



LIMITS

SPECIAL ISSUE

A multi-model analysis of post-2020 mitigation efforts of five major economies

By Mariësse A.E. van Sluisveld, David E.H.J. Gernaat, Shuichi Ashina, Katherine V. Calvin, Amit Garg, Morna Isaac, Paul L. Lucas, Ioanna Mouratiadou, Sander A.C. Otto, Shilpa Rao, Priyadarshi R. Shukla, Jasper van Vliet and Detlef P. van Vuuren



LIMITS Special Issue on Durban Platform scenarios

A multi-model analysis of post-2020 mitigation efforts of five major economies

Mariësse A.E. van Sluisveld ^{(1)*}, David E.H.J. Gernaat ⁽¹⁾, Shuichi Ashina ⁽²⁾, Katherine V. Calvin ⁽³⁾, Amit Garg ⁽⁴⁾, Morna Isaac ⁽¹⁾, Paul L. Lucas ⁽⁵⁾, Ioanna Mouratiadou ⁽⁶⁾, Sander A.C. Otto ⁽¹⁾, Shilpa Rao ⁽⁷⁾, Priyadarshi R. Shukla ⁽⁴⁾, Jasper van Vliet ⁽⁵⁾, Detlef P. van Vuuren ^(1,5)

Affiliation:

⁽¹⁾: Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, NL-3584 CS Utrecht, The Netherlands

⁽²⁾: NIES National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba-City, Ibaraki, 305-8506 Japan.

⁽³⁾: Joint Global Change Research Institute, Pacific Northwest National Laboratory and University of Maryland, USA

⁽⁴⁾: IIMAHD Indian Institute of Management Ahmedabad, Vastrapur, Ahmedabad, India

⁽⁵⁾: PBL Netherlands Environment Assessment Agency, PO Box 303, 3720 BA Bilthoven, The Netherlands

⁽⁶⁾: Potsdam Institute for Climate Impact Research (PIK), PO Box 60 12 03, 14412 Potsdam, Germany

⁽⁷⁾: International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria

* Corresponding author: M.A.E.vanSluisveld@uu.nl

This paper is part of the LIMITS special issue, which will be published in Climate Change Economics in early 2014.

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement n° 282846 (LIMITS).

A multi-model analysis of post-2020 mitigation efforts of five major economies

Abstract

This paper looks into the regional mitigation strategies of five major economies (China, EU, India, Japan and USA) in the context of the 2°C target, using a multi-model comparison. In order to stay in line with the 2°C target, a tripling or quadrupling of mitigation ambitions is required in all regions by 2050, employing vigorous decarbonization of the energy supply system and achieving negative emissions during the second half of the century. In all regions looked at, decarbonization of energy supply (and in particular power generation) is more important than reducing energy demand. Some differences in abatement strategies across the regions are projected: In India and the USA the emphasis is on prolonging fossil fuel use by coupling conventional technologies with carbon storage, whereas the other main strategy depicts a shift to carbon-neutral technologies with mostly renewables (China, EU) or nuclear power (Japan). Regions with access to large amounts of biomass, such as the USA, China and the EU, can make a trade-off between energy related emissions and land related emissions, as the use of bioenergy can lead to a net increase in land use emissions. After supply-side changes, the most important abatement strategy focuses on end-use efficiency improvements, leading to considerable emission reductions in both the industry and transport sectors across all regions. Abatement strategies for non-CO₂ emissions and land use emissions are found to have a smaller potential. Inherent model, as well as collective, biases have been observed affecting the regional response strategy or the available reduction potential in specific (end-use) sectors.

Key words: Regional, mitigation efforts, abatement, technological implication, climate policy

1. Introduction

In the last few years, the international community has broadly agreed to aim at limiting the increase of global mean temperature to a maximum of 2°C compared to pre-industrial levels (UNFCCC, 2009), although opinions differ on the acceptable level of risks, preferred mitigation strategies and the distribution of costs. Scenario studies indicate that, globally, emission reductions in the order of 35-80% by 2050 are needed in order to be consistent with this target (e.g. Rogelj et al. (2011) and Van Vuuren and Riahi, (2010)). Such reductions cannot be achieved without significant contributions from all major greenhouse gas emitting countries, which raises questions concerning the different emission reduction strategies in major economies (Clarke et al. 2009). So far, most of the literature on scenarios has focused on globally coordinated responses, in particular on the consequences of climate policy at the global level or for large aggregated regions (van Vuuren et al., 2012). However, the Copenhagen Conference and subsequent UNFCCC dialogues have not led to a comprehensive and long-term multilateral agreement on emission limitation and reduction commitments. Given the present fragmentation in global climate action, the exploration of the role of national strategies across different economies and the implications of delayed global action have become more important (Bertram et al., submitted; Bosetti et al., 2008; Luderer et al., submitted)

This paper presents a comparative analysis focusing on long-term mitigation efforts across five major economies, including the USA, the European Union (EU), Japan, China and India, based on a multi-model scenario analysis oriented towards the 2°C target. The use of multiple models allows us to estimate the robustness of these responses. The analysis discusses two key mitigation scenarios, both starting from a fragmented policy approach, namely the implementation of the national pledges according to the Copenhagen Accords until 2020. The first scenario extends the 2020 pledges by a similar level of ambition in the subsequent decades. The second scenario increases the mitigation ambition after 2020 by assuming a global carbon market aimed at the 2°C climate stabilization target.

The paper is structured as follows: section 2 describes the scenario and data used for this study. Section 3 discusses scenario results, addressing differences between both scenarios and the models included in the analysis. The focus is on national mitigation efforts, sectoral changes and changes in electricity production. Section 4 discusses the results followed by overall conclusions in Section 5.

2. Scenarios and data

The scenarios that are used in this paper are based on different policy assumptions for long-term international climate policy (see Table 1) and have been developed as part of the LIMITS project. The baseline (*Base*) scenario addresses the future energy system and emission developments in the absence of climate policy. The fragmented policy scenario (*RefPol*) is based on formulated 2020 national energy and climate targets reflecting the unconditional Copenhagen pledges. The scenario is extended after 2020 by assuming a similar national effort in the subsequent decades (see Table 2). Finally, the delayed global cooperation scenario (*RefPol-450*) mimics the *RefPol* scenario until 2020, and thereafter all regions adopt the long-term 2.8 W/m² radiative forcing target, consistent with a high likelihood (>70%) of staying within 2°C temperature increase, as a binding commitment for joint mitigation action. Implementation of the target is achieved via a global (harmonized) carbon tax. This scenario can be used to obtain information on attractive strategies at the regional level.

The 2020 targets in the *RefPol* and *RefPol-450* scenarios include capacity and renewable energy share targets as well as greenhouse gas (GHG) emission reduction and intensity targets (see table 2). Given the uncertainty in the actual interpretation of the pledges, the targets reflect the lower end of the Copenhagen pledges for plausibility considerations (Kriegler et al., this issue). As such, the European GHG emission reduction target is based on the unconditional pledge of 20% in 2020 relative to 1990 levels, recalculated to reflect 2005 as a base year. Similarly for China and India, who pledged to reduce their emission intensity by respectively a range of 40-45% and 20-25% by 2020 (Townshend et al., 2011), the lower end of their pledge has been included in this study. In the case of Japan the ambition level for GHG emission reductions has been set at the unconditional Kyoto Protocol target (-6%) rather than the conditional Copenhagen target (of -25% relative to 1990 levels) (UNFCCC, 2011) – and has been amended downward to -1% to account for policy changes after the Fukushima incident in 2011¹. The USA target reflects the general Kyoto Protocol target for industrialized countries. The level of stringency in these 2020 ambitions is extrapolated thereafter until the end of the model time horizon in the form of an annual greenhouse gas intensity reduction rate calculated for Kyoto GHG equivalent emissions including land-use, land-use change and forestry (LULUCF).

¹ The policy tendencies after the Fukushima incident are based on calculations from the Japanese National Institute of Environmental Science (NIES) and the Research Institute of Innovative Technology for the Earth (RITE)

Table 1 - Scenario definitions ^{*1}

Scenario name	Abbreviation	Explanation
Baseline	Base	No climate policy baseline
Fragmented policy baseline	RefPol	Regional policy reflecting the Copenhagen pledges of individual countries for 2020, and a fixed regional greenhouse gas intensity reduction percentage afterwards based on the current pledges.
Delayed global cooperative action	RefPol-450	Radiative forcing target of 2.8 W/m ² in 2100, with RefPol (fragmented) policy reflecting the Copenhagen pledges of individual countries prior to global cooperation in 2020.

^{*1} See Kriegler et al. (this issue) for a more detailed description of the scenarios.

^{*2} The policy target assumed for the depicted scenarios refers to the aggregate radiative forcing from the following substances: Kyoto gases (CO₂, CH₄, N₂O, HFCs, PFCs, SF₆), Non-Kyoto gases (substances controlled under the Montreal protocol, i.e. chlorides, halons, bromine; tropospheric and stratospheric ozone; stratospheric water vapor), and aerosols (sulfate, black and organic carbon from fossil fuel and biomass burning, indirect aerosol forcing).

Table 2 - Regional climate policy targets for RefPol and RefPol-450^{*1}

Target in 2020	Unit	China	EU	India	Japan	USA
Across the board GHG emission reduction pledges	% (2005)		-15		-1	-5
GHG intensity reductions	%	40		20		
Modern renewable energy share in electricity production	%	25	20			13
Installed (renewable) energy capacity	GW wind	200		20	5	
	GW solar	50		10	28	
	GW nuclear	41		20		
Average GHG emission intensity improvements after 2020	% /yr	3.3	3	3.3	2.2	2.5

^{*1} See Kriegler et al. (this issue) or the Supplementary Online Material (SOM) for a more detailed description of the policy scenarios.

To get an indication of the robustness of the regional responses we use a multi-model approach, involving seven (global) models (AIM-Enduse: Kainuma et al. (2003) GCAM; Clarke et al. (2007); REMIND: Luderer et al. (2012); MESSAGE: Messner & Strubegger (1995); IMAGE: Bouwman et al. (2006); WITCH: Bosetti et al. (2006); TIAM-ECN: (Keppo and Zwaan, 2011)) which differ in model characteristics, coverage of sectors, disaggregation and definitions (economy wide or energy system) and baseline assumptions (see Table 3). As the sources of key parameters tend to vary (e.g. population and GDP growth projections) this will impact the relative mitigation potential per model (Clapp et al., 2009), but will also allow for the exploration of associated ranges of structural uncertainty and the robustness across a diversity of methodologies (Keppo and Zwaan, 2011). To incorporate outcomes of all models we limit the analysis to 2005-2050 but for models that have a time horizon up to 2100 we extend the timescale for trend analysis of key drivers. When model outcomes overlap we assume modeling consensus, in which case the relative position of individual models is considered less relevant. Clearly deviating model behaviour is seen in 'outlier' values. Results for the world region are included as a weighted average.

Table 3 - key model characteristics

Name	Time horizon	Model category	Intertemporal Solution Methodology
AIM-ENDUSE	2050	Partial equilibrium	Recursive dynamic
GCAM	2100	Partial equilibrium	Recursive dynamic
IMAGE	2100	Partial equilibrium	Recursive dynamic
MESSAGE	2100	General equilibrium	Intertemporal optimization
REMIND	2100	General equilibrium	Intertemporal optimization
TIAM-ECN	2100	Partial equilibrium	Intertemporal optimization
WITCH	2100	General equilibrium	Intertemporal optimization

3. Results

3.1 Mitigation efforts

Trends in major drivers of emissions

Population and income are major drivers of CO₂ emission growth in the absence of climate policy. Models differ with respect to population and GDP assumptions as a result of varying statistical data sources, base year and methods for accounting (Chaturvedi et al., 2012), creating a band that can be seen in figure 1a-b. For population, India and the USA show a rapid increase in population size in the 2010-2050 period. After 2050, growth rates in both regions are considerably reduced, resulting in a declining population in all models for India and in diverging trends for the USA. In China and the EU population growth stagnates by 2050, followed by a decline. For Japan, the population is projected to decline in all models throughout the whole century. In China, EU and Japan, the projected 2100 population is below the 2005 level. For income, there is a clear distinction between the developing countries and industrialized regions. The average growth rate for India and China is rapid in the short term (respectively 7-8% and 8-9% per year). In contrast, in the EU, Japan and the USA the growth rate is only 1-2% per year (Figure 1b).

It should be noted that socioeconomic trends are exogenous inputs derived from sources independent of the integrated assessment models, hence trends are equal in every scenario and show no relation to the implemented climate policy. MESSAGE is found to adopt both higher relative and absolute values for population in China, EU and India compared to other models, which may have a noticeable effect on the available abatement potential under 2°C constraints. For GDP growth we find IMAGE to be relatively optimistic in both relative and absolute terms for China, EU and India. The implications of this are not clear, since the literature is inconclusive concerning the possible implications of rapid economic development for meeting the radiative forcing target (van Vuuren et al., 2012).

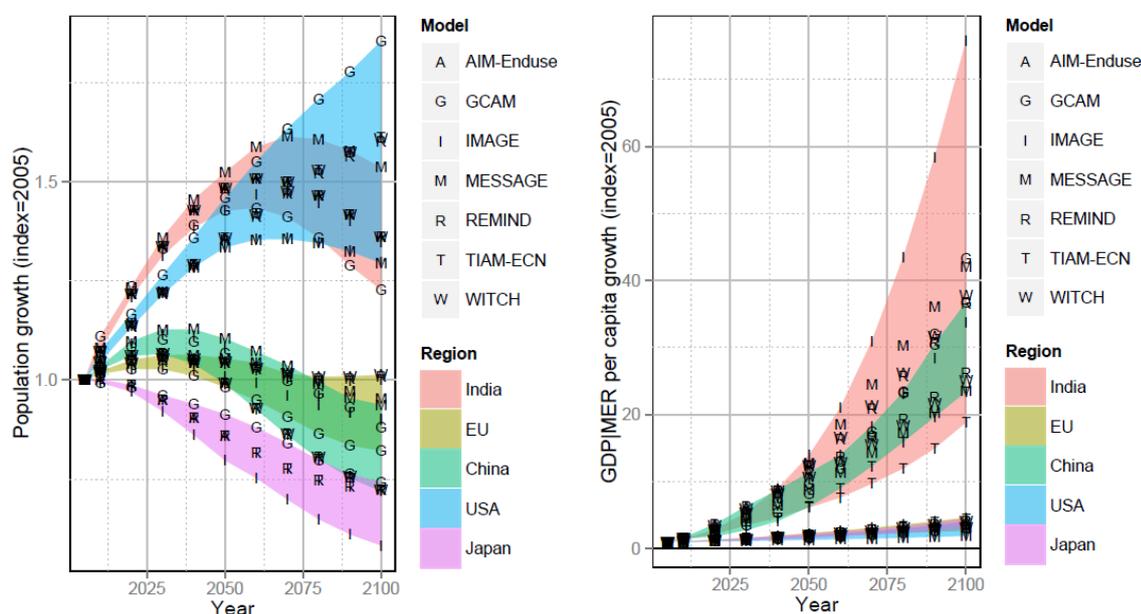


Figure 1 - (a-b) Indexed growth figures of population and GDP (MER) per capita of all the considered regions.

Trends in CO₂ emissions

Figure 2 shows the regional emission projections for all three scenarios. Baseline CO₂ emissions are generally projected to gradually increase for all regions and most models show either a peak or stabilization in the second half of the century. Only the WITCH and TIAM-ECN models depict constant growth throughout the century in nearly all regions.

The short term targets included in the RefPol scenario (reflecting the Copenhagen pledges) lead to emission reductions compared to the baseline scenario in all regions. The level of emission reduction differs strongly across regions. While in India and China the 2020 commitments lead to noteworthy reductions compared to baseline, emissions are still projected to increase and reach a peak near 2050 in China, and later in India. This is in contrast to the EU, Japan and the USA, for which the Copenhagen commitments are projected to lead to immediate decreasing emission pathways. In fact, the difference between the EU ambition level in the RefPol scenario and in the RefPol-450 scenario is small, implying that the assumed policies for the EU in the RefPol scenario aim for emission reductions that seem to be in line with the 2°C target (Clapp et al., 2009).

It should be noted that for China and India the RefPol-450 emission trajectory peaks immediately after 2020. For the high income regions the RefPol-450 emissions need to be more than halved by 2050 compared to 2005 levels. All economies and models show that negative emissions are needed near the end of the century to reach the 2°C stabilization target.

As described earlier, the assumptions concerning socioeconomic development are considered to be important drivers of total emissions. However, the results show that clearly deviating assumptions (e.g. population in relative and absolute terms in China for MESSAGE and the USA for GCAM) do not necessarily define the borders of the outcome space but lead to outcomes that remain more or less within the range of future (baseline) emissions. In the reference scenario most regions show a significantly larger range of possible outcomes than in the mitigation scenarios. This is due to the interplay of various fundamental processes and different base-year values for key metrics (Chaturvedi et al., 2012; Edenhofer et al., 2010) in the reference scenario and due to the unanimous shift to (vigorous) mitigation options that lower energy demand across all regions (van Vuuren et al., 2012) in the mitigation scenarios.

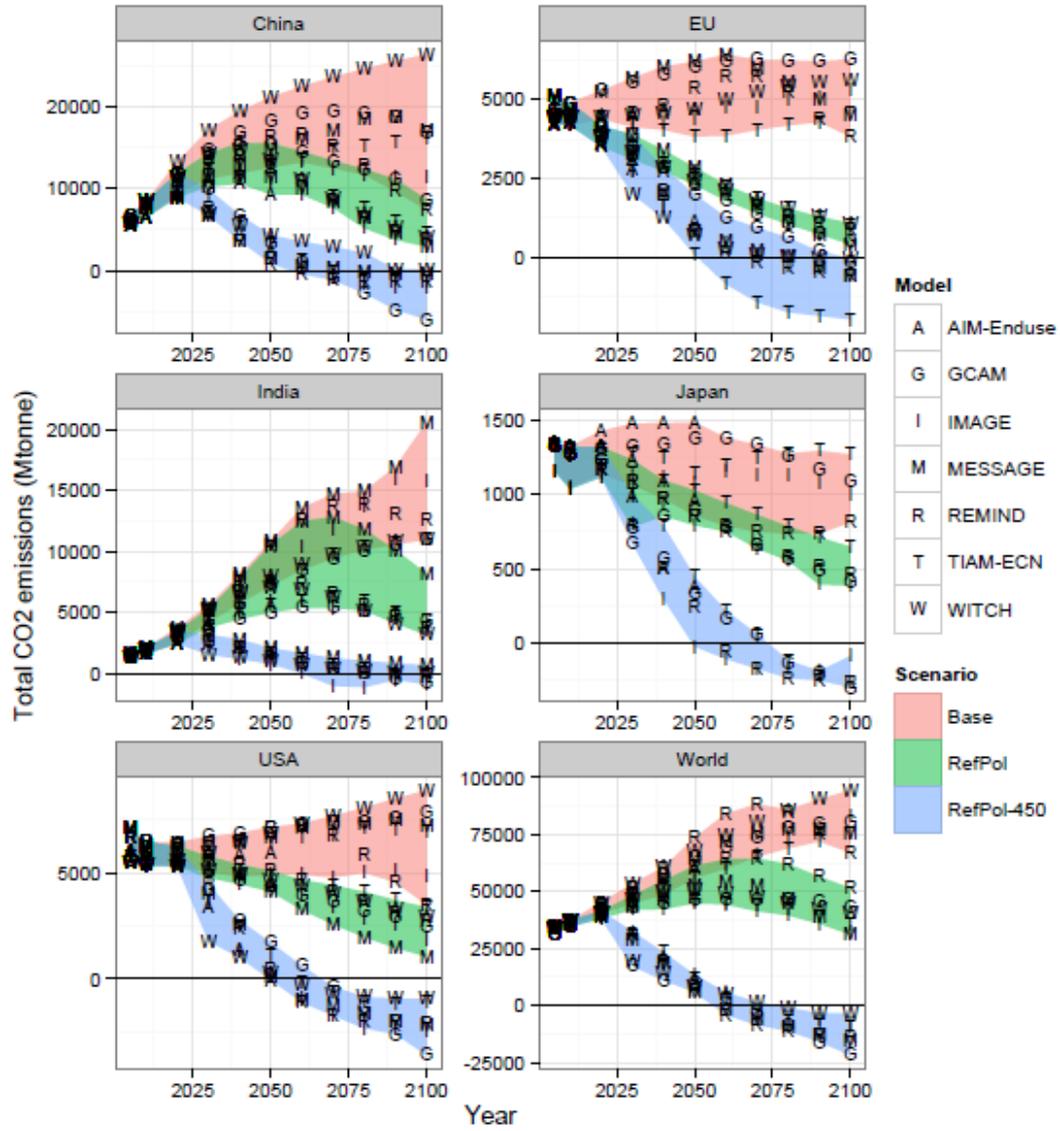


Figure 2 – Total CO₂ emission paths of the no policy baseline (red), RefPol (green), Refpol-450 (blue) scenarios over the 2005-2100 period.

In order to achieve the 2°C climate stabilization target a sustained global annual CO₂ emission reduction rate of approximately 2%-5% is required for all regions between 2020 and 2050, which is in contrast to the 1-2% sustained annual emission reduction rate under RefPol circumstances for developed regions and the emission increase in developing regions (see Figure 3). Reduction rates of this order are considered as extremely rapid and well beyond rates known in history and require much greater mitigation efforts than projected under current Copenhagen Accord pledges (see Van Vuuren and Stehfest, 2013). In the USA the relatively rapid increase in population results in a projection that requires greater efforts relative to the RefPol scenario. The differences between India and China in Figure 3 are related to future projections of rapid economic change and the rate of capital stock turnover in the energy production sector (Lucas et al., submitted).

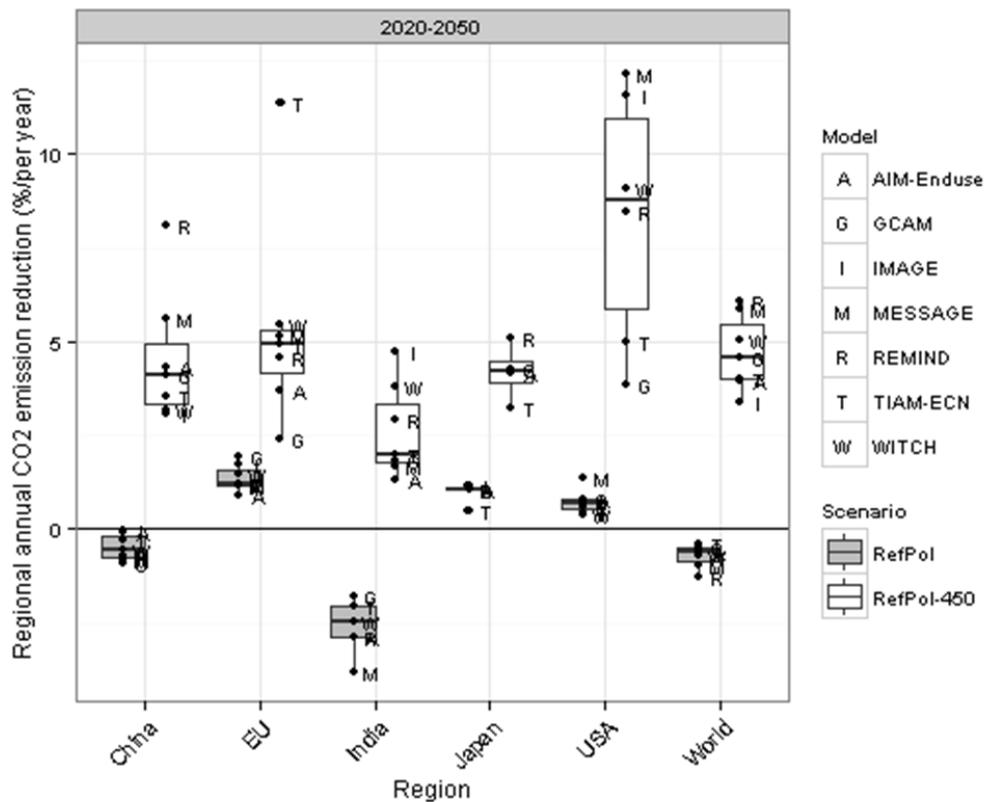


Figure 3 - Average CO₂ emission reduction rate per year between 2020-2050. Negative CO₂ emission reductions indicate emission growth.

3.2 Emission decomposition

We apply the Kaya-identity (Kaya, 1990) to examine the regional contribution to CO₂ emissions reductions of changes in efficiency and consumption patterns (energy intensity) and of changes in the choice of energy carriers (carbon factor). For further elaboration on the calculation the reader is referred to Steckel et al. (2011) and Zhang et al. (2009). It appears that in all regions decarbonization is the leading strategy and the level of climate policy determines to which extent this occurs. However, it should be noted that the emission reductions shown in Figure 4 are relative to the no policy baseline scenario, which implicitly entails some bias as the reference scenario encompasses a degree of autonomous efficiency improvements whereas the carbon factor remains unchanged. In India and China the reduction of emissions through energy efficiency is projected to play a larger role. This can be explained by looking at the absolute values for carbon intensity and energy intensity. The data show that in 2050 the carbon intensity is at a similar level for all regions (near 60 kg/GJ), whereas the energy intensity can still be reduced by a factor of 4-6 in the developing regions.

Another type of bias can be observed in the model types present in this study, as earlier studies (Johansson et al., in prep; van Vuuren et al., 2009) argue that CGE/econometric models (top-down) show more demand side changes than energy-system models (bottom-up) and therefore favour energy savings. In this study this tendency is apparent as well since the WITCH model (a hybrid energy system and economic growth model) shows a greater preference for energy efficiency solutions (particularly in China, as shown in figure 3), whereas more strongly technology based (bottom-up) models (such as AIM-Enduse, GCAM and TIAM-ECN) generally show more carbon intensity reductions.

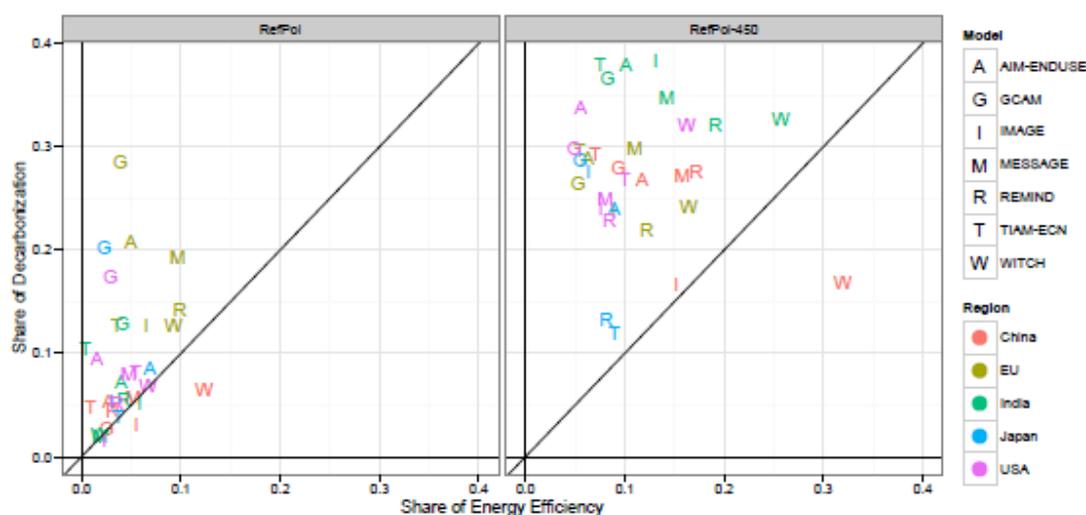


Figure 4 – Decomposition of regional emission reductions relative to Base emissions, axes depict the share of a strategy in total emission reductions between 2005-2050 for the RefPol and RefPol-450 approach.

3.3 Sectoral emission changes

By zooming in to the sectoral level (Figure 5), it can be observed that the energy production sector (combining power and heat supply, extraction, transformation and distribution) is projected to contribute the most to emission reductions in all regions and models in a 2°C regime, which can be explained by the large amount of greenhouse gas emissions for this sector, the relatively large potential for emission reduction (including technologies such as CCS, nuclear

power and renewables) and the possibility for 'negative emissions' (through combining biofuels with CCS) (Hallding et al., 2011; Van Vuuren et al., 2009). For the EU, models agree that the additional emission reductions in the energy production sector are limited as projections of Copenhagen or 2°C ambitions show similar emission reductions in this sector in the short term. In contrast, the emission reduction in emerging regions such as China and India is larger as 2°C ambitions diverge from the reference scenario to a greater extent. A considerable spread in outcomes can be seen across the models, yet models that project higher baseline emissions (Figure 2) consistently report higher emission reductions as well (e.g. WITCH and REMIND).

Changes in the end-use sectors (including industry, transport, residential and commercial and other sectors) typically contribute 10-20% of total emission reductions in the RefPol-450 scenario. No systematic differences in reduction percentages across the different regions can be observed (despite the expectation of higher reduction rates in India and China as a result of reportedly lower levels of end-use efficiency). In the results, some differences between the models can be noted, with relatively high reduction rates in MESSAGE and AIM-Enduse, possibly caused by greater detail in end-use sector systematic in these models. In GCAM and REMIND relatively lower rates are observed, which is partly due to higher decarbonization rates in the energy production (both REMIND and GCAM) and land use (GCAM) sectors, reducing the relative contribution of the end-use sector in the mitigation strategy.

Not all models report emission reductions from land use, land-use change and forestry (LULUCF) measures (GCAM alone reports consistently LULUCF emission reductions for each region). The results suggest a limited abatement potential, i.e. up to 10% emission reduction relative to cumulative baseline emissions for both climate policy scenarios. In fact, the contribution of this category is lower in the RefPol-450 scenario than in the RefPol scenario, showing that emission savings from LULUCF measures might be offset by the increasing need for bioenergy and CCS under strict climate policies (see. Calvin et al., this issue, Wise et al., 2009). GCAM's greater projected LULUCF abatement potential in the EU and USA is directly linked to the explicit implemented policies that incentivize afforestation. For Japan, the potential for emission reductions from land-use change and forestry is argued to be too low to justify developing explicit abatement policies (OECD, 2010).

Non-CO₂ sources, although considered a relatively important short to medium term mitigation option (Rao and Riahi, 2006; Lucas et al. 2007; Elzen et al. 2008), appear to have limited abatement potential for all regions by 2050, ranging around 5-10% of total cumulative emission reductions relative to the baseline. China, India and the USA show the largest greenhouse gas abatement potential through non-CO₂ emission reductions, whereas the non-CO₂ abatement potential is considered negligible for Japan.

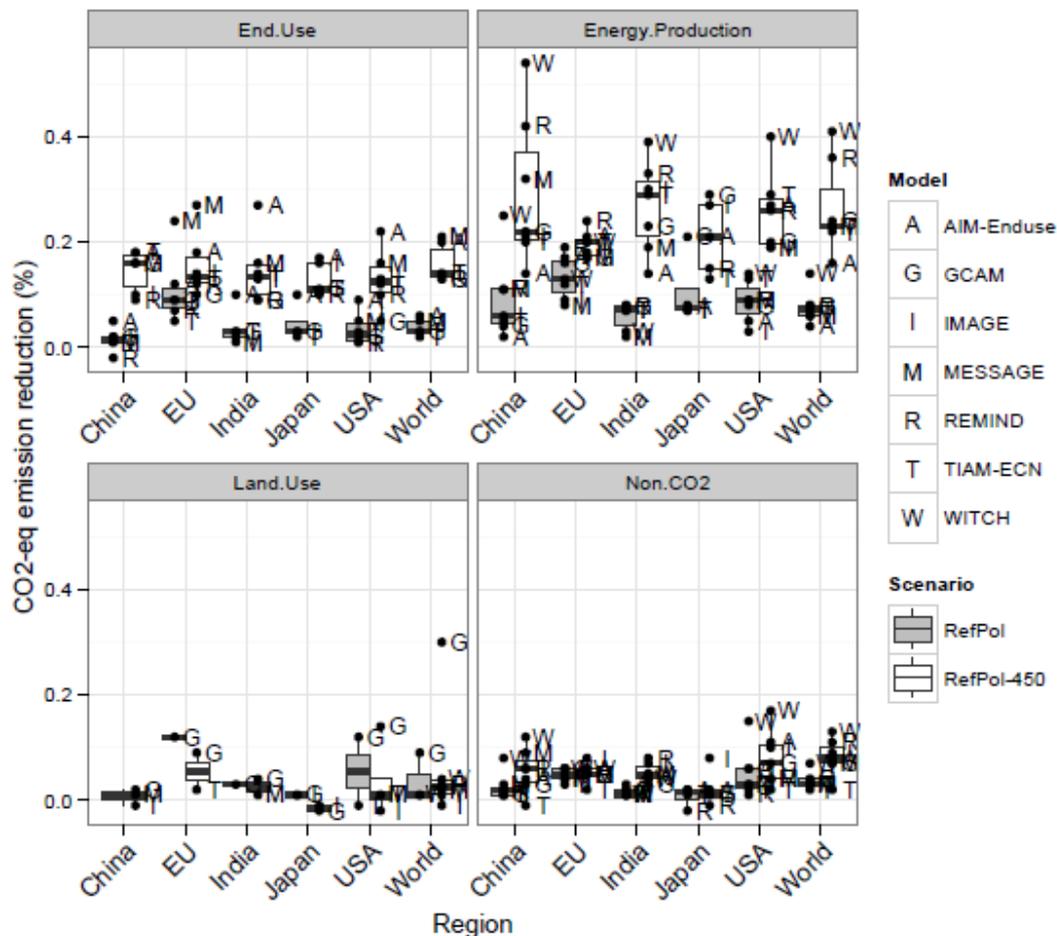


Figure 5 (a-f) – Reduction percentage of cumulative emissions between 2005 and 2050 for the RefPol and RefPol-450 scenarios, compared to the baseline scenario in different sectors. Energy supply covers CO₂ emissions from power and heat generation, other energy conversion (e.g. refineries, synfuel production), resource extraction and energy transmission and distribution (e.g. gas pipelines). Energy end-use sectors encompass the industry, residential and commercial, transportation and other sectors. Land-use encompasses net carbon dioxide emissions from all categories of land use and land-use change (e.g. pasture conversion, deforestation, afforestation, reforestation, soil management, etc.). Non-CO₂ emissions encompass residual Kyoto gas emissions (CH₄, N₂O and F-gases) of all the former described sectors.

Looking at emission reductions in subsectors of the end-use sector, we observe that the industry sector (including feedstocks, agriculture and fishery) is the main source for abatement in China and India, whereas the USA and the EU achieve significant emission reductions through measures in the transport sector (see Figure 6). Japan forms an exception among developed regions, which could be explained by the high level of energy efficiency already implemented in the Japanese transport sector (Lipsy and Schipper, 2013). Transportation abatement is smaller in GCAM than in other models due to the abundance of other low cost mitigation measures (e.g. LULUCF, bioenergy with CCS). In all regions, as the contribution of industry to total end-use sector emission reduction increases, emission reductions from other end-use sectors become less important. The residential and commercial sector

shows a marginal contribution to the regional abatement potential for all regions, except for a single result by TIAM-ECN for China.

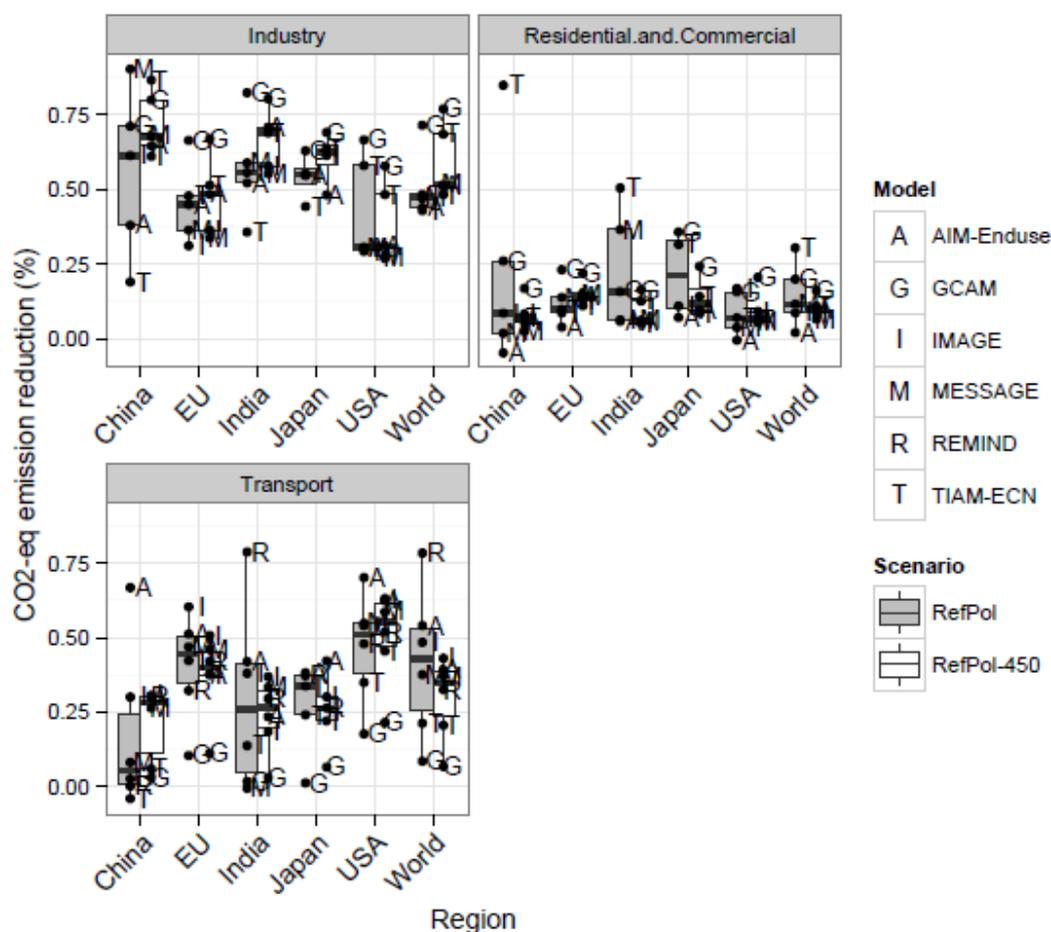


Figure 6 – Emission reductions shares per end-use-sector, reductions are relative to total end-use abatement potential compared to baseline emission reductions (indicating relative importance of the abatement potential of a sector within the aggregated energy end use category)

3.4 Changes in electricity production

In the previous section, in all regions the energy supply sector is shown to have the largest potential for emission reductions. Here, we examine the changes in electricity production in detail. Figure 7 shows the percentage of electricity production from different electricity generation technologies in 2050 in specific regions for the two mitigation scenarios. Several regional patterns can be identified in the figure:

- In terms of coal-based electricity production, the Chinese and Indian regions show the largest fraction of coal energy use in RefPol, due to the large available reserves (Garg and Shukla, 2009; Halding et al., 2011; Shukla and Chaturvedi, 2012). Coal also makes a substantial contribution to electricity production in Japan

and USA in the RefPol scenario but with considerable spread across the models. The EU generally has a lower fraction of coal and a higher fraction of natural gas and nuclear electricity (but with little consensus among the various models). The RefPol-450 scenario shows that, with the introduction of a global carbon tax, coal-based electricity production decreases drastically over time regardless of the model or region.

- Natural gas plays a key role in the power systems of the USA and Japan and to some degree in the other three regions in the RefPol scenario. This contribution is significantly reduced in the 2°C scenario and is eventually to be phased out, albeit later than coal, at the end of the century.
- Fossil fuels combined with CCS technologies are important in most regions, particularly coal w/CCS in India, for which the bandwidth of reported model outcomes is relatively small, thus implying modeling consensus. For China, however, only GCAM reports a high share of coal w/CCS compared to other models, which can be explained by the high capture rates assumed in the model. In the RefPol scenario, CCS technology is almost exclusively used in the EU as in other regions the policies are seemingly not ambitious enough to make CCS attractive. The use of biomass for electricity production without CCS is limited for most regions, but is more commonly applied in combination with CCS (BECCS) in all regions and all models in the case of the 2°C scenario. Shares of BECCS are higher in USA, China and the EU, most likely because these regions have a better access to biomass feedstock.
- No clear transition strategy can be extracted from the renewable energy production and nuclear energy use plots as there is a high diversity in model outcomes for low-carbon and clean technology deployment (see also Zwaan et al., this issue). However, nearly all regions show a 2-3 fold increase of the (non-biomass) renewable energy share in electricity production. Nuclear energy use increases on average, but more conservatively for all regions except China, hence making it an important technology towards a 2°C transition. Consensus exists for Japan, showing greater dependence on nuclear energy production due to limited renewable energy potential, implying limited alteration in the national strategic energy plan of Japan as designed prior to the Fukushima nuclear incident.

In general it can be concluded that in the RefPol scenario, in 2050, the electricity system in China and India will rely mostly on coal and gas, therefore leading to a higher carbon content in electricity for these regions; whereas the electricity mix in the EU, USA and Japan has shifted to a greater reliance on nuclear and non-biomass renewable energy. If the 2°C climate stabilization target is to be achieved, China and India's electricity systems must urgently start the shift away from coal dependency, albeit with different transition strategies. In the projections India employs CCS to prolong fossil fuel use, whereas China replaces coal with alternative carbon-neutral and carbon removal technologies. For other, developed, regions, a greater effort is required to stay in line with the 2°C climate stabilization target, which will be further discussed in the next paragraph.

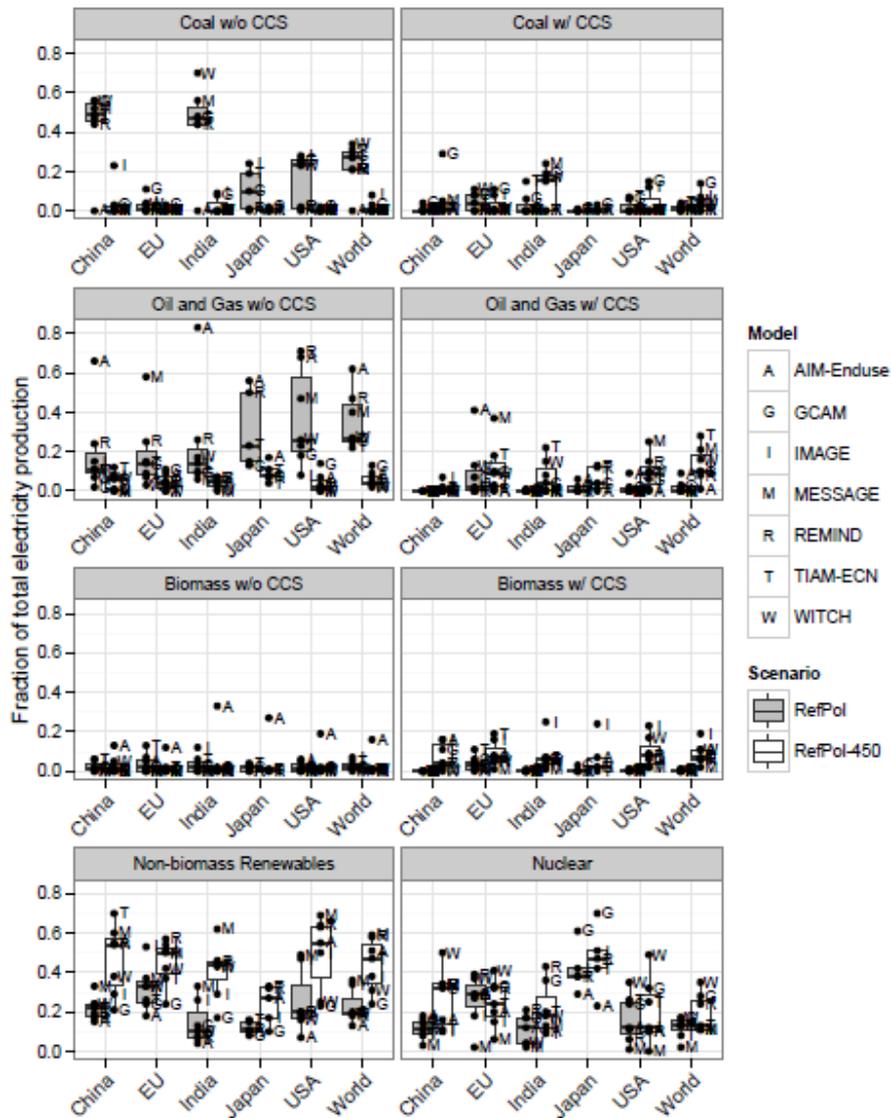


Figure 7: Fraction of electricity production for major and upcoming regions in 2050 in RefPol and Refpol-450 scenario (Non-biomass Renewables: PV, CSP (concentrated solar power), on- and offshore wind and hydropower; CCS: Carbon Capture and Storage)

4. Discussion

Integrated assessment models are useful tools to help understand the consequences of decision-makers' actions, through providing quantitative information about possible pathways for economic, social and environmental developments under different circumstances. In this study, the designed scenarios have been based on formulated 2020 national energy and climate targets, reflecting unconditional Copenhagen pledges or amended Copenhagen pledges to account for restraining occurrences in specific regions. In order to look further into the consequences of

current 2020 commitments, we consider a limited set of policy relevant indicators to discuss the projected and required regional mitigation efforts (see Table 4):

- For Europe, the reference scenario includes the targets of 20% emission reductions, 20% share of renewable energy and 20% more energy efficiency by 2020 (relative to 1990 levels, as part of the Europe 2020 strategy) (see also IEA, 2012). This strategy implies an annual emission reduction rate of 1-2% till 2020. However this commitment, or the continuation of such rate of change after 2020, shows to be insufficient as a 2-11% emission reduction per annum is more likely to stay in line with 2°C ambitions. Moreover, energy efficiency needs to improve at a faster rate while doubling the 2020 renewable energy deployment rate by 2050.
- In the US, several sectoral and state level policies have currently been implemented (such as regional cap-and-trade programs, renewable portfolio standards and, to a smaller degree, feed-in tariffs at a state level) yet a long-term (federal) commitment is missing (Schuman and Lin, 2012). In the reference scenario this translates to an emission reduction of around 1% per annum till 2020. In a 2°C scenario this requires a much higher annual emission reduction rate (of 4-12% per year depending on the model) in subsequent years till 2050. Some models even suggest lower per capita emissions for the USA than in other OECD regions in 2050, resulting from the available potential for CCS, renewable energy and bio-energy (especially CCS use is much higher than in other regions).
- As Japan has formally committed itself to a conditional pledge of 25% of emission reductions relative to 2005 (conditional to the participation of all major economies)(UNFCCC, 2011), an consistent annual emission reduction rate of 2% would be minimally required to comply to this 2020 target. Although this rate is much higher than currently assumed in the reference scenario (accounting for possible revised nuclear policies in Japan), it still shows to be misaligned with 2°C ambitions. After 2020, a more rapid annual decrease in emissions is required regardless of the considered commitment. Furthermore, the results also suggest that nuclear power will play a significant role in reducing emissions in Japan. However, since the Fukushima accident, several initiatives to reduce the reliance on nuclear energy have been proposed (e.g. achieved through more renewable energy, greater energy efficiency improvements, reforms in energy systems and a (restrained) increase in fossil-fuel generated energy) which may lead to the sacrifice of nationally pledged climate change goals (National Policy Unit, 2013). The combination of both an inadequate emission reduction commitment and a diverging mitigation strategy may thus lead to a bigger post-2020 challenge for Japan than currently anticipated.
- In the 2°C scenario, Chinese emissions would more-or-less peak in 2020 followed by a decline. In order to follow this pathway, China needs to maintain a similar annual emission intensity reduction rate of 4% as committed to in the Copenhagen pledges and extend this rate till 2050. This requires a major energy transition, surpassing the non-hydro renewables generation of regions like the USA and EU by 2025-2030 to fulfill its future energy demand.
- A similar pattern is observed for India, as emissions are projected to peak and decline in the first half of the century while returning to 2005 emission levels no sooner than 2050 in the 2°C scenario. However, unlike China, current efforts are found to be inconsistent with 2°C ambitions, as the emission intensity improvement committed to in the Copenhagen Accord is slightly below the value that is needed (currently describing a constant annual emission intensity reduction of 2.9% till 2020, whereas at least 3.4% is needed till 2050). As less 'easy' reduction options will be available and increasing economic growth is expected, this will represent a clear challenge for India. Moreover, per capita emissions in India are projected to remain significantly below the OECD average (which could be very important in the context of proposals on emission allocation and financing).

Table 4 thus emphasizes that significant emission reductions are needed in all regions, yet more rapid changes than currently described in the Copenhagen commitments are required per region. For the three high-income regions this implies that emissions need to be reduced more rapidly than accounted for in the 2020 commitments, whereas a turnaround in emission trajectories and faster decarbonization rates are required for China and India. Lastly, it should

be noted that some evidence in earlier studies suggest that global assessment models are more optimistic about emission reductions and technological developments than national models (either due to better representation of national policies or assumed higher economic growth), possibly implying even greater regional challenges than described in this paper (Chen et al., submitted; Johansson et al., in prep; Yang et al., 2011).

Policy consequences of current model projections

Another policy implication relates to the wide variation in the future portfolio choice among nuclear, CCS and non-biomass renewables across the models. For example, models that assume a greater scope for bioenergy, or the combination of bioenergy and CCS, allow regions with high application rates (such as the USA and EU) to rely heavily on the assumed technologies. As negative emission technologies will specifically play a key role in the second half of the century (considering how net negative emissions will be achieved in the 2060-2080 period in developed regions and no sooner than 2080-2100 in developing regions), it implies that global and local decisions made today will partly be based on our expectations of long-term technology developments over multiple decades.

Other factors that are not explicitly modeled may also influence the choices for available future energy portfolios, such as technological constraints, geopolitical limitations and suboptimal policies. For example, the depicted rapid growth in renewable energy production in the scenarios (45-55% by 2050 relative to 2005 across every region except Japan) will be very challenging in all regions given the intermittency of these resources, but even more so in developing regions due to the poor current infrastructure, the slower market signals and lack of conducive renewable energy push policies (Hong et al., 2013; Shukla and Chaturvedi, 2011; Shukla et al., 2007). Interesting in this context are also the expectations on economic growth. Economic stagnation may dampen the available resources and thus endanger the continuity of policies, creating suboptimal policies in the long run. The European Union, for instance, suffers from the impact of the economic crisis on the emission trading scheme, and has also abandoned subsidy programs and postponed planned investments in long-term infrastructure (Townshend et al., 2011). The effect of inconsistencies in climate mitigation policies has also been particularly critical for the renewable technology investment climate in the USA, causing boom and bust cycles over time (IEA, 2012).

Table 4 – Quantitative overview table of the median and the bandwidth of modeled regional outcomes

Policy relevance	Scenario	Unit	China	EU	India	Japan	USA
GHG emission reduction relative to 2005	RefPol	%2030	-88 (-127 - -63)	25 (22-29)	-129 (-218 - -108)	13 (7-39)	11 (10-20)
		%2050	-79 (-103 - -52)	44 (35-47)	-243 (-334 - -174)	31 (28-33)	22 (18-38)
	RefPol-450	%2030	-14 (-41 - -8)	33 (17-49)	-63 (-87 - -20)	33(25-48)	37 (26-64)
		%2050	45 (25-72)	74 (51-77)	-15 (-56-30)	74 (69-96)	86 (61-90)
GHG emission intensity relative to 2005	RefPol	%2030	38 (32-66)	62 (57-79)	46 (36-57)	76 (62-89)	64 (57-70)
		%2050	23 (20-33)	50 (42-66)	25 (22-44)	59 (45-68)	47 (38-51)
	RefPol-450	%2030	27 (23-57)	58 (47-78)	35 (27-51)	70 (53-84)	55 (43-67)
		%2050	17 (12-29)	47 (30-61)	21 (11-38)	54 (37-60)	40 (26-46)
Per capita CO ₂ emissions	RefPol	tCO ₂ /cap2030	8.4 (6.2-10.1)	6.2 (5.8-6.8)	2.6 (2.5-3.4)	9 (6-10)	14 (13-16)
		tCO ₂ /cap2050	9 (7-10)	5 (4-5)	4 (3-5)	8 (8-9)	11 (9-13)
	RefPol-450	tCO ₂ /cap2030	5.1 (4.1-6.3)	5.2 (3.8-6.4)	1.7 (1.0-2.0)	6.8 (5.4-8.3)	9.8 (4.9-12.3)
		tCO ₂ /cap2050	2.2 (0.7-3.3)	1.6 (0.1-3.4)	0.9 (0.5-1.1)	2.9 (-0.2 – 4.1)	0.8 (-0.1 – 3.9)
Average annual CO ₂ reduction rate 2020-2050	RefPol	%	-1 (-1-0)	1 (1-2)	-2 (-4 - -2)	1	-1 (-1 – 0)
	RefPol-450	%	4 (3-8)	5 (2-11)	2 (1-5)	4 (3-5)	9 (4-12)
Peak year emissions	RefPol	Mt CO ₂ eq	2030-2045	<2005	2045-2070	<2005-2020	<2005
	RefPol-450	Mt CO ₂ eq	2020	<2005	2020	<2005-2020	<2005
Negative GHG emissions	RefPol	Mt CO ₂ eq	>2100	>2100	>2100	>2100	>2100
	RefPol-450	Mt CO ₂ eq	2080->2100	2100	2070->2100	2060-2080	2060-2080

Year of CCS application	RefPol	Year	2030-2070	2020-2035	2030-2070	2020-2050	2020-2050
	RefPol-450	Year	2020-2070	2020-2025	2020-2025	2025	2020-2025
Share of non-biomass renewable energy in electricity production	RefPol	%2030	22 (19-28)	40 (26-47)	12 (6-19)	15 (9-15)	14 (6-30)
		%2050	22 (15-33)	33 (18-53)	10 (4-33)	13 (8-16)	20 (7-49)
	RefPol-450	%2030	30 (26-38)	40 (28-47)	20 (15-37)	16 (11-27)	25 (18-38)
		%2050	54 (21-70)	50 (24-57)	44 (17-62)	29 (10-33)	55 (23-69)
Share of CCS in total fossil fuels and industry CO ₂ emissions	RefPol	%2030	0	1 (0-4)	0 (0-1)	0 (0-1)	0 (0-2)
		%2050	3 (0-6)	20 (15-26)	1 (0-10)	1 (0-9)	5 (0-10)
	RefPol-450	%2030	2 (0-6)	6 (2-17)	6 (2-37)	2 (1-5)	4 (3-27)
		%2050	49 (0-65)	47 (36-91)	47 (5-78)	35 (23-82)	78 (44-103)
Share of Nuclear energy in electricity production	RefPol	%2030	6 (5-9)	23 (19-27)	7 (3-10)	31 (26-55)	17 (10-27)
		%2050	10 (3-16)	29 (2-39)	12 (2-21)	38 (29-62)	12 (1-35)
	RefPol-450	%2030	13 (9-33)	24 (15-40)	12 (8-23)	36 (27-57)	21 (11-54)
		%2050	33 (10-50)	24 (6-41)	18 (9-43)	44 (23-70)	12 (0-49)

5. Conclusions

In this paper we have identified trends in region specific responses to climate policy by looking at the results of a multi-model scenario study. The analysis is based on (1) a reference scenario assuming policy implementation of Copenhagen Accord pledges followed by similar mitigation action after 2020 and (2) a scenario that assumes strengthening of regional action after 2020 in order to reach the 2°C target (assuming an international carbon market). The main conclusions of this analysis are:

Optimal reduction pathways leading to the achievement of the 2°C target require greater energy system transformations compared to current policies in all regions after 2020.

The results indicate that without more stringent climate policy emissions in the assessed regions will not stay in line with the 2°C climate stabilization target. Emissions in India and China are projected to rise under unilateral climate ambitions, with an energy-related CO_{2-eq} emissions peak arriving no sooner than 2030. Due to the accelerating growth in socioeconomic indicators, developing regions face increasingly greater challenges over time. While the reference scenario in the EU, based on the pledged targets, leads to considerable emission reductions close in line with 2°C ambitions, further reaching reduction commitments are needed. In order to stay in line with the 2°C regime, the EU will be required to at least double its 2020 commitments in terms of renewable energy capacity by 2050. In the USA, as well as Japan, the rate of emission reduction in the reference scenario is lower than 1% per annum till 2020. For both regions this means that more rapid reductions are required in a 2°C regime after 2020 to compare to at least similar per capita levels as in Europe under increasing socioeconomic trends (USA) or to correct for possible changes to be made in the mitigation strategy (Japan).

Both similarities and differences in mitigation strategies are observed for all regions.

Putting in place a 2°C global climate stabilization target leads to an immediate inflection point in emission trajectories. Such a target requires a tripling or quadrupling of currently pledged mitigation efforts across each region. The results show that most emission reductions come from decarbonization of the energy supply sector in all regions and from the deployment of technologies with negative emissions in the second half of the century.

The most important response strategy observed in this study is the shift away from fossil-fuelled power plants without CCS towards renewable energy and carbon-neutral sources. This shift in energy production leads to a diversification of the energy supply sector in all regions, with some differences in terms of mitigation strategy per region. Two specific directions become apparent, namely prolonging fossil fuel consumption by coupling conventional methods with carbon storage technologies (India, USA) and rigorously shifting to carbon-neutral technologies and mostly renewables (China, EU) or nuclear power (Japan). Regions with access to large amounts of biomass, such as the USA, China and the EU, can make a trade-off between energy related emissions and land related emissions, as the use of bioenergy can lead to a net increase in land use emissions. Japan shows a distinct preference for the

expansion of nuclear power generation as its main mitigation strategy, despite the current reduced social acceptance of nuclear power accounted for in this study. This result is mainly due to supply constraints of other sources in the country. All regions are found to require power generation from all available renewable sources to fulfill future energy demand while substituting for conventional fossil fuelled power generation. In China, the expansion of renewable energy is very rapid and the countries' deployment rate is projected to surpass those of the USA and EU by 2025-2030. More stringent ambitions appear to extend the response capacity of the regions, rather than lead to deviating mitigation strategies.

The next most important abatement strategy is energy efficiency in end-use sectors, leading to considerable and more or less homogeneous emission reductions across all regions. Other mitigation strategies focusing on non-CO₂ emissions and land use emission can be considered as complementary response strategies as they contribute only marginally to the total emissions reductions for each region.

Models may show a tendency to favour a specific transition strategy in all regions.

In this study we used multiple models to examine regional response strategies. The results highlight the importance of the underlying assumptions and structure of each model. It can be seen that models have a tendency to favour specific response strategies in all regions, due to (1) their baseline assumptions (higher baseline emissions tend to result in more emission reductions being needed), (2) the model structure (which influences the level of decarbonization or efficiency improvement that can be achieved) or (3) the assumptions on technology developments (as models assuming a greater scope for specific technologies also project a greater reliance on the assumed technologies). Model comparison studies can expose these biases, but it should be noted that there can also be collective biases, for instance, in the abundance of lower cost mitigation measures in the energy supply sector, underestimating the available abatement potential in specific (end-use) sectors such as industry or transport.

Further in-depth research is recommended into the implications of inherent model differences, uncertainties and underlying assumptions influencing the outcome space in baseline as well as mitigation scenarios. For regional assessments, it is also recommended to include more detailed 'real world' challenges in the scenarios that take into account factors such as limited availability of resources, limited participation of regions, suboptimal design of policy instruments and other barriers to implementation.

References

- Bertram, C., Johnson, N., Luderer, G., Riahi, K., Isaac, M., Eom, J., n.d. Carbon Lock-in and Path Dependency associated with weak near-term climate policies. *Technological Forecasting and Social Change* Submitted.
- Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., Tavoni, M., 2006. WITCH: A World Induced Technical Change Hybrid Model. *The Energy Journal*, Special Issue: Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down.
- Bosetti, V., Carraro, C., Sgobbi, A., Tavoni, M., 2008. Delayed Participation of Developing Countries to Climate Agreements: Should Action in the EU and US be Postponed?
- Bouwman, A.F., Kram, T., Klein Goldewijk, K., 2006. Integrated modelling of global environmental change. An overview of IMAGE 2.4. Netherlands Environmental Assessment Agency. available at: www.mnp.nl/en, Bilthoven, The Netherlands.
- Calvin, K., Wise, M., Klein, D., Mccollum, D., Tavoni, M., Van Der Zwaan, B., Van Vuuren, D.P., 2013. A multi-model analysis of the regional and sectoral roles of bioenergy in near-term and long-term carbon mitigation 1–9.
- Chaturvedi, V., Waldhoff, S., Clarke, L., Fujimori, S., 2012. What are the starting points? Evaluating base-year assumptions in the Asian Modeling Exercise. *Energy Economics* 34, S261–S271.
- Chen, W., Yin, X., Zhang, H., n.d. Towards low carbon development: Findings from the China TIMES model. *Climatic Change*.
- Clapp, C., Karousakis, K., Buchner, B., Chateau, J., 2009. National and sectoral GHG mitigation potential: a comparison across models.
- Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., Tavoni, M., 2009. International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Economics* 31, S64–S81.
- Clarke, L., Kim, S.H., Edmonds, J.A., Dooley, J., 2007. Model Documentation for the MiniCAM Climate Change Science Program Stabilization Scenarios: CCSP Product 2.1a.
- Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Barros, V., Field, C.B., Zwicker, T., Schlömer, S., Ebi, K., Mastrandrea, M., Mach, K., Von Stechow, C., 2010. IPCC Workshop on Socio-Economic Scenarios.
- Elzen, M.G.J., Lucas, P.L., Vuuren, D.P. Van, 2008. Regional abatement action and costs under allocation schemes for emission allowances for achieving low CO₂-equivalent concentrations. *Climatic Change* 90, 243–268.
- Garg, A., Shukla, P.R., 2009. Coal and energy security for India: Role of carbon dioxide (CO₂) capture and storage (CCS). *Energy* 34, 1032–1041.
- Hallding, K., Olsson, M., Atteridge, A., Vihma, A., Carson, M., Román, M., 2011. Together Alone - BASIC countries and the climate change conundrum.
- Hong, L., Zhou, N., Fridley, D., Raczkowski, C., 2013. Assessment of China's renewable energy contribution during the 12th Five Year Plan. *Energy Policy* null.
- IEA, 2012. *World Energy Outlook 2012*.

- Johansson, D.J.A., Lucas, P.L., Weitzel, M., Ahlgren, E.O., Bazaz, A.B., n.d. Multi-model analyses of the economic and energy implications for China and India in a post-Kyoto climate regime 46, 1–57.
- Kainuma, M., Matsuoka, Y., Morita, T., 2003. Climate policy assessment, Asia-Pacific Integrated Modeling.
- Kaya, Y., 1990. Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios, Paper presented at the IPCC Energy and Industry Subgroup.
- Keppo, I., Zwaan, B., 2011. The Impact of Uncertainty in Climate Targets and CO₂ Storage Availability on Long-Term Emissions Abatement. *Environmental Modeling & Assessment* 17, 177–191.
- Kriegler, E., Tavoni, M., Aboumahboub, T., Luderer, G., Demaere, G., Krey, V., Riahi, K., Rosler, H., 2013. Can we still meet 2 °C with global climate action? The LIMITS study on implications of Durban Action Platform scenarios 1. *Climate Change Economics* 282846.
- Lipsy, P.Y., Schipper, L., 2013. Energy efficiency in the Japanese transport sector. *Energy Policy* In press.
- Lucas, P.L., Shukla, P.R., Chen, W., Dhar, S., Van Ruijven, B., Den Elzen, M.G.J., Van Vuuren, D.P., n.d. Implications of the international reduction pledges on long-term energy system changes and costs in China and India. *Energy Policy*.
- Lucas, P.L., van Vuuren, D.P., Olivier, J.G.J., den Elzen, M.G.J., 2007. Long-term reduction potential of non-CO₂ greenhouse gases. *Environmental Science & Policy* 10, 85–103.
- Luderer, G., Bertram, C., Calvin, K., De Cian, E., Kriegler, E., n.d. Implications of weak near-term climate policies on long-term climate mitigation pathways. *Climatic Change*.
- Luderer, G., Pietzcker, R.C., Kriegler, E., Haller, M., Bauer, N., 2012. Asia's role in mitigating climate change: A technology and sector specific analysis with ReMIND-R. *Energy Economics* 34, pp. S378–S390.
- Messner, S., Strubegger, M., 1995. User's guide for MESSAGE III. Working Paper WP-95-069. International Institute for Applied Systems Analysis (IIASA).
- National Policy Unit, 2013. Options for Energy and the Environment The Energy and Environment Council Decision on June 29, 2012 [Outline] [WWW Document]. 2012. URL https://s3-ap-northeast-1.amazonaws.com/sentakushi01/public/pdf/Outline_English.pdf
- OECD, 2010. Climate Change. In: *OECD Environmental Performance Reviews: Japan 2010*.
- Rao, S., Riahi, K., 2006. The Role of Non-CO₂ Greenhouse Gases in Climate Change Mitigation: Long-term Scenarios for the 21st Century. *Energy Journal* 27, 177–200.
- Rogelj, J., Hare, W., Chen, C., 2011. Discrepancies in historical emissions point to a wider 2020 gap between 2 °C benchmarks and aggregated national 024002.
- Schuman, S., Lin, A., 2012. China's Renewable Energy Law and its impact on renewable power in China: Progress, challenges and recommendations for improving implementation. *Energy Policy* 51, 89–109.
- Shukla, P.R., Chaturvedi, V., 2011. Sustainable energy transformations in India under climate policy. *Sustainable Development*.

- Shukla, P.R., Chaturvedi, V., 2012. Low carbon and clean energy scenarios for India: Analysis of targets approach. *Energy Economics*.
- Shukla, P.R., Garg, A., Dhar, S., Halsnaes, K., 2007. Balancing Energy, Development and Climate Priorities in India. UNEP Risoe Centre on Energy, Climate and Sustainable Development, Roskilde, Denmark.
- Steckel, J., Jakob, M., Marschinski, R., Luderer, G., 2011. From carbonization to decarbonization?—Past trends and future scenarios for China's CO₂ emissions. *Energy Policy* 39, 3443–3455.
- Townshend, T., Frankhauser, S., Matthews, A., Feger, C., Liu, J., Narciso, T., 2011. GLOBE Climate Legislation Study.
- UNFCCC, 2009. Report of the Conference of the Parties on its fifteenth session, held in Copenhagen from 7 to 19 December 2009 [WWW Document]. URL <http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf#page=4>
- UNFCCC, 2011. Framework Convention on Climate Change Compilation of economy-wide emission reduction targets to Convention 1–8.
- Van Vuuren, D.P., Hoogwijk, M., Barker, T., Riahi, K., Boeters, S., Chateau, J., Scricciu, S., van Vliet, J., Masui, T., Blok, K., Blomen, E., Kram, T., 2009. Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials. *Energy Policy* 37, 5125–5139.
- Van Vuuren, D.P., Kok, M.T.J., Girod, B., Lucas, P.L., de Vries, B., 2012. Scenarios in Global Environmental Assessments: Key characteristics and lessons for future use. *Global Environmental Change* 22, 884–895.
- Van Vuuren, D.P., Lowe, J., Stehfest, E., Gohar, L., Hof, A.F., Hope, C., Warren, R., Meinshausen, M., Plattner, G.-K., 2009. How well do integrated assessment models simulate climate change? *Climatic Change* 104, 255–285.
- Van Vuuren, D.P., Riahi, K., 2010. The relationship between short-term emissions and long-term concentration targets. *Climatic Change* 104, 793–801.
- Van Vuuren, D.P., Stehfest, E., 2013. If climate action becomes urgent: the importance of response times for various climate strategies. *Climatic Change*.
- Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., Smith, S.J., Janetos, A., Edmonds, J., 2009. Implications of limiting CO₂ concentrations for land use and energy. *Science (New York, N.Y.)* 324, 1183–6.
- Yang, L., Mingqi, P., Deetman, S., Hof, A., 2011. Country report on mitigation and adaptation policies in China.
- Zhang, M., Mu, H., Ning, Y., 2009. Accounting for energy-related CO₂ emission in China, 1991–2006. *Energy Policy* 37, 767–773.
- Zwaan, B.C.C. Van Der, Rösler, H., Kober, T., Aboumahboub, T., Calvin, K. V., 2013. A Cross-model Comparison of Global Long-term Technology Diffusion under a 2 ° C Climate Change Control Target. *Climate Change Economics* 1–17.