully reporting the non-feasible results (Rogelj et al 2013a). The more aggregated approach presented here has the advantage of a much higher number of scenarios (and exploration of uncertainty) but makes it more difficult to account for such bias. For this reason, we have not included parameters that may be more sensitive to this issue such as costs, while presented indicators are generally hardly affected. Finally, the results can be prone to collective biases in the IAM models, such as their focus on supply-side technologies. This risk is partly mitigated by the fact that the database includes results from a very large range of models and model types, but it should still be realized that the majority focus on cost-optimal solutions.

The analysis thus clearly shows that for stringent carbon budgets (e.g. those consistent with the goals currently discussed in international policy making) a distinct emission corridor can be identified from scenarios published in the literature. A carbon budget of 1000 GtCO₂, for instance, is consistent with an emission peak before 2020 and decarbonisation rates of 4.5%–8% per year. At the same time, the analysis also shows that there is still some flexibility in such indicators, which increases for higher budgets. For low budgets, the difference between cost-optimal and delay scenarios plays an important role for 2030. For 2050, however, this distinction is not so important. Interestingly, the relationship between cumulative emissions and the emission reduction rate seems to be relatively strong, while for the emissions peak, nearly all mitigation scenarios show a very early emission peak. The results show that non-CO₂ forcing is the most important factor determining deviations from the default relationship between cumulative emissions and temperature.

Above all, we show that carbon budgets that are consistent with the 2 °C target, generally, require a massive scale up of low carbon technologies. While this general relationship is obvious, the paper provides key insight into the quantitative characteristics of these relationships, given the current scenario literature. For the 1000 GtCO₂ budget, the contribution of such technologies is around 50%–75% in 2050 in the assessed scenarios. For renewable energy, bio-energy and CCS technologies, similar rapid expansions are found, with each of these technologies reaching shares in primary energy use of between 15% and 30% by 2050 (typical median values). The level of deployment, however, clearly depends on energy demand. In low energy demand scenarios, scale up requirements can be halved. The deployment in 2030 depends strongly on the timing of policies. However, delays in mitigation need to be compensated for by more rapid deployment rates over the 2030–2050 period. Previous studies (see references earlier) have shown that this rapid deployment comes at significantly increased transition challenges and a larger amount of stranded fossil fuel assets, leading to overall higher costs. It will therefore be important in the international climate negotiations to identify credible pathways for scaling up demand- and supply-side technologies, even in the short-term,
if countries aim to implement the stringent targets now being discussed against relatively low costs.

Acknowledgments

The authors thank all IAM teams contributing to the AR5 scenario database, IIASA for hosting and supporting this database, and Malte Meinshausen for making available the MAGICC model. The contribution of Detlef van Vuuren benefited from the funding from the European Union’s Seventh Programme FP7/2007–2013 under grant agreement n°603942 (PATHWAYS).

References

Allen M R, Frame D J, Huntingford C, Jones C D, Lowe J A, Meinshausen M and Meinshausen N 2009 Warming caused by cumulative carbon emissions towards the trillionth tonne Nature 458 1163–6
Anderson K 2015 Duality in climate science Nat. Geosci. 8 898–900
Anderson K, Bos A and Mander S 2008 From long-term targets to cumulative emission pathways: reframing UK climate policy Energy Policy 36 3714–22
Azar C, Lindgren K, Obersteiner M, Riahi K, van Vuuren D P, den Elzen M G J, Mollersten K and Larson E D 2010 The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies Clim. Change 123 353–67
Kriegler E et al 2015a A short note on integrated assessment modeling approaches: rejoinder to the review of ‘making or breaking climate targets’—the AMPERE study on staged accession scenarios for climate policy Technol. Forecast. Soc. Change 99 273–6
Kriegler E et al 2015b Making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy Technol. Forecast. Soc. Change 99 24–44
Le Quéré C et al 2015 Global carbon budget 2015 Earth System Science Data 7 349–96
Luderer G, Pietzcker R C, Bertram C, Kriegler E, Meinshausen M and Edenhofer O 2013 Economic mitigation challenges: how further delay closes the door for achieving climate targets Environ. Res. Lett. 8 034033
Matthews H D and Caldeira K 2008 Stabilizing climate requires near-zero emissions Geophys. Res. Lett. 35 L04705
Matthews H D, Gillett N, Stott P A and Zickfeld K 2009 The proportionality of global warming to cumulative carbon emissions Nature 459 829–32
Meinshausen M, Meinshausen N, Hare W, Raper S C B, Frieler K, Knutti R, Frame D J and Allen M R 2009 Greenhouse-gas emission targets for limiting global warming to below 2 °C Nature 458 1158–62
Meinshausen M, Raper S C B and Wigley T M L 2011 Emulating coupled atmosphere–ocean and carbon cycle models with a simpler model, MAGICC6: I. Model description and calibration Atmos. Chem. Phys. 11 1417–50
Obersteiner M et al 2001 Managing climate risks Science 294 786–7
O’Neill B C, Riahi K and Keppo I 2010 Mitigation implications of midcentury targets that preserve long-term climate policy options Proc. Natl Acad. Sci. USA 107 1011–6
Peters G P, Andrew R M, Solomon S and Friedlingstein P 2015 Measuring a fair and ambitious climate agreement using cumulative emissions Environ. Res. Lett. 10 105004
Popp A et al 2014 Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options Clim. Change 123 495–509
Riahi K et al 2012 Energy pathways for sustainable development The Global Energy Assessment: Toward a More Sustainable Future (Cambridge: Cambridge University Press; London: Taylor Francis/Boutledge)
Rogelj J, Luderer G, Pietzcker R, Kriegler E, Schaeffer M, Krey V and Riahi K 2015a Energy system transformations for limiting end-of-century warming to below 1.5 °C Nat. Clim. Change 5 519–27
Rogelj J, McCollum D L, O’Neill B C and Riahi K 2013a 2020 emissions levels required to limit warming to below 2 °C Nat. Clim. Change 3 402–12
Rogelj J, McCollum D L, Reisinger A, Meinshausen M and Riahi K 2013b Probabilistic cost estimates for climate change mitigation Nature 493 79–83
Rogelj J, Meinshausen M, Schaeffer M, Knutti R and Riahi K 2015b Impact of short-lived non-CO2 mitigation on carbon budgets for stabilizing global warming Environ. Res. Lett. 10 075001
Rogelj J, Meinshausen M, Sedlacek J and Knutti R 2014 Implications of potentially lower climate sensitivity on climate projections and policy Environ. Res. Lett. 9 034003
Schaeffer M, Gohar L, Kriegler E, Lowe J, Riahi K and van Vuuren D 2015 Mid- and long-term climate projections for fragmented and delayed-action scenarios Technol. Forecast. Soc. Change 90 257–68
Searchinger T, Heimlich R, Houghton R A, Dong F, El Obeid A, Fabiosa J, Tokgoz S, Hayes D and Hsiang T 2008 Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change Science 319 1238–40
Smith P et al 2014 Agriculture, forestry and other land use (AFOLU) IPCC, 2014: Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed O Edenhofer et al (Cambridge: Cambridge University Press)
Tavoni M et al 2015 Post-2020 climate agreements in the major economies assessed in the light of global models *Nature Clim. Change* 5 119–26
Tavoni M and Socolow R H 2013 Modeling meets science and technology: an introduction to a special issue on negative emissions *Clim. Change* 118 1–14
Tavoni M and Tol R 2010 Counting only the hits? The risk of underestimating the costs of stringent climate policy *Clim. Change* 100 769–78
van Sluisveld M et al 2015 Comparing future patterns of energy system change in 2 °C scenarios with historically observed rates of change *Glob. Environ. Change* 35 436–49
van Vuuren D P et al 2011 The representative concentration pathways: an overview *Clim. Change* 109 5–31
van Vuuren D P et al 2015 Pathways to achieve a set of ambitious global sustainability objectives by 2050: explorations using the IMAGE integrated assessment model *Technol. Forecast. Soc. Change* 98 303–23
van Vuuren D P, den Elzen M G J, Lucas P L, Eickhout B, Strengers B J, van Ruijven B, Wonink S and van Houdt R 2007 Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs *Clim. Change* 81 119–59
van Vuuren D P and Riahi K 2011 The relationship between short-term emissions and long-term concentration targets *Clim. Change* 104 793–801
van Vuuren D P and Stehfest E 2013 If climate action becomes urgent: the importance of response times for various climate strategies *Clim. Change* 121 473–86
Wilson C et al 2013 Future capacity growth of energy technologies: are scenarios consistent with historical evidence? *Clim. Change* 118 381–95
Zickfeld K, EBY M, Damon Matthews H and Weaver A J 2009 Setting cumulative emissions targets to reduce the risk of dangerous climate change *Proc. Natl Acad. Sci. USA* 106 16129–34