Climatic Change (2011) 104:793–801
DOI 10.1007/s10584-010-0004-6

LETTER

The relationship between short-term emissions and long-term concentration targets

A letter

Detlef P. van Vuuren · Keywan Riahi

Received: 28 July 2010 / Accepted: 21 November 2010 / Published online: 15 December 2010

Abstract The relationship between long-term climate goals and short/medium-term emission targets forms crucial information for the design of international climate policy. Since IPCC's 4th Assessment Report (AR4), a large number of new scenario studies have been published. This paper reviews this new literature and finds that there is more flexibility in the timing of short-term emission reductions compared to the earlier scenarios assessed by the AR4. For instance, the current literature suggests that a peak of emissions in 2020 and even 2030 would be consistent with limiting temperature change to about 2°C in the long term. The timing when emissions peak depends on whether negative emissions in the long-term can be achieved. The recent scenarios further indicate that global emissions by 2050 should be 40–80% below 2000 levels. Above all, the paper argues that there is no clear, single "law" that would directly determine the required emissions levels in 2020, but that instead policy-makers need to consider trade-offs between the likelihood of achieving long-term targets, the short-term costs, and their expectation with respect to future technologies (and their possible failure). The higher flexibility might be important in finding acceptable agreements on international climate policy.

1 Introduction

The question how much short-term emission reduction is needed in order to reach long-term climate targets plays a crucial role in discussions about international

Electronic supplementary material The online version of this article (doi:10.1007/s10584-010-0004-6) contains supplementary material, which is available to authorized users.

D. P. van Vuuren (✉)
Netherlands Environmental Assessment Agency, PO Box 303, 3720 Bilthoven, The Netherlands
e-mail: detlef.vanvuuren@pbl.nl

K. Riahi
International Institute of Applied Systems Analysis, Schlossplatz 1, 2361 Laxenburg, Austria

climate policy (especially related to the 2°C target mentioned by the Copenhagen Accord). Specifically, the implications for 2020 emissions represented crucial information both during and after the Copenhagen Summit to assess the results of the negotiations (Climate Interactive 2010; ECOFYS 2010; Rogelj et al. 2010; UNEP 2010). Mitigation scenarios form thus an important source to explore these linkages. In IPCC's Fourth Assessment Report (AR4, Working Group III), Section 3.3 and Table 3.5 summarize the scenario literature based on categories representing different levels of ambition of the long-term climate target (Fisher et al. 2007). Decision makers and scientists alike regularly refer to this overview for the required short-term emissions reductions to achieve certain long-term goals (for example Izrael 2008; Larsen 2009; The Prince of Wales's Corporate Leaders Group on Climate Change 2009). In reality, however, Table 3.5 provided characteristics of the existing literature, which does not exclude that there might be other scenarios that could achieve similar goals in different ways. The descriptive nature of the information is particularly important for the lowest concentration levels for which just a small number of scenarios were available at the time of AR4.

Since AR4, new scenarios studies have been performed. Here, we review this large body of new literature to update the information of the IPCC report, focusing specifically on the lowest three scenario categories from the IPCC (i.e. concentration targets leading to a radiative forcing of 4 W/m^2 or less). Moreover, we compare the results with two specific studies that explicitly explored the short-term emission range for achieving long-term targets.

2 Methodological considerations

Emission scenarios in the literature differ in many ways: e.g. they aim for different targets (concentrations, radiative forcing, or temperature change), focus on different gases (CO_2 only or all greenhouse gases), and are derived from different baseline assumptions. Systematic comparisons need to somehow group scenarios according to common characteristics. The six AR4 categories group scenarios based on the concentration levels by the end of the century, either expressed in radiative forcing, CO_2-equivalent or CO_2 concentration (Fisher et al. 2007). While the correlations of these metrics allows such grouping, this is subject to uncertainty (see for instance Meinshausen et al. 2006, 2009) and the Supplementary material).

The IPCC AR4 reported several statistics of each scenario group. If the literature comprises a sufficiently large sample of independently published scenarios, these characteristics may be interpreted as indicative of the full range of possible outcomes. Biases in the literature, however, limit such interpretation. For example, the vast majority of the literature assumes that emissions can be reduced worldwide. Scenarios considering limited participation (resulting in a delay in emission reductions) are underrepresented and have only recently been explored more widely (see Clarke et al. 2010). The risk of biases becomes larger if only a small number of scenarios are available. In fact, for the lowest climate targets in the AR4, where only six scenarios from three independent modelling studies could be assessed (Azar et al. 2006; Riahi et al. 2007; Van Vuuren et al. 2007).

The new studies published since AR4 allow updating the IPCC assessment with a larger sample set (Table 1). The original database underlying the IPCC AR4

Table 1 Table 1 Characteristics of CO_2 emissions pathways of scenarios in the IPCC categories I, II and III. Values reported in the AR4, new scenario literature (this study; see main text), and studies by O'Neill et al. (2010) and Den Elzen et al. (2007)

	No. of scenarios/models[c]	Cumulative emissions 2000–2050 (GtC)	Cumulative emissions 2000–2100 (GtC)	Peak year	Emissions in 2050 (% of 2000 emissions)	Emissions in 2020 (% of 2000 emissions)
Cat. I (2.5–3.0 W/m^2)						
This study	27 (9)	310 (226 to 373)	333 (273 to 433)	2010 to 2020	−60 (−80 to -42)	4 (−14 to 27)
-Neg. emissions	18 (8)	328 (269 to 384)	319 (252 to 379)	2010 to 2020	−57 (−77 to −35)	14 (−4 to 27)
-No neg. emis.	9 (5)	274 (211 to 334)	360 (299 to 441)	2010 to 2020	−65 (−82 to −48)	−15 (−52 to 19)
IPCC 2007	6 (3)	–	–	2000–2015	−85 to −50	
O'Neill et al. (2010)[a]	9 (1)	380 to 480	210 to 410	< 2030	−85 to −15	
Den Elzen et al. (2007)	12 (1)	312 to 360	372 to 470	< 2020	−85 to −40	
Cat. II (3.0–3.5 W/m^2)						
This study	19 (11)	336 (284 to 417)	451 (387 to 495)	2010 to 2020	−39 (−52 to −22)	5 (−14 to 18)
-Neg. emissions	4 (2)	421 (381 to 458)	462 (376 to 555)	2020 to 2030	−16 (−27 to −4)	16 (15 to 18)
-No neg. emis.	15 (10)	313 (272 to 341)	447 (403 to 484)	2000 to 2020	−45 (−54 to −34)	2 (−14 to 17)
IPCC 2007	18 (9)	–	–	2000–2020	−60 to −30	
Den Elzen et al. (2007)	12 (1)	370 to 415	520 to 600	< 2025	−35 to −15	
Cat. III (3.5–4 W/m^2)						
This study	76 (15)	403 (355 to 459)	603 (549 to 656)	2010 to 2030	−6 (−32 to 25)	21 (4 to 35)
-Neg. emissions	6 (4)	467 (441 to 487)	644 (622 to 659)	2030 to 2040	37 (21 to 52)	33 (28 to 36)
-No neg. emis.	70 (15)	398 (354 to 446)	599 (546 to 656)	2010 to 2030	−10 (−35 to 19)	20 (0 to 35)
IPCC 2007	21 (13)	–	–	2010–2030	−30 to 5	
O'Neill et al. (2010)[b]	11 (1)	460 to 560	530 to 710	< 2040	−35 to 45	
Den Elzen et al. (2007)	19 (1)	405 to 465	630 to 750	< 2030	−20 to 10	

Ranges refer to the 15–85% interval

[a]Includes scenarios down to 415 ppm CO_2 eq by the end of the century

[b]Most O'Neill et al. scenarios are pronounced overshoot scenarios with declining concentrations in the second half of the century, with some of the category III scenarios reaching the defined concentration level shortly after 2100

[c]Number between brackets indicates the number of different models within the set

assessment (Fisher et al. 2007; Nakicenovic et al. 2006) has been extended by the scenarios developed for EMF-22 (Clarke et al. 2010), the ADAM project (Knopf et al. 2009) and a MESSAGE/IMAGE scenario project (Rao et al. 2008; van Vuuren et al. 2010b). This implies that for the three lowest IPCC categories together the scenario set now covers 129 scenarios (instead of 45) based on much more modelling groups (Table 1). Category I now includes 27 scenarios (instead of 6) from 9 different modelling groups (instead of 3).

In the analysis, we focus, like AR4, only on the CO_2 emissions from energy and industry sources, as not all studies report land-use CO_2 emissions. Analysis of the studies that include total CO_2 emissions shows that their trends are very similar to those from energy and industry emissions alone (see Supplementary electronic information). All information was analysed with a step size of 10 years, based on data availability from model comparison studies and the coarse resolution of most models. This determines the precision of the analysis.

An important question is how to best represent large scenario datasets. Showing the full range tends to overemphasize the results of outliers, while focusing, on a too narrow range runs the risk to exclude scenarios of special interest. For reasons of comparability with the AR4, we focus primarily on the 15–85th percentile of the scenario distribution. In addition, we have highlighted results from some selected studies.

The timing of emission reductions depend on the assumed technology portfolio. Especially, the combination of bio-energy and carbon capture and storage (BECCS) may play an important role, since it permits to reach negative CO_2 emissions in the long term (Azar et al. 2010). Therefore, a distinction has been made between scenarios with and without net negative emissions. Similar to AR4, all scenarios have been categorised based on the reported long-term concentrations. Some scenarios which clearly violated 2010 emission levels have been excluded from the data set.

This method can only review scenarios that are able to meet specific emission reduction targets. Recently, Tavoni and Tol (2010) indicated that such an approach may lead to an underestimation of mitigation costs, since models that found a target to be infeasible are likely to have had higher costs. Such a "selection bias", however, is less likely to be important here, since there is no a priori reason to assume that models which found a target infeasible would show a specific bias toward either higher or lower 2020 emissions.

3 Comparison of new literature and AR4 numbers

We first discuss the general characteristics of the scenarios, followed by the influence of the assumed technology portfolio. As shown in Table 1 and Fig. 1, the emission ranges in each scenario category are relatively wide, caused by uncertainties such as different technology assumptions, the role of non-CO_2 gases, and the carbon cycle representations (for the latter, see van Vuuren et al. 2009). Moreover, each category encompasses a wide range of forcing targets, also leading to a spread in emissions. Often scenarios with steep declines early in the century show less pronounced reductions later on (and vice versa) (Fig. 1).

IPCC category I (CO_2 concentration <400 ppm; forcing <3.0 W/m^2) corresponds to a probability of 50–75% of staying below a 2°C target (Meinshausen et al.

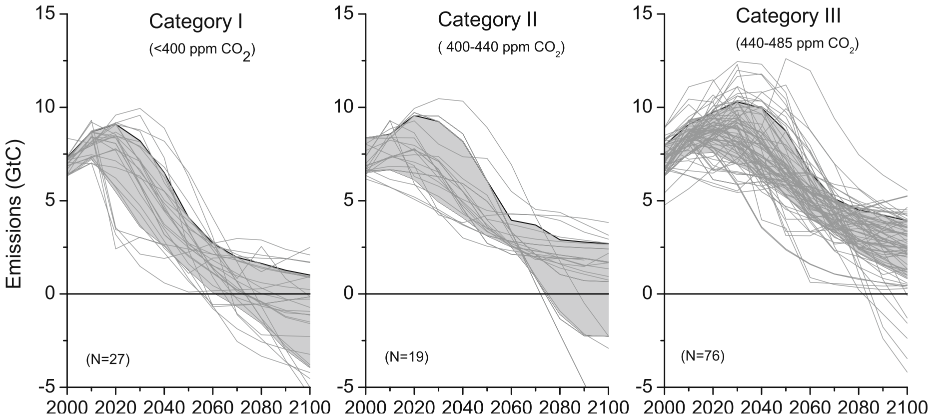

Fig. 1 Development of energy and industrial CO_2 emission for scenarios in the IPCC categories I, II and III. *Grey areas* indicate 15–85% percentile; *lines* indicate individual scenarios

2009). Scenarios in this category show an emission peak around 2020 and emission reductions of 40 to 85% by 2050 (compared to 2000) (Table 1). The 2020 emissions of these scenarios vary around the 2000 level (−14 to 27%). Compared to the IPCC AR4 results, the peak seems somewhat delayed (but here the reporting interval should be noted) and the 2050 emission reductions are less stringent. The cumulative emissions for the 2000–2050 period are in the order of 230–370 GtC, similar to Meinshausen et al. (2009) who report a range of 270 to 390 GtC for a 75% and 50% probability of 2°C respectively (after 2050 category I scenarios show little further emissions).

For category II scenarios (400–440 ppm CO_2) both the timing of the emissions peak and the 2020 emission level seem to be not very different from category I. Emission reductions by 2050 for category II scenarios are, however, considerably less strong than for category I. Again compared to the AR4 numbers, the current scenario literature includes somewhat higher 2050 emissions (Table 1).

For category III (440–485 ppm CO_2), the peak-year is similar to AR4 (2010–2030) but the range of 2050 emissions has moved up. 2050 emissions are now near the 2000 level, with a wide uncertainty range. The 2020 emission levels for category III are considerably higher than the previous categories, on average 21% above the 2000 level.

We thus find for all categories that the extended database shows somewhat more modest short-term reductions, compensated by more stringent emission declines in the second half of the century.

4 Discussion: impact of the assumed technology portfolio

Most scenarios in the literature are developed to project long-term "optimal" emissions pathways. O'Neill et al. (2010) and Den Elzen et al. (2007), in contrast, focused on the assessment of wider range of trajectories. While both studies are based on a single model (and therefore less robust), they are added for comparison to Table 1. Interestingly, their results confirm the findings that there is more flexibility for short-term emissions than suggested by a normative interpretation of AR4. In fact, the emission peak in these studies occurs even later than in the literature overview (consistent with the explicit focus on feasibility).

Emission reduction pathways depend strongly on technology assumptions. Crucial technology options considered by many scenarios in the literature include energy efficiency, renewable and nuclear energy, carbon capture and storage (CCS), reduction of non-CO_2 gases, but also technologies that allow for negative emissions (reforestation and BECCS) (Azar et al. 2010; Edenhofer et al. 2010; Fisher et al. 2007; Van Vuuren et al. 2007). Negative emissions occur in the second half of the century (Table 1 and Fig. 2), thus allowing for more modest 2020 and 2050 emission reductions. The category I scenarios with negative emissions show an increase in 2020 of 14%, while scenarios without negative emissions have a reduction of 15%. The difference can also be noted for cumulative emission budgets: while the 2000–2100 budget hardly depends on the presence of negative emission options, there are large consequences for the 2000–2050 budget. These differences occur across all categories and for most variables. For 2050, the difference is larger for category II and III given the more binding constraints in category I. In fact, the majority of scenarios in category I include negative emissions: for many models the target is infeasible without negative emissions. In category II and III a considerably smaller fraction of scenarios show net negative emissions.

The possible contribution of BECCS depends on the potential and societal acceptance of bio-energy production and CCS. While there might be a considerable potential for bio-energy, uncertainties are large, and concerns regarding technology development, carbon-neutrality, food security and biodiversity may reduce the potential (van Vuuren et al. 2010a). Also for CCS, storage capacity and societal acceptance are uncertain. Therefore, the possibility of higher short-term emissions in scenarios with BECCS is associated with a risk that BECCS might not become available at full potential in the long-run.

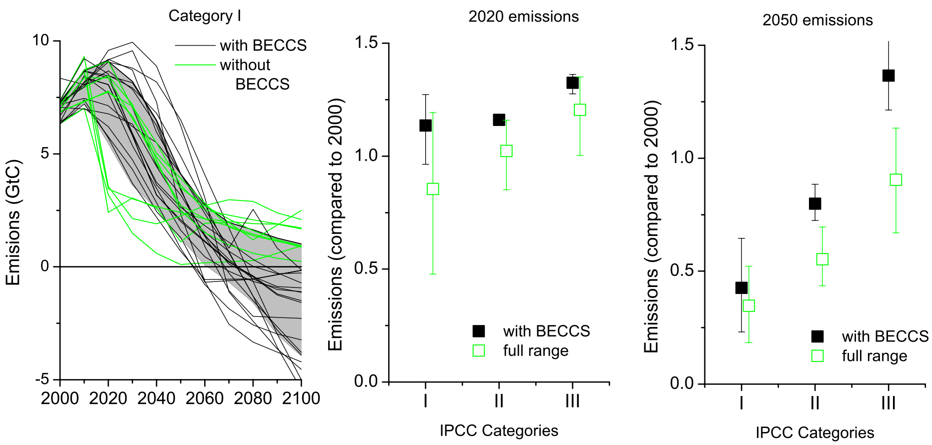

Fig. 2 *Left panel*: development of CO_2 emission in scenarios of category I (*grey area* is 15–85% percentile). *Middle and right panels*: average emissions levels of category I–III scenarios by 2020 and 2050 (compared to 2000). Scenarios with BECCS are shown in *green* and scenarios without BECCS in *black*. Error bands in the *middle and right-hand panels* indicated 15–85% percentile

We can also illustrate the importance of technology assumptions by focussing on the O'Neill and Den Elzen studies. In the O'Neill et al. (2010) results, relatively late emissions reductions are strongly associated with large negative emission levels in the long-term. In the work of Den Elzen et al. (2007), in contrast, emission reductions in non-CO_2 gases are larger than in most other studies, explaining the relatively high CO_2 emissions.

Various factors may play a role in the shift in scenario literature between AR4 and the current overview. Although some of the literature assessed in AR4 already included overshoot scenarios and BECCS, BECCS has been added to more models now, leading to a significant extension of the literature in the lowest category (partly looking into the attainability of low concentration targets following the work of Van Vuuren et al. (2007) (see Moss et al. 2010)). In the overview here, some of the scenarios included in AR4 category I have been excluded as they assume strong emission reductions before 2010, leading by itself to an upward shift. Interestingly, however, a shift can also be noted for categories II and III while here little scenarios with net negative emissions are found. Therefore, the more important factor seems to be the publication time. As global emissions increased rapidly between 2000 and 2008, the additional lock-in into fossil fuels limits the potential for emissions reductions by 2020. In addition, new studies assume introduction of climate policy at a later point in time.

5 Implication of the findings

The review shows that stringent long-term targets seriously constrain short-term emissions, but that there is more flexibility than suggested by the normative interpretation of AR4 table. Obviously, the additional flexibility is not unlimited: delaying emission reductions too far into the future imputes the risk that some long-term targets become infeasible (Den Elzen et al. 2010; O'Neill et al. 2010). For the lowest category the emission peak is found to be around 2020. Such reductions are very challenging as studies show that this is likely to require the participation of all major emitters (Clarke et al. 2010).

The results above all emphasise that the focus should be less on the emissions in a specific year, but more on the medium-term emission trajectory and the budgets that are associated with those. As such, decisions on short-term emission reductions need to consider the path-dependency of the system and factor in trade-offs between (1) the short-term costs of emissions reductions, (2) risks of overshooting long-term temperature targets, (3) the risks associated with the uncertainty of long-term technological options and (4) expectations about the attainable rate of emissions reductions that can be implemented. In other words, there is not a single 'law' to determine short-term targets consistent with long-term objectives. As some conclusions reached by studies evaluating the Copenhagen Accord have relied on specific assumptions for post-2020 emission reductions, they may not necessarily be fully robust against the uncertainty space mentioned above (Climate Interactive 2010; ECOFYS 2010; Rogelj et al. 2010; UNEP 2010). We want to emphasise that while our review could be useful to guide policy making, the results should not be over-interpreted as an ultimate indication of necessary conditions for achieving long-term climate targets. For a better understanding of short-term feasibility thresholds, model comparison studies are needed, with explicit consideration of short-term emission targets and alternative technology assumptions.

Acknowledgements The authors thank the coordinators of the EMF-22 and ADAM studies for making the scenario data available for analysis. This writing of the paper benefited from financial support of the RESPONSES project (EU DG Research).

References

Azar C, Lindgren K, Larson E, Möllersten K (2006) Carbon capture and storage from fossil fuels and biomass-costs and potential role in stabilizing the atmosphere. Clim Change 74:47–79

Azar C, Lindgren K, Obersteiner M, Riahi K, van Vuuren DP et al (2010) The feasibility of low CO2 concentration targets and the role of bio-energy carbon-capture and storage. Clim Change submitted

Clarke L, Edmonds J, Krey V, Richels R, Rose S et al (2010) International climate policy architectures: overview of the EMF 22 international scenarios. Energy Econ 31(Suppl. 2):S64–S81

Climate Interactive (2010) Copenhagen accord reaffirms 2 degree goal, but Gap with National Proposals Remain. The Sooner the Action, the Cheaper and Easier. http://climateinteractive.wordpress.com/2009/12/20/copenhagen-accord-reaffirms-2-degree-goal-but-gap-with-national-proposals-remain-the-sooner-the-action-the-cheaper-and-easier/

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

Den Elzen MGJ, Van Vuuren DP, Van Vliet J (2010) Postponing emission reductions from 2020 to 2030 increases climate risks and long-term costs. Clim Change. doi:10.1007/s10584-010-9798-5

ECOFYS (2010) Ambition of only 2 developed countries sufficient for Copenhagen Accord meeting 2°C target. http://www.ecofys.nl/com/news/pressreleases2009/pressrelease_02022010_climate_action_tracker.htm

Edenhofer O, Knopf B, Barker T, Baumstark L, Bellevrat E et al (2010) The economics of low stabilization: model comparison of mitigation strategies and costs. Energy J 31:11–48

Fisher B, Nakicenovic N, Alfsen K, Corfee Morlot J, de la Chesnaye F et al (2007) Issues related to mitigation in the long-term context. In: Metz B, Davidson O, Bosch P, Dave R, Meyer L (eds) Climate change 2007. Mitigation of climate change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, pp 169–250

Izrael YA (2008) About modern climate state and suggestions on actions to counteract climate changes. Russ Meteorol Hydrol 33:611–613

Knopf B, Edenhofer O, Barker T, Baumstark L, Criqui P et al (2009) The economics of low stabilisation: implications for technological change and policy. In: Hulme M, Neufeld H (eds) Making climate work for us

Larsen J (2009) Options for WI GHG Reduction Targets. http://dnr.wi.gov/environmentprotect/gtfgw/documents/MbTF20080501.pdf

Meinshausen M, Hare B, Wigley TML, van Vuuren DP, den Elzen MGJ et al (2006) Multi-gas emission pathways to meet arbitrary climate targets. Clim Change 75:151–194

Meinshausen M, Meinshausen N, Hare W, Raper SCB, Frieler K et al (2009) Greenhouse-gas emission targets for limiting global warming to 2°C. Nature 458:1158–1162

Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK et al (2010) The next generation of scenarios for climate change research and assessment. Nature 463:747–756

Nakicenovic N, Kolp P, Riahi K, Kainuma M, Hanaoka T (2006) Assessment of emissions scenarios revisited. Environmental Economics and Policy Studies 7:137–173

O'Neill B, Riahi K, Keppo I (2010) Mitigation implications of midcentury targets that preserve long term climate policy options. Proc Natl Acad Sci 107(3):1011–1016. doi:10.1073/pnas.0903797106

Rao S, Riahi K, Stehfest E, van Vuuren D, Cheolhung C et al (2008) IMAGE and MESSAGE scenarios limiting GHG concentration to low levels. IIASA, Laxenbourg

Riahi K, Grübler A, Nakicenovic N (2007) Scenarios of long-term socio-economic and environmental development under climate stabilization. Technol Forecast Soc Change 74:887–935

Rogelj J, Nabel J, Chen C, Hare B, Markmann K et al (2010) Copenhagen accord pledges are paltry. Nature 464:1126–1128

Tavoni M, Tol R (2010) Counting only the hits? The risk of underestimating the costs of stringent climate policy. Clim Change 100:769–778

The Prince of Wales's Corporate Leaders Group on Climate Change (2009) The Copenhagen Communique on Climate Change. http://www.copenhagencommunique.com/images/stories/final-copenhagen-communique-english.pdf

UNEP (2010) How close are we to the two degree limit? http://www.unep.org/PDF/PressReleases/temperature-briefing-21-02-10-final-e.pdf

Van Vuuren DP, Den Elzen MGJ, Lucas PL, Eickhout B, Strengers BJ 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, Lowe J, Stehfest E, Gohar L, Hof AF et al (2009) How well do integrated assessment models simulate climate change? Clim Change. doi:10.1007/s10584-009-9764-2

van Vuuren DP, Bellevrat E, Kitous A, Isaac M (2010a) Bio-energy use and low stabilization scenarios. Energy J 31:193–222

van Vuuren DP, Stehfest E, den Elzen MGJ, van Vliet J, Isaac M (2010b) Exploring IMAGE model scenarios that keep greenhouse gas radiative forcing below 3W/m2 in 2100. Energ Econ 32(5):1105–1120