

NOTA DI LAVORO

110.2015

Regional Low-Emission Pathways from Global Models

Heleen van Soest, Lara Aleluia Reis,
Detlef van Vuuren, Christoph Bertram,
Laurent Drouet, Jessica Jewell, Elmar
Kriegler, Gunnar Luderer, Keywan
Riahi, Joeri Rogelj, Massimo Tavoni,
Michel den Elzen

Aayushi Awasthy, Katherine Calvin, Pantelis
Capros, Leon Clarke, Michel Colombier, Teng
Fei, Amit Garg, Fernanda Guedes, Mariana
Imperio, Mikiko Kainuma, Jiang Kejun,
Alexandre C. Köberle, Peter Kolp, Volker Krey,
Alban Kitous, Paroussos Leonidas, Andre
Lucena, Toshihiko Masui, Larissa Nogueira,
Roberta Pierfederici, Bert Saveyn, Roberto
Schaeffer, Fu Sha, Bianka Shoai, P.R. Shukla,
Thomas Spencer, Alexandre Szklo, Henri
Waisman⁹

Climate Change and Sustainable Development

Series Editor: Carlo Carraro

Regional Low-Emission Pathways from Global Models

By Heleen van Soest¹, Lara Aleluia Reis², Detlef van Vuuren¹, Christoph Bertram³, Laurent Drouet², Jessica Jewell⁴, Elmar Kriegler³, Gunnar Luderer³, Keywan Riahi⁴, Joeri Rogelj⁴, Massimo Tavoni^{2,5}, Michel den Elzen¹

Aayushi Awasthy⁶, Katherine Calvin⁷, Pantelis Capros⁸, Leon Clarke⁷, Michel Colombier⁹, Teng Fei¹⁰, Amit Garg¹¹, Fernanda Guedes¹², Mariana Imperio¹², Mikiko Kainuma¹³, Jiang Kejun¹⁴, Alexandre C. Köberle¹², Peter Kolp⁴, Volker Krey⁴, Alban Kitous¹⁵, Paroussos Leonidas¹⁶, Andre Lucena¹², Toshihiko Masui¹³, Larissa Nogueira¹², Roberta Pierfederici⁹, Bert Saveyn¹⁵, Roberto Schaeffer¹², Fu Sha¹⁷, Bianka Shoai¹⁸, P.R. Shukla¹¹, Thomas Spencer⁹, Alexandre Szklo¹², Henri Waisman⁹

- 1) PBL Netherlands Environmental Assessment Agency, The Netherlands
- 2) Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Italy and Fondazione Eni Enrico Mattei
- 3) Potsdam-Institut für Klimafolgenforschung (PIK), Germany
- 4) International Institute for Applied Systems Analysis (IIASA), Austria
- 5) Politecnico di Milano, Italy
- 6) The Energy and Resources Institute (TERI), India
- 7) Pacific Northwest National Laboratory (PNNL), United States
- 8) Institute of Communication and Computer Systems (ICCS), Greece
- 9) Institut du Développement Durable et des Relations Internationales (IDDRI), France
- 10) Tsinghua University (TU), China
- 11) Indian Institute of Management Ahmedabad (IIMA), India
- 12) The Alberto Luiz Coimbra Institute for Graduate Studies and Research, Federal University of Rio de Janeiro (COPPE/UFRJ), Brazil
- 13) National Institute for Environmental Studies (NIES), Japan
- 14) Energy Research Institute of NDRC (ERI), China
- 15) European Commission, DG Joint Research Centre (JRC), Spain
- 16) Energy - Economy - Environment Modelling Laboratory (E3M Lab), Greece
- 17) Renmin University and National Centre for Climate Change Strategy and International Cooperation, China
- 18) Research Institute of Innovative Technology for the Earth (RITE), Japan

This publication has been prepared by PBL and FEEM/CMCC for the MILES project Consortium under contract to DG CLIMA (No. 21.0104/2014/684427/SER/CLIMA.A.4).

Summary

Governments worldwide have agreed that international climate policy should aim to limit the increase of global mean temperature to less than 2°C with respect to pre-industrial levels. The purpose of this paper is to analyse the emission reductions and related energy system changes in various countries in pathways consistent with the 2°C target. We synthesize and provide an overview of the national and regional information contained in different scenarios from various global models published over the last few years, as well as yet unpublished scenarios submitted by modelling teams participating in the MILES project (Modelling and Informing Low-Emission Strategies). We find that emissions in the mitigation scenarios are significantly reduced in all regions compared to the baseline without climate policies. The regional cumulative CO₂ emissions show on average a 76% reduction between the baseline and 450 scenario. The 450 scenarios show a reduction of primary energy demand in all countries of roughly 30-40% compared to the baseline. In the baseline scenario, the contribution of low-carbon energy technology remains around 15%, i.e. similar as today. In the mitigation scenario, these numbers are scaled up rapidly towards 2050. Looking at air quality, sulphur dioxide and black carbon emissions are strongly reduced as a co-benefit of greenhouse gas emission reductions, in both developing and developed countries. However, black carbon emissions increase in countries that strongly rely on bioenergy to reach mitigation targets. Concerning energy security, energy importing countries generally experience a decrease in net-energy imports in mitigation scenarios compared to the baseline development, while energy exporters experience a loss of energy export revenues.

Keywords: Climate policy, Mitigation, Global and national policy comparison

JEL Classification: Q54

Address for correspondence

Heleen van Soest
PBL Netherlands Environmental Assessment Agency
PO box 303
3720 AH Bilthoven
The Netherlands
E-mail: Heleen.vanSoest@pbl.nl

Regional Low-emission pathways from global models

Deliverable 1.1 for the MILES project

MILES: Modelling and Informing Low-Emission Strategies

**Heleen van Soest^{* 1)}, Lara Aleluia Reis²⁾, Detlef van Vuuren¹⁾,
Christoph Bertram³⁾, Laurent Drouet²⁾, Jessica Jewell⁴⁾, Elmar
Kriegler³⁾, Gunnar Luderer³⁾, Keywan Riahi⁴⁾, Joeri Rogelj⁴⁾,
Massimo Tavoni^{2,5)}, Michel den Elzen¹⁾**

*Aayushi Awasthy⁶⁾, Katherine Calvin⁷⁾, Pantelis Capros⁸⁾, Leon Clarke⁷⁾,
Michel Colombier⁹⁾, Teng Fei¹⁰⁾, Amit Garg¹¹⁾, Fernanda Guedes¹²⁾, Mariana
Imperio¹²⁾, Mikiko Kainuma¹³⁾, Jiang Kejun¹⁴⁾, Alexandre C. Köberle¹²⁾,
Peter Kolp⁴⁾, Volker Krey⁴⁾, Alban Kitous¹⁵⁾, Paroussos Leonidas¹⁶⁾, Andre
Lucena¹²⁾, Toshihiko Masui¹³⁾, Larissa Nogueira¹²⁾, Roberta Pierfederici⁹⁾,
Bert Saveyn¹⁵⁾, Roberto Schaeffer¹²⁾, Fu Sha¹⁷⁾, Bianka Shoai¹⁸⁾, P.R.
Shukla¹¹⁾, Thomas Spencer⁹⁾, Alexandre Szklo¹²⁾, Henri Waisman⁹⁾*

- 1) PBL Netherlands Environmental Assessment Agency, The Netherlands
- 2) Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Italy and Fondazione Eni Enrico Mattei
- 3) Potsdam-Institut für Klimafolgenforschung (PIK), Germany
- 4) International Institute for Applied Systems Analysis (IIASA), Austria
- 5) Politecnico di Milano, Italy
- 6) The Energy and Resources Institute (TERI), India
- 7) Pacific Northwest National Laboratory (PNNL), United States
- 8) Institute of Communication and Computer Systems (ICCS), Greece
- 9) Institut du Développement Durable et des Relations Internationales (IDDRI), France
- 10) Tsinghua University (TU), China
- 11) Indian Institute of Management Ahmedabad (IIMA), India
- 12) The Alberto Luiz Coimbra Institute for Graduate Studies and Research, Federal University of Rio de Janeiro (COPPE/UFRJ), Brazil
- 13) National Institute for Environmental Studies (NIES), Japan
- 14) Energy Research Institute of NDRC (ERI), China
- 15) European Commission, DG Joint Research Centre (JRC), Spain
- 16) Energy - Economy - Environment Modelling Laboratory (E3M Lab), Greece
- 17) Renmin University and National Centre for Climate Change Strategy and International Cooperation, China
- 18) Research Institute of Innovative Technology for the Earth (RITE), Japan

* Corresponding author: Heleen.vanSoest@pbl.nl

21 December, 2015

Abstract

Governments worldwide have agreed that international climate policy should aim to limit the increase of global mean temperature to less than 2°C with respect to pre-industrial levels. The purpose of this paper is to analyse the emission reductions and related energy system changes in various countries in pathways consistent with the 2°C target. We synthesize and provide an overview of the national and regional information contained in different scenarios from various global models published over the last few years, as well as yet unpublished scenarios submitted by modelling teams participating in the MILES project (Modelling and Informing Low-Emission Strategies). We find that emissions in the mitigation scenarios are significantly reduced in all regions compared to the baseline without climate policies. The regional cumulative CO₂ emissions show on average a 76% reduction between the baseline and 450 scenario. The 450 scenarios show a reduction of primary energy demand in all countries of roughly 30-40% compared to the baseline. In the baseline scenario, the contribution of low-carbon energy technology remains around 15%, i.e. similar as today. In the mitigation scenario, these numbers are scaled up rapidly towards 2050. Looking at air quality, sulphur dioxide and black carbon emissions are strongly reduced as a co-benefit of greenhouse gas emission reductions, in both developing and developed countries. However, black carbon emissions increase in countries that strongly rely on bioenergy to reach mitigation targets. Concerning energy security, energy importing countries generally experience a decrease in net-energy imports in mitigation scenarios compared to the baseline development, while energy exporters experience a loss of energy export revenues.

SUMMARY

The purpose of this paper is to synthesize and provide an overview of the national and regional information contained in different scenarios from various global models published over the last few years. We use this information to analyse the emission reductions and related energy system changes in various countries in pathways consistent with the 2°C target. This analysis provides input for international policy processes, and the context for more detailed analyses of meaningful indicators at the national level. We note that although we present the results of several models, these are used to build significant corridors and not as a basis for an inter-model comparison, which is not the scope of this work.

In our work, the scenarios were characterized on the basis of the assumed climate policies: i.e. baseline scenarios (no new policies), reference scenarios (existing policies) and scenarios aiming at 550 and 450 ppm CO₂-eq targets. The latter were divided into scenarios with and without assumed delay in policy implementation in the near term. Each of the global models contains information for about 10-30 regions and countries. The scenarios with delay implement prescribed policies per region. After the delay period, a uniform global carbon price is assumed. This implies that the contribution of each country (or region) is mostly determined by the marginal abatement costs. This is also the case for the scenarios without delay for the full scenario period. Differences in model outcomes have been used to indicate model uncertainty ranges for the various indicators that are shown.

Emission trends

In this summary, we focus on the baseline and 450 ppm CO₂-eq scenarios (see Box 1).

Box 1: Model-based scenario analysis

The baseline scenario shows the situation in the absence of climate policy. Such a scenario is not realistic (as most countries have indicated elaborate plans to implement policies), but forms a counterfactual scenario that can be used to show the effect of policies in each region in a compatible way. For the 450 ppm scenarios, two categories are shown, i.e. with and without delay. The scenarios without any policy delay are also not realistic, but again, provide a reference showing the situation if a globally cost-efficient response could be formulated. In the database, results from various models were available for 13 regions.

Models provide insights into cost-optimal trajectories for achieving specific climate goals given assumptions on the costs, efficiency and preferences for specific technologies, their interaction in the energy system and existing policies.

The information can be used to explore costs and benefits of alternate pathways. Future policy developments are beset with uncertainty. The use of multiple models is one way to obtain some insights into the impact of different model assumptions.

Figure S.1 shows the mean values of projected trends in per capita GDP levels and associated per capita emissions for all models (baseline and 450 ppm CO₂-eq) for 13 regions covered in this study. This figure leads to the following conclusions:

- Without climate policy, **greenhouse emissions are expected to increase rapidly in low-income regions, driven by a projected further increase in economic activity and population. Per capita emissions are projected to remain more or less stable in high-income regions.** The emissions per capita in high-income countries are expected to remain more or less stable as a result of opposing trends in activity growth, efficiency improvement and (slow) decarbonisation of fuel supply.
- **Emissions in the mitigation scenarios are significantly reduced compared to the baseline in all regions, independent of income-level.** Further analysis of the scenarios shows global average CO₂ emissions to range from about 0.3 to 2 tCO₂/capita in 2050 under delayed 450 scenarios. This range results from differences in non-CO₂ emissions assumptions and assumed mitigation action beyond 2050 (especially the use of negative emissions). Figure S.1 shows that low-income countries generally remain below the global average, although the upper end of the ranges for China, Indonesia and South Africa are slightly above the global average. Most OECD countries show per capita emissions ranges similar to or higher than the global average.
- **The results also show that CO₂ emissions from fossil fuels and industry represent the majority of global total emissions in the baseline, while the mitigation scenarios result in about equal shares of non-CO₂ emissions and CO₂ emissions from fossil fuels and industry globally in 2050.** CO₂ emissions are reduced more than non-CO₂ emissions. There are, however, regional differences in the contribution of the different emission categories. In China, for example, CO₂ emissions from fossil fuels and industry remain the major contributor to total emissions, while in Indonesia, land use emissions represent the lion's share. All countries show increasing shares of low-carbon primary energy sources (i.e. all energy sources except coal, oil and gas without carbon sequestration) with lower cumulative carbon emissions. For developed countries, this generally means a substantial increase on 2010 levels.

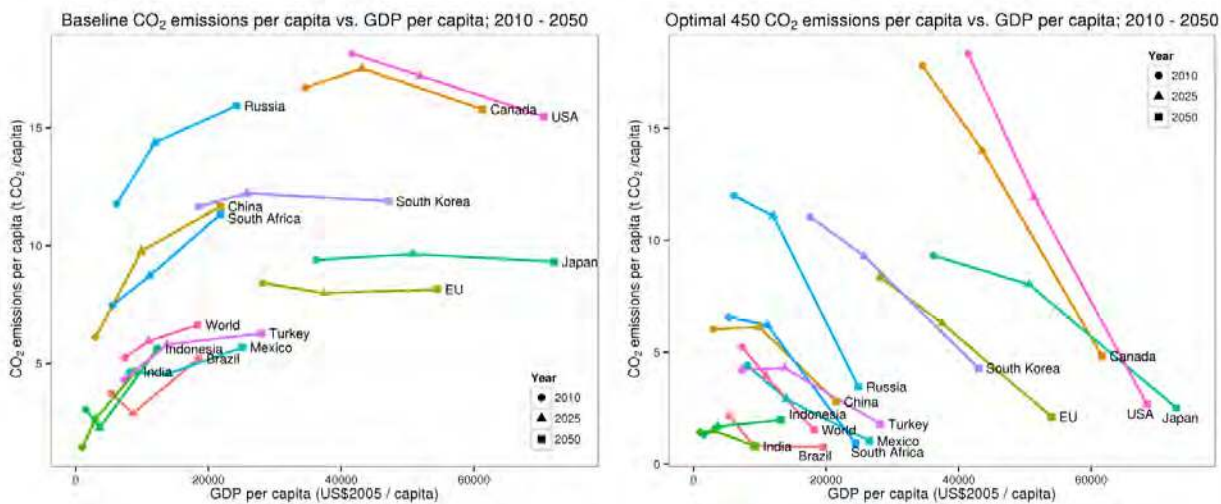


Figure S.1: CO₂ emissions per capita (tCO₂/capita) versus GDP per capita (US\$2005/capita) between 2010 and 2050 for baseline scenarios (left panel) and cost-optimal 450 scenarios (right panel).

Greenhouse emissions in 2030

The results across the different models for 2030 greenhouse gas emissions are summarized in Figure S.2.

- The data show a **clear difference in 2030 emission levels between the baseline scenarios and the cost-optimal 450 ppm scenarios.** The delayed 450 ppm scenarios typically show slightly higher emissions than the cost-optimal 450 ppm scenarios.

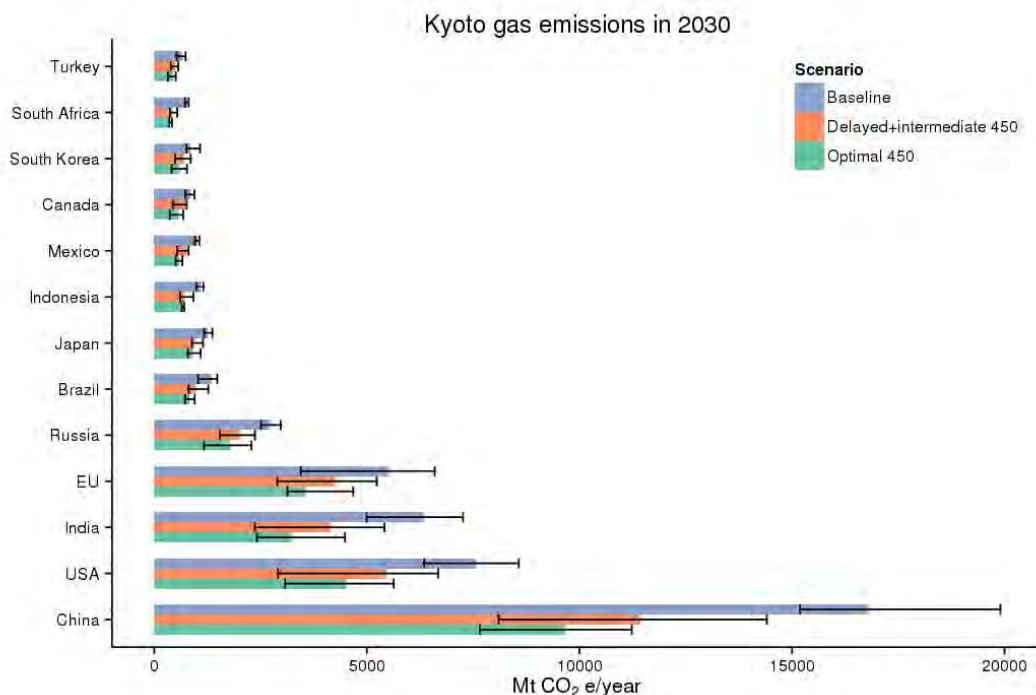


Figure S.2: Kyoto gas emissions (MtCO₂e) in 2030 for cost-optimal 450 ppm scenarios, delayed 450 ppm scenarios and baseline scenarios. Filled bars show the median value across models, error bars show the 10th to 90th percentile range.

Cumulative emissions

A key outcome of the models are the **regional cumulative emissions consistent with different global climate targets**. These can be interpreted as regional emission constraints assuming cost-efficient implementation of the global target across all regions. Note that the cumulative emissions linked to e.g. a <2°C temperature outcome need to be constantly updated to account for revised estimates of past, current and future emissions as well as developments in climate science.

- Figure S.3 shows the regional cumulative emissions for the baseline and optimal 450 scenarios for the period 2010-2100. The results indicate the actual emissions in the cost-optimal scenarios and do not make any assumptions as to who pays for the emission reductions. **The cumulative emissions between the baseline and 450 scenario are very different, showing on average around 76% reduction across all regions.** The important role of China, India, and the USA is illustrated by the fact that in the baseline scenario, each of these regions alone accounts for at least half the global cumulative emissions consistent with the 2°C target. The different ratios between baseline emissions and the cost-optimal 450 emissions mostly reflect abatement opportunities in the various regions.

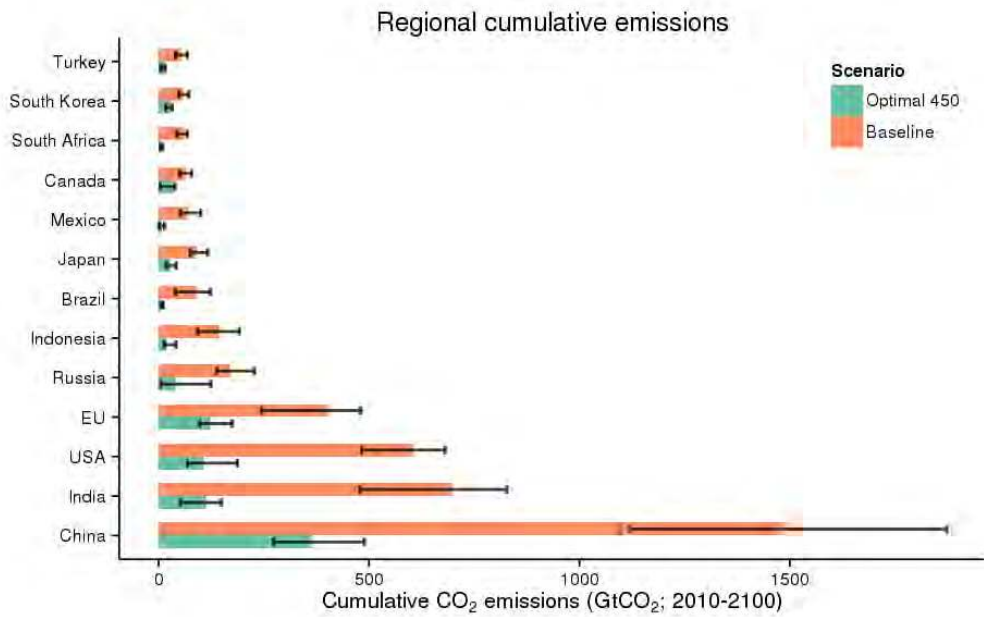


Figure S.3: Regional cumulative CO₂ emissions between 2010 and 2100, for cost-optimal 450 ppm and baseline scenarios. Filled bars represent the median, error bars give the 10th to 90th percentile ranges across models.

Emissions peak

- A similar picture of stringent climate action in all regions emerges when looking at the peak year of CO₂ emissions (Figure S.4). Under the optimal 450 scenarios that assume direct implementation of policies, most countries' CO₂ emissions peak before 2025 (except for India). Under delayed 450 scenarios (taking into account 2020 pledges and introducing cost-optimal policies between 2020 and 2025), this peak generally shifts to later in the century, although not by much.

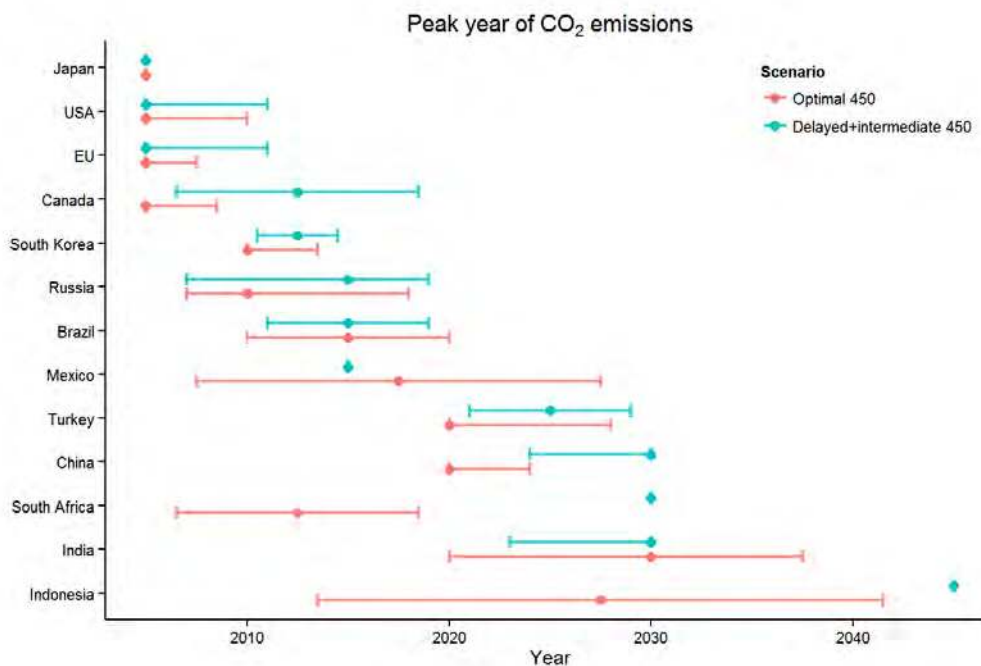


Figure S.4: Regional peak years of CO₂ emissions for cost-optimal 450 ppm, delayed 450 ppm and baseline scenarios. Dots give the median of the models, error bars give the 10th to 90th percentile ranges. The median results can be at the outer end of the range, for instance for OECD countries, as a majority of these regions show an immediate peak with only a few exceptions.

Consequences for energy use

- Primary energy demand decreases strongly in the mitigation scenarios, compared to the baseline scenario, especially in developing countries. **The 450 scenarios show a reduction in all countries of roughly 30-40% compared to the baseline.** There are regional differences, with e.g. South Africa halving its primary energy demand under mitigation scenarios.
- **Key differences between the baseline scenario and the 450 ppm scenario occur for the composition of the energy mix** (Figure S.5). In the baseline scenario, the contribution of low-carbon energy technology remains around 15%, i.e. similar as today. Large differences across the different regions can be seen in the baseline projections for 2030 and 2050, with Brazil showing significantly higher shares of low-carbon energy technology than other regions. In the mitigation scenario, the shares of low-carbon energy technology are scaled up rapidly towards 2050. While some differences across the regions can be noticed, the large model uncertainty ranges indicate that this differs strongly across the models.

Policy costs

- **There is a cost advantage to starting mitigation early.** Delayed 450 scenarios show lower median policy costs in the short term in some

regions (China and World), but higher policy costs in the long term in all regions, compared to the optimal 450 scenarios.

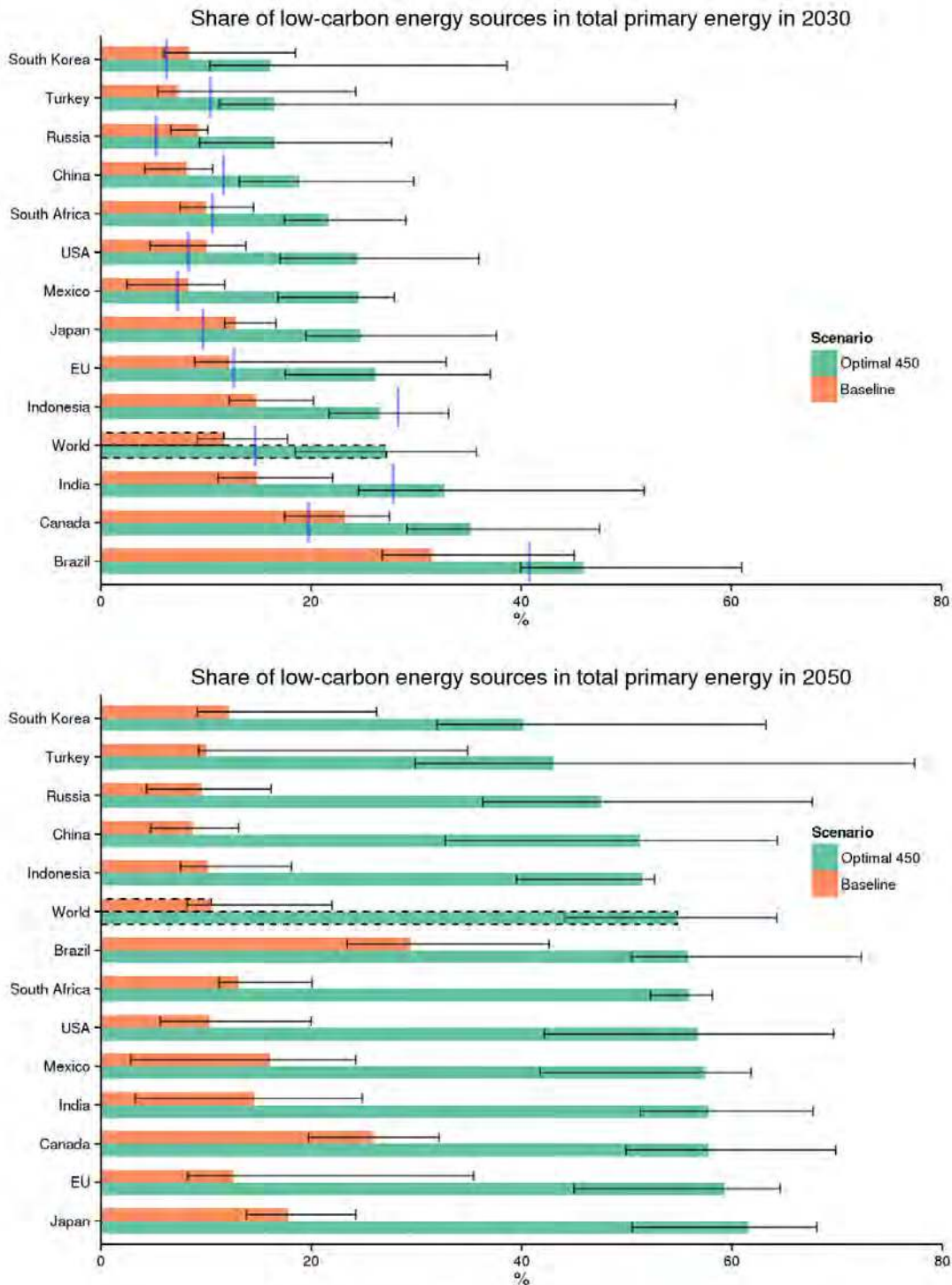


Figure S.5: Share (%) of low-carbon primary energy sources (all energy sources except oil, coal and gas without carbon sequestration) in total primary energy supply in 2030 (upper panel) and 2050 (lower panel), for cost-optimal 450 ppm and baseline scenarios. Filled bars represent the median, error bars give the 10th to 90th percentile ranges across models, and vertical blue lines give the 2010 shares.

Co-benefits

Mitigation action does not only impact greenhouse gas emissions, but also the energy mix – and thus energy security and air pollution. Overall, it has been shown on the global level that mitigation action is likely to result in co-benefits. The analysis here shows such co-benefits for air pollution (although showing clear regional differences), but for energy security, the impacts of mitigation action are dependent on the region.

- Looking at **air quality**, **sulphur dioxide emissions are strongly reduced as a co-benefit of greenhouse gas emission reductions**, in both developing and developed countries (Figure S.6). Also **significant reductions of black carbon emissions** can be found, although emissions increase in countries that strongly rely on bioenergy to reach mitigation targets. In these cases, additional policies are required to reduce air pollution from black carbon.

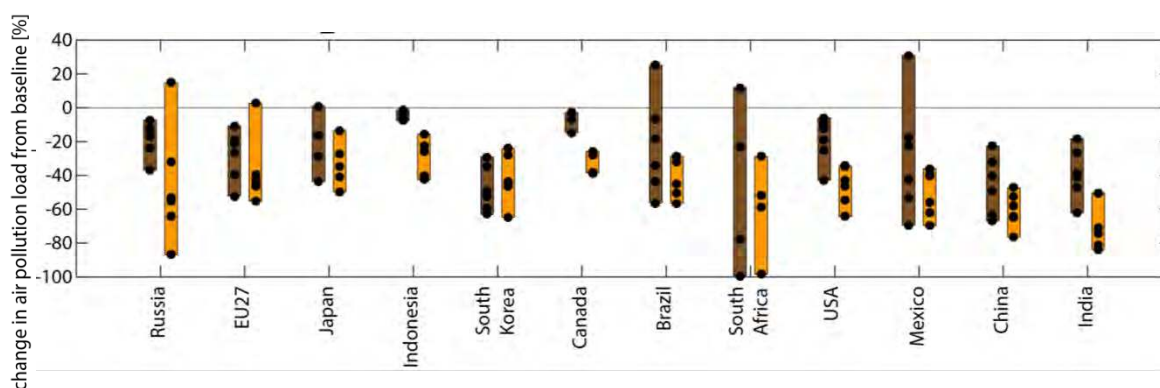


Figure S.6: Changes, in 2050, in black carbon (brown) and sulphur dioxide (orange) emissions when moving from a baseline without new climate policies to a pathway in line with stabilizing atmospheric CO₂-equivalent concentrations at 450 ppm. Dots show single model results, bars the full range.

- Concerning **energy security**, energy importing countries generally experience a decrease in net-energy imports in climate stabilization scenarios compared to the baseline development, while energy exporters experience a loss of energy export revenues from climate stabilization policies (Figure S.7).

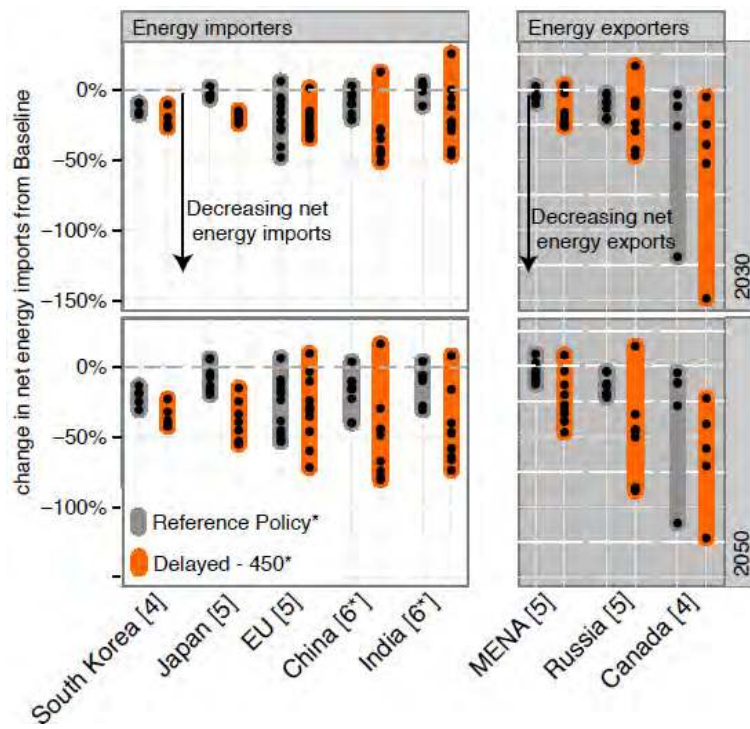


Figure S.7: Change in net-energy imports (left) and net-energy exports (right) for major energy importers and exporters. The number for each country represents the number of models.

Contents

INTRODUCTION	14
METHODOLOGY	16
Main Method	16
Regional Coverage of the Models	17
RESULTS	21
Population and GDP	21
Primary Energy	24
Energy Intensity	26
Greenhouse Gas Emissions	28
Emissions: CO ₂ Energy, CO ₂ Land Use, Non-CO ₂	31
Regional cumulative emissions	33
Peak Year	34
Low-carbon energy technology as a function of cumulative emissions	35
Policy Costs	38
Implications of Technology Availability Assumptions	39
Co-benefits	41
Energy Security and Energy Independence Co-benefits of Mitigation	41
Air Pollution Co-benefits of Mitigation	43
CONCLUSIONS	45

Introduction

Governments worldwide have agreed that international climate policy should aim to limit the increase of global mean temperature to less than 2°C with respect to pre-industrial levels (UNFCCC, 2010). The IPCC Fifth Assessment Report (AR5) indicates that scenarios without new climate policies typically result in an increase of global mean temperature of around 3-4°C by 2100 (Clarke et al., 2014). In order to reach the 2°C target, urgent and drastic emission reductions are required. Such reductions are needed in all regions around the world (Tavoni et al., 2014).

Global modelling teams have worked on developing a set of scenarios for international climate policy in projects such as AMPERE (Kriegler et al., 2014a), LIMITS (Kriegler et al., 2014b, Riahi et al., 2014, Tavoni et al., 2014) and EMF27 (Kriegler et al., 2014c). These scenarios look into possible emission trajectories without new climate policies, estimates of current policies and different variants of scenarios aiming at the 2°C target (these scenarios vary in terms of the probability of achieving the target, technology assumptions and the timing of climate policy). The scenarios also played an important role in the analysis performed in the last report of IPCC (Clarke et al., 2014). Typically, these models contain around 10–30 regions in order to describe trends in global emissions. While several projects have started to use the regional information of the global models to look into climate policy strategies at the scale of countries and regions (e.g. Herreras Martínez et al., 2015, Tavoni et al., 2014, Van Sluisveld et al., 2013), in general, the regional information has not been used extensively.

The purpose of this paper, therefore, is to analyse the energy system changes in various countries in pathways consistent with the 2°C target, by looking into the national/regional information contained in different global scenarios from various global models. The objectives of this study are:

- To better understand the transition pathways at the level of major economies in a set of global scenarios developed over the past few years;
- To specifically investigate various policy relevant indicators such as peak years and cumulative emissions at the level of major economies;
- To provide insights in potential co-benefits of different pathways.

The information presented here was evaluated by both national and international modelling teams. This analysis could in particular help positioning the different countries regarding low-emission pathways. The focus of the analysis is on regional results (and thus not on a model comparison).

Methodology

Main Method

In this paper, we compare scenarios developed in previous studies using global models in terms of the results for key countries/regions. We use data from the following studies: AMPERE, LIMITS, and EMF27 (see earlier references), which include several models such as DNE21+, GCAM, GEM-E3, IMAGE, MESSAGE, POLES, REMIND, and WITCH.

In addition, new scenarios, developed after these previous studies or specifically for the MILES project, have been added by the teams participating in MILES. The MILES project (Modelling and Informing Low Emission Strategies) is an international cooperation project between 19 international research teams¹. Key objectives of the project are: 1) to explore different country-level strategies consistent with the 2°C target, 2) to increase understanding of differences between strategies in different parts of the world, and 3) to enhance in all participating countries the capacity to perform analysis of mitigation strategies.

In this study, we look into regional results evaluating the drivers, emission trajectories, and energy system changes. The national and regional emission pathways in the global studies provide insight into the required energy transitions at this level. It should be noted that in these studies, the contribution of each country (or region) in global reductions is determined by the marginal abatement costs. The results of the global models have been compared with the results of the national models.

The discussion of the results is divided into three parts, each of them oriented at the following key questions:

- What do regional/national emission and energy system pathways consistent with different assumptions on international climate policy look like?
- How do assumptions on the availability of different technologies influence these results?
- What are important co-benefits at the national/regional level of the different policies?

For this analysis, existing scenarios were characterized as indicated in Table 1.

¹ ERI, RUC, TU, TERI, IIM, COPPE, PNNL, NIES, RITE, ICCS, IIASA, PIK, PBL, CMCC, CLU, IDDRI, CCROM, CRE, INECC

Table 1: Scenario categories used in this study.

<i>Category</i>	<i>Description</i>
Baseline	Scenarios that do not include new climate policies other than via the calibration to the historical period. This scenario category thus acts as a counterfactual scenario providing a consistent reference across all regions for showing the impact of climate policies.
Reference policy	Describes possible development assuming implementation of existing policies and some continuation of these policies in the longer term (without strengthening these policies).
Cost-optimal 500-550 ppm CO ₂ eq	Scenarios aimed at stabilizing GHG concentrations at the level of 500-550 ppm CO ₂ -eq at the lowest costs (within the model).
Cost-optimal 450	A universal global carbon tax is implemented immediately in order to reach a target of 450 ppm CO ₂ eq, resulting in the lowest costs (within the model).
Intermediate 450	This scenario type follows the implementation of the pledges in 2020 and assumes cost-optimal policies (based on intermediate policies) to be introduced after 2020-2025.
Delayed 450 ppm CO ₂ eq	Scenarios that include the current description of pledges until 2020, and assume some further delayed policies up to 2025. In the longer term, cost-optimal policies are implemented. As a result, global emissions peak after 2025.

Regional Coverage of the Models

Table 2 indicates how the information of the different models was used in this study to look into regional trends. Table 3 provides the main characteristics of the models included in this study.

Table 2: Regional coverage per model (X indicates that the region is represented in the model; in case slightly different regions were used this is indicated in the Table).

	DNE21+	GCAM	GEM-E3	IMAGE	MESSAGE	POLES	Remind	WITCH
Brazil	X	X	X	X		X		
Canada	X	X	X	X		X		
China	X <i>Includes Hong Kong</i>	X <i>Includes Hong Kong, Macau</i>	X <i>Includes Hong Kong, Macau</i>	X <i>Includes Mongolia and Taiwan</i>	X <i>Centrally planned Asia and China</i>	X <i>Includes Hong Kong, Macau, Taiwan</i>	X <i>Includes Hong Kong</i>	X
EU	X <i>Includes Greenland</i>		X	X <i>Includes Norway, Switzerland, Iceland, Balkan countries</i>	X <i>Includes Iceland, Turkey, Norway, Switzerland, Greenland</i>	X	X	X <i>Includes EFTA</i>
India	X	X	X	X	X <i>South Asia</i>	X	X	X
Indonesia		X	X	X		X		
Japan	X	X	X	X		X	X	
Mexico	X	X	X	X		X		
Russia	X	X	X	X		X	X	
South Africa		X	X	X		X		
South Korea	X	X	X	<i>Includes North Korea</i>		X		
USA	X	X <i>Includes Puerto Rico</i>	X	X	X <i>North America (includes Canada, Guam, Puerto Rico)</i>	X	X <i>Includes Puerto Rico</i>	X
World	X	X	X	X	X	X	X	X

Table 3: Main characteristics of the models included in this study

		DNE21+	GCAM	GEM-E3	IMAGE	MESSAG E	POLES	Remind	WITCH
Model objective		DNE21+ is a linear programming model that seeks the optimal strategy to minimize the cost of world energy systems and mitigate climate change. The model is composed of three sub-models: an energy systems, a macro economic and a climate change model and is useful at the global level, divided into 10 regions.	GCAM is an integrated assessment model that couples representation of energy, agriculture, emissions, climate, and water. Originally, the model focused on energy-emissions-climate interactions.	The purpose of GEM-E3 is to provide long-term quantitative model-based assessment in the fields of energy and climate policies, economic and employment policies, tax & price reform, environmental regulation, trade and competitiveness policies	IMAGE represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change, biodiversity and human well-being, to explore long-term dynamics and impacts of global changes that result from interacting demographic, technological, economic, social, cultural and political factors.	MESSAG E at its core is a technology-detailed energy-engineering optimization model used for energy planning. Through linkage to macro-economic, land-use and climate models it is capable of taking into account important feedbacks and limitations in these areas outside of the energy system.	Detailed global energy system model, with module to cover industry GHGs, Agriculture and LULUCF GHG coming from GLOBIOM	Construct self-consistent optimal benchmark scenarios for the transformation of the global energy-economy system, for different assumptions on climate policies or targets. Comparison with no-policy benchmark scenarios allows for the calculation of mitigation costs.	The model is designed to assist in the study of the socio-economic dimensions of climate change and to help policy makers understand the economic consequences of climate policies.
Model type:	Solution concept	Energy systems model with minimizing world energy system cost	Partial equilibrium (price elastic demand)	General equilibrium (closed economy)	Partial equilibrium (price elastic demand)	General equilibrium (closed economy)	Partial equilibrium (price elastic demand)	General equilibrium (closed economy)	General equilibrium (closed economy)
	Solution horizon	Inter-temporal (foresight)	Recursive-dynamic (myopic)	Recursive-dynamic (myopic)	Recursive-dynamic (myopic)	Inter-temporal (foresight) Recursive-dynamic (myopic)	Recursive-dynamic (myopic)	Inter-temporal (foresight)	Inter-temporal (foresight)
	Solution method	Optimization	Simulation	Optimization	Simulation	Optimization	Simulation	Optimization	Optimization
Time		2050; 5	2100; 5	2050; 5	2100; 1	2110; 5	2100; 1	2100; 5	2150; 5

horizon and time step	years (2005-2030); 10 years (2030-2050)	years	years	year	years; 10 years	year	years	years
Number of energy conversion technologies (rough estimate)	50	50	10	50	200	100	60	25
Energy technology substitution	Linear choice (lowest cost)	Logit choice model	Production function	Logit choice model	Linear choice (lowest cost)	Logit choice model	Production function	No discrete technology choices

Results

What do regional/ national emission and energy system pathways consistent with different assumptions on international climate policy look like?

We selected a set of variables, presented hereafter, which are relevant for the analysis of national emission and energy system pathways consistent with the 2°C target. The selection includes: population, GDP, primary energy demand, energy intensity, GHG emissions, cumulative emissions, peak years, shares of low-carbon energy sources, and policy costs.

Population and GDP are two important socio-economic drivers that have a direct influence on primary energy demand and GHG emissions. The energy intensity variable is a measure of the energy use per unit of economic activity and informs about the general level of efficiency of a given region. Another widely used indicator is cumulative emissions, which correlates well with the temperature at the end of the century. The study of peak years allows us to compare countries in terms of stringency of emission pathways. The shares of low-carbon energy sources show the transitions needed in energy systems to meet the long-term climate target. Finally, policy costs are relevant in this study in order to address the regional impacts of delaying optimal mitigation.

Population and GDP

Figure 1 and Table 4 show the population and GDP per capita projections for the different countries. Assumptions on the trends in these drivers do not vary across different scenario categories.

The global population growth in the 2010–2050 period is projected to be about 30–40%. The GDP per capita growth over the same period is considerably faster and the range in the assumed GDP growth across models is large for individual regions, but also for the projected global GDP growth (i.e. 110–210%).

Table 4: Projected change in population and GDP per capita per region between 2010 and 2050 (2050 values expressed relative to 2010). UN population projections (medium variant) are also included for reference.

Region	Population	Population (UN medium)	Population (national scenarios)	GDP per capita	GDP per capita (national scenarios)
Brazil	[1.12, 1.19]	1.18	1.11	[2.53, 5.35]	3.14
Canada	[1.29, 1.33]	1.33		[1.69, 1.87]	
China	[0.97, 1.07]	1.02		[4.91, 10.53]	
EU	[1, 1.05]	0.96	1.05	[1.77, 2.22]	1.71
India	[1.33, 1.45]	1.34		[6.29, 14.65]	
Indonesia	[1.24, 1.34]	1.34		[4.82, 10.68]	
Japan	[0.81, 0.86]	0.85	0.80	[1.72, 2.19]	1.75
Mexico	[1.17, 1.33]	1.32		[2.78, 4.01]	
Russia	[0.85, 0.91]	0.84		[2.44, 4.45]	
South Africa	[1.13, 1.24]	1.23		[3.28, 5.48]	
South Korea	[0.91, 1.06]	1.05		[2.36, 2.79]	
USA	[1.28, 1.3]	1.28		[1.25, 1.88]	
World	[1.33, 1.39]	1.38		[2.09, 3.12]	

Population growth

The projected population growth rates of the OECD countries lie well below the global average. The populations of Japan and the Russian Federation are projected to fall. In general, the different global model-based scenarios do not include a very wide range of population projections, and agree well with UN population projections. A notable exception is the EU, which shows slightly higher population projections than the UN medium scenario. A key reason is that some models include more countries in their EU region than the 28 EU member states (e.g. Turkey, Greenland or Iceland).

The projected population growth rate of the low-income countries covered in this study also lies below the global average. Again, the regional model projections correspond well with the UN medium scenario, with a relatively small range across the different models. The projected global average population growth rate is higher than the growth rates of all countries covered in this study (except India) due to high growth rates in other regions not covered here, most notably Africa, and India.

Comparison with the national model results

The projections for Brazil are similar to the population projections by the national modelling team. The Brazilian population is projected to reach around 200 million

inhabitants by 2030 and 230 million by 2050, which is based on the official projections by the Brazilian Institute of Geography and Statistics (Herreras Martínez et al., 2015). The projections for Mexico are in line with the findings by Veysey et al. (2015), reporting on *The Climate Modeling and Capacity Building in Latin America* project (CLIMACAP) and the *Latin American Modeling Project* (LAMP). They project the Mexican population to reach about 150 million by 2050, with MILES projections for Mexico reaching about 125 – 175 million.

GDP growth

GDP per capita is projected to increase in all countries. Again, the average of the OECD countries lies significantly below the global average – although here Russia forms an exception. The projected increase of other OECD countries is around 1–1.7% per year, while the Russian growth included in the projections is 2.3-3.8% per year.

The projected growth rate of the non-OECD countries is more than twice as high as in OECD countries. The average growth rate of GDP per capita between 2010 and 2050 is projected to be around 3-6% per year in non-OECD countries, and up to 4.7-6.8% per year for India.

Comparison with the national model results

Growth rates projected by the Indian team are slightly higher than most global model projections (around 6.5% per year). Also the Brazilian national team's GDP projections were higher than those of (most of) the global models, with a growth rate of 2.3–3.5% in the 2010-2030 period. These national GDP projections are based on the Brazilian long term National Energy Plan, which projects an average GDP growth of 4% per year until 2050. Mexico's GDP in the global model projections reaches a level of about US\$ 2 – 4 trillion by 2050, which is the same as the range reported by Veysey et al. (2015).

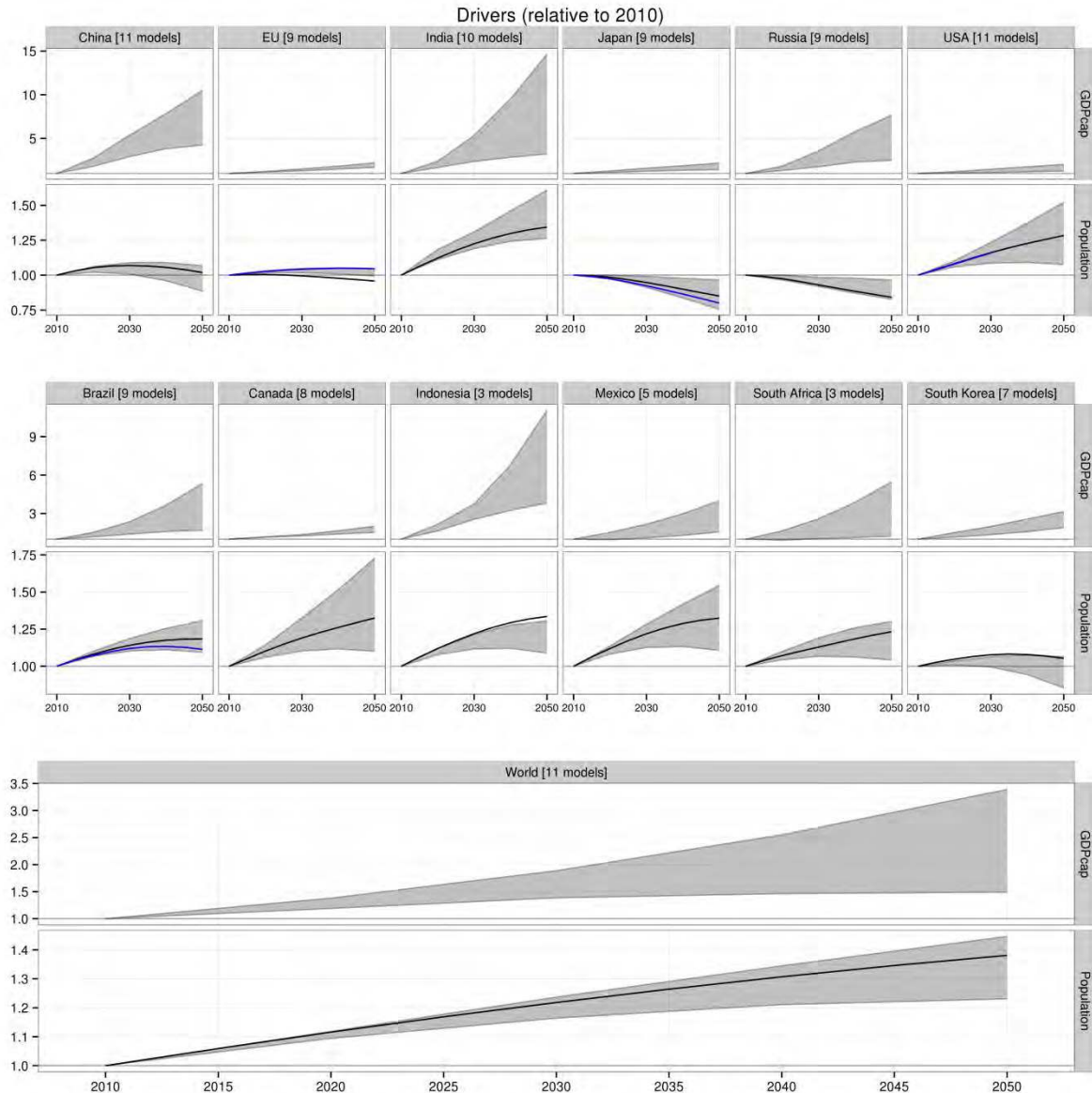


Figure 1: Population and GDP per capita in the 12 countries + world, relative to 2010 values. The number of models per country reporting these variables is indicated². No scenario category dimension is shown here, as assumptions on trends in drivers do not vary across scenario categories. Solid black lines show UN population projections (medium variant), solid blue lines show available national scenario projections.

Primary Energy

Primary energy demand projections under baseline, delayed, intermediate, and optimal 450 scenarios are shown in Figure 2 (delayed and intermediate 450 scenarios are combined into one category). Primary energy demand decreases strongly in the mitigation scenarios compared to the baseline scenario. This

² Some regions and variables may show a larger number of models than the eight reported in Table 2, because models exist in different versions and with results of various studies in the database; these different model versions are counted individually.

effect is strongest in developing countries. For most countries, the scenarios from the global models encompass the IEA's World Energy Outlook projections. The largest difference can be observed in China. Here baseline results are quite comparable, but the models show an outcome range for the optimal 450 scenarios that lies significantly below the IEA's 2°C scenario. This may be explained by the different accounting methods for total primary energy supply applied by the IEA and official Chinese statistics. The Figure also emphasises the considerable model uncertainty ranges for individual countries in the scenarios in the literature.

OECD countries

In general, the primary energy projections for the OECD countries under baseline assumptions show relatively small changes over time (increase or decrease). The projections for the 450 scenarios show typically a 30-40% reduction compared to the baseline scenarios by 2050.

Non-OECD countries

In baseline scenarios, the primary energy demand is projected to increase strongly in most of the non-OECD countries. In contrast, the 450 scenarios show a reduction of roughly 30-40% compared to the baseline by 2050, the same order of magnitude as the reduction in the OECD countries. There are regional differences, with e.g. South Africa showing a reduction up to 50% between the baseline and the delayed + intermediate 450 scenarios.

Comparison with the national model results

Compared to national projections, not all global models show a similar reduction of Indian energy demand (implying that the IEA scenarios are closer to the national scenario projections than some of the global model projections). The global model projections for Brazil are slightly lower than the projections by the national modelling team. Primary energy demand is projected to be about 15 EJ by 2050 under the intermediate 450 scenario in the global models, compared to 20 EJ according to the national model, which used the same carbon tax to create a scenario similar to the ones developed by the global models. For the delayed 450 scenario, the Brazilian national model projection shows a slightly different trajectory but a similar total primary energy demand in 2050 (about 40 EJ).

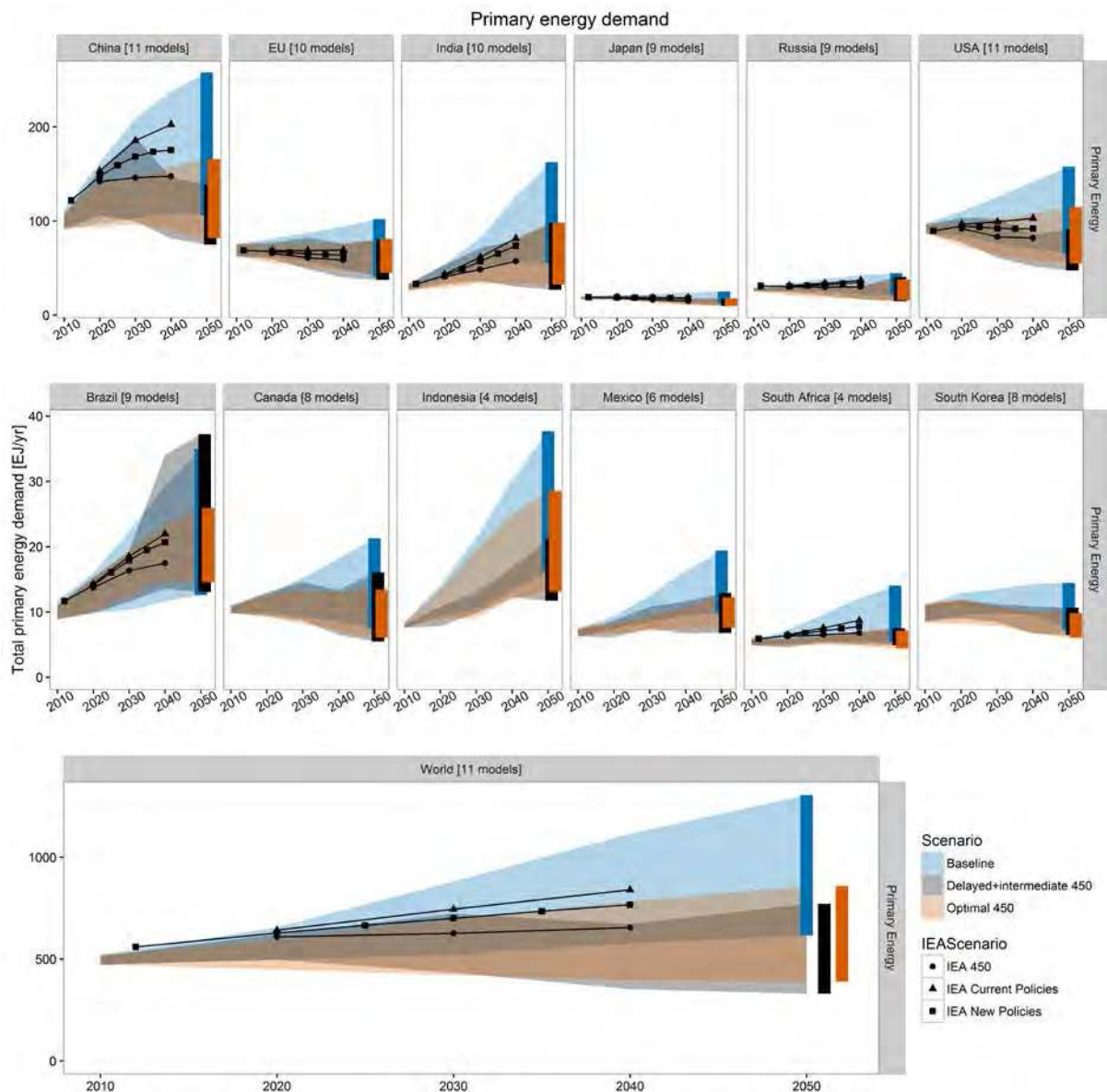


Figure 2: Total primary energy demand (EJ/year) in baseline, delayed + intermediate 450 ppm, and optimal 450 ppm scenarios. IEA World Energy Outlook scenarios (450 ppm, current policies, new policies) are also plotted for reference. The number of models per country reporting this variable is indicated. Coloured vertical bars show the 2050 scenario ranges.

Energy Intensity

Primary and final energy intensity decrease strongly in all countries and all scenarios, including the baseline scenario, but especially in developing countries and the Russian Federation (Figure 3).

Comparison with the national model results

The projected trends in energy intensity are generally in line with national scenario projections. For Brazil, the pathways as well as the absolute values are

very similar to the projections by the national modelling team. The Indian team noted that the projected trend of declining energy intensity agrees with their results of decoupling of energy use and GDP growth, although rates of decoupling might differ. Veysey et al. (2015) expect some improvement in energy intensity in Mexico between 2010 and 2020, and substantially more improvement towards 2050. This trend is most pronounced in the delayed + intermediate 450 scenarios shown in Figure 3.

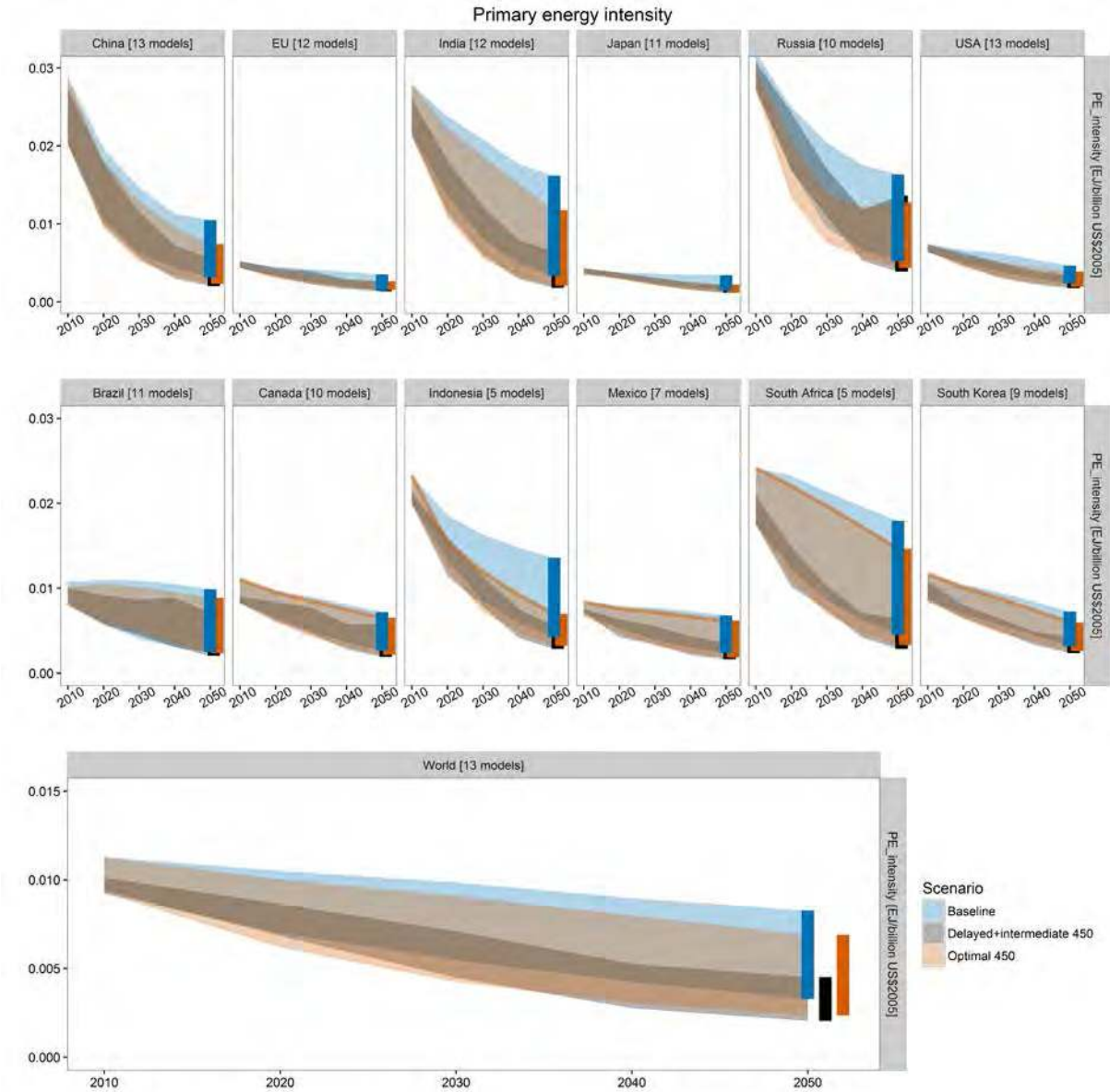


Figure 3: Primary energy intensity (EJ/billion US\$2005) in baseline, delayed + intermediate 450 ppm, and optimal 450 ppm scenarios. The number of models per country reporting the variables used to calculate energy intensity is indicated.

Greenhouse Gas Emissions

Figure 4 gives projected total CO₂ emissions, while Figure 5 presents projected CO₂ emissions per capita. Worldwide, a strong emission increase can be observed in the baseline scenarios, mostly driven by the trend in low-income countries. In contrast, total CO₂ emissions decrease rapidly for the mitigation scenarios in all countries, and even turn negative in Brazil, as a result of land-use management. Some differences can be observed across the different regions in the reduction rates – reflecting assumptions on mitigation potential. The Figure also shows quite substantial differences across the models for the various regions. The IEA emissions projections are at the lower end of the global model range, because they exclude land use change emissions.

Per capita CO₂ emissions are projected to decline in all countries under mitigation scenarios. Global average CO₂ emissions reach about 0.3 – 2 tCO₂/capita by 2050 under delayed 450 scenarios, with intermediate 450 scenarios falling within that range. Developing countries generally remain below the global average, although the upper end of the ranges for China, Indonesia and South Africa are slightly above the global average for the delayed 450 scenario category. Most OECD countries show per capita emissions ranges similar to or higher than the global average.

Figure 6 shows that total greenhouse gas emissions in 2030 need to decrease significantly below the baseline in all countries to remain on a 2°C pathway, as in the delayed and especially optimal 450 scenarios.

Comparison with the national model results

Indian national scenarios project per capita emissions that remain below the global average, which is also projected by the global models included in this study (0.2 – 1.4 tCO₂/capita by 2050 under delayed 450 scenarios). Herreras Martínez et al. (2015) report the results of the MESSAGE-Brazil model with projected CO₂ emissions for Brazil of 1633 MtCO₂ by 2050 under their reference scenario, and 212 MtCO₂ under a 450 ppm scenario. These numbers agree with the results from the global models in MILES, considering that the projections by Herreras Martínez et al. (2015) do not include land use emissions, while the projections shown in Figure 4 do. Global model emission projections for the European Union are in line with regional scenarios developed for the EU.

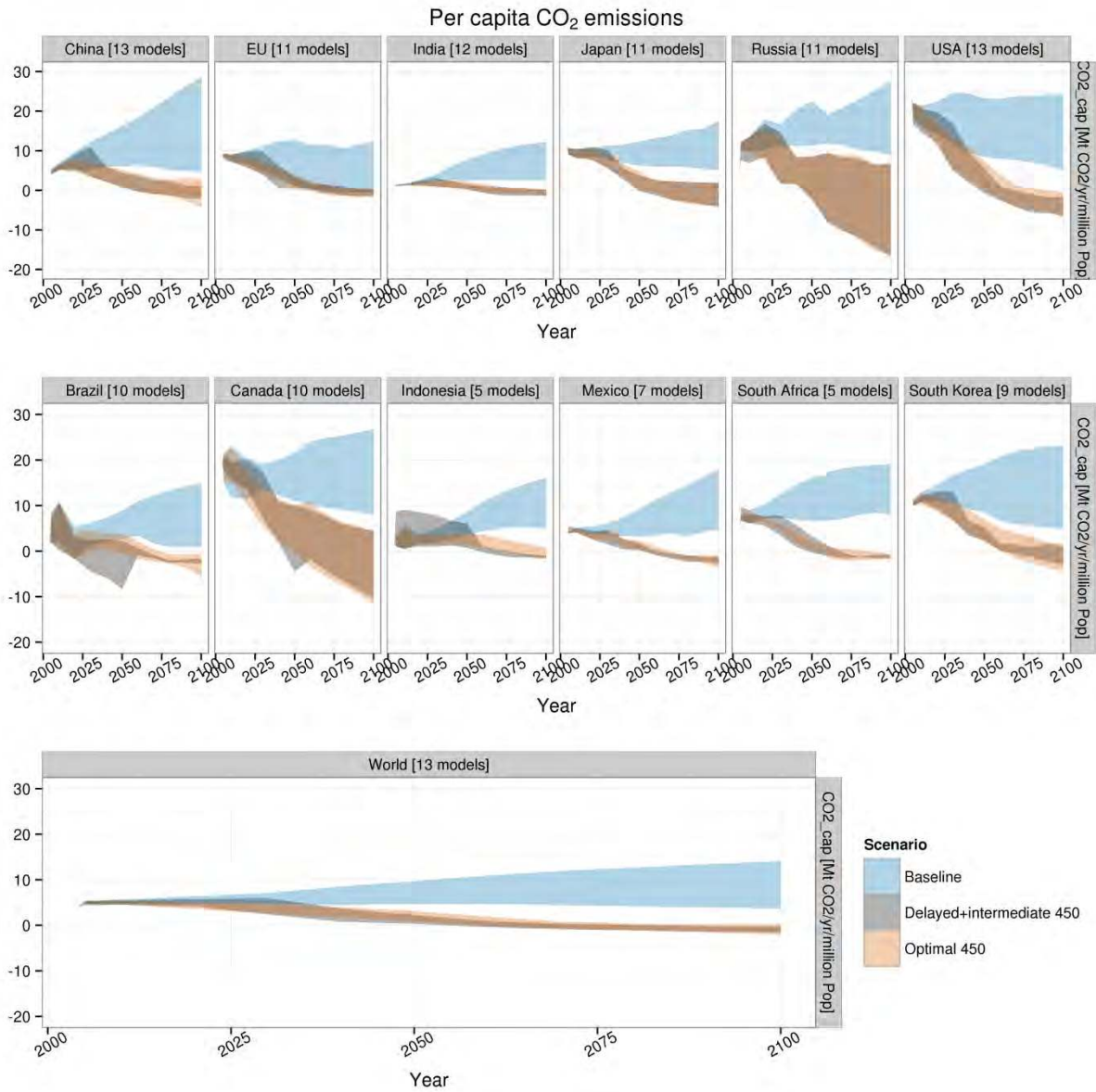


Figure 5: Per capita CO₂ emissions (tCO₂/capita) in baseline, delayed + intermediate 450 ppm, and optimal 450 ppm scenarios. The number of models per country reporting the variables used to calculate per capita emissions is indicated.

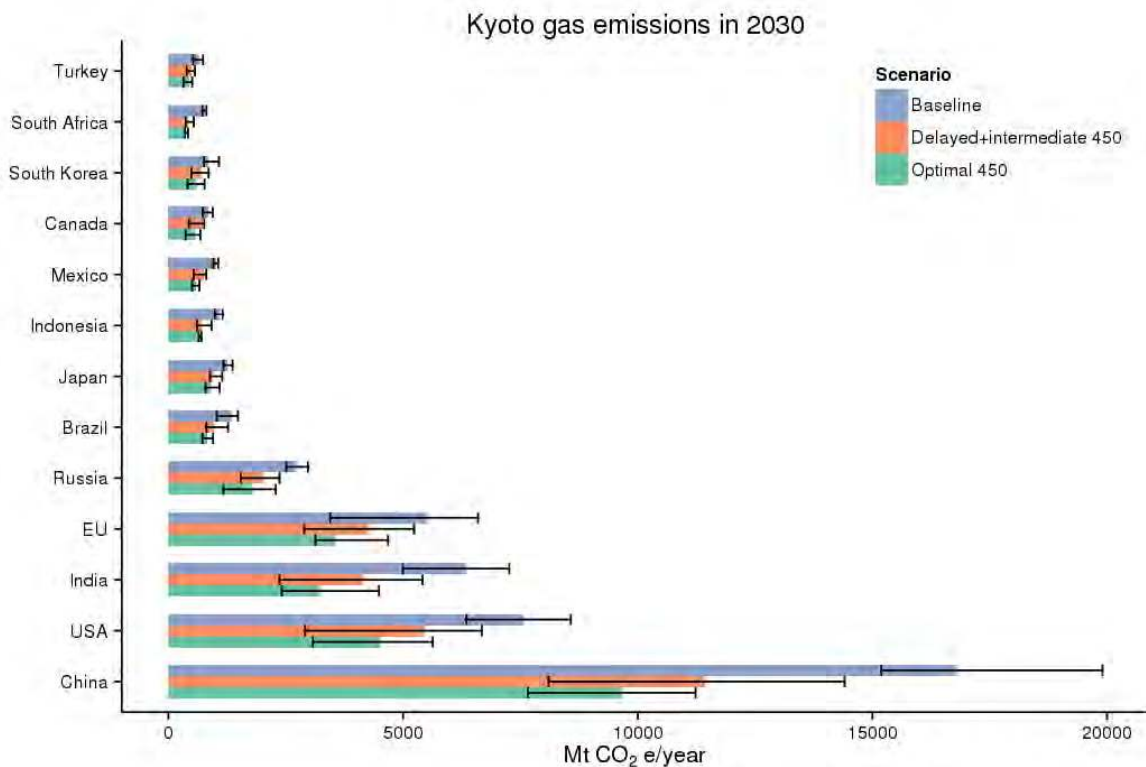


Figure 6: Kyoto gas emissions (MtCO₂e) in 2030 for Baseline, Delayed + intermediate 450, and Optimal 450 scenarios. Filled bars show the median value across models, error bars show the 10th to 90th percentile range.

Emissions: CO₂ Energy, CO₂ Land Use, Non-CO₂

Figure 7 shows the projected greenhouse gas emissions in 2050 in terms of CO₂ emissions from fossil fuels and industry, CO₂ emissions from land use, and non-CO₂ emissions. The emissions in each of these categories decline in the mitigation scenarios with respect to the baseline projections, with land use emissions even turning negative in some cases (Brazil, USA). CO₂ emissions from fossil fuels and industry represent the majority of global total emissions in the baseline, while the mitigation scenarios result in about equal shares of non-CO₂ emissions and CO₂ emissions from fossil fuels and industry globally. There are, however, regional differences. In China, for example, CO₂ emissions from fossil fuels and industry remain the major contributor to total emissions, while in Indonesia, land use emissions represent the largest share.

Looking at the change between 2010 and 2050 (lower part of Figure 7), globally, all emission categories show values lower than one in the mitigation scenarios, i.e. all emission sources decrease between 2010 and 2050. Please note that there are three emissions categories so the reference value for comparison with 2010 levels is three and not one. The Delayed 450 scenario shows larger reductions in all emission categories than the Optimal 450 scenario, because the Delayed 450 scenario requires faster and deeper emission reductions in the long

term than the Optimal 450 scenario.

Note that the intermediate 450 scenario category is not directly comparable to the other scenario categories, because it is mostly based on one model run, whereas the other scenario categories show the median of a larger number of runs.

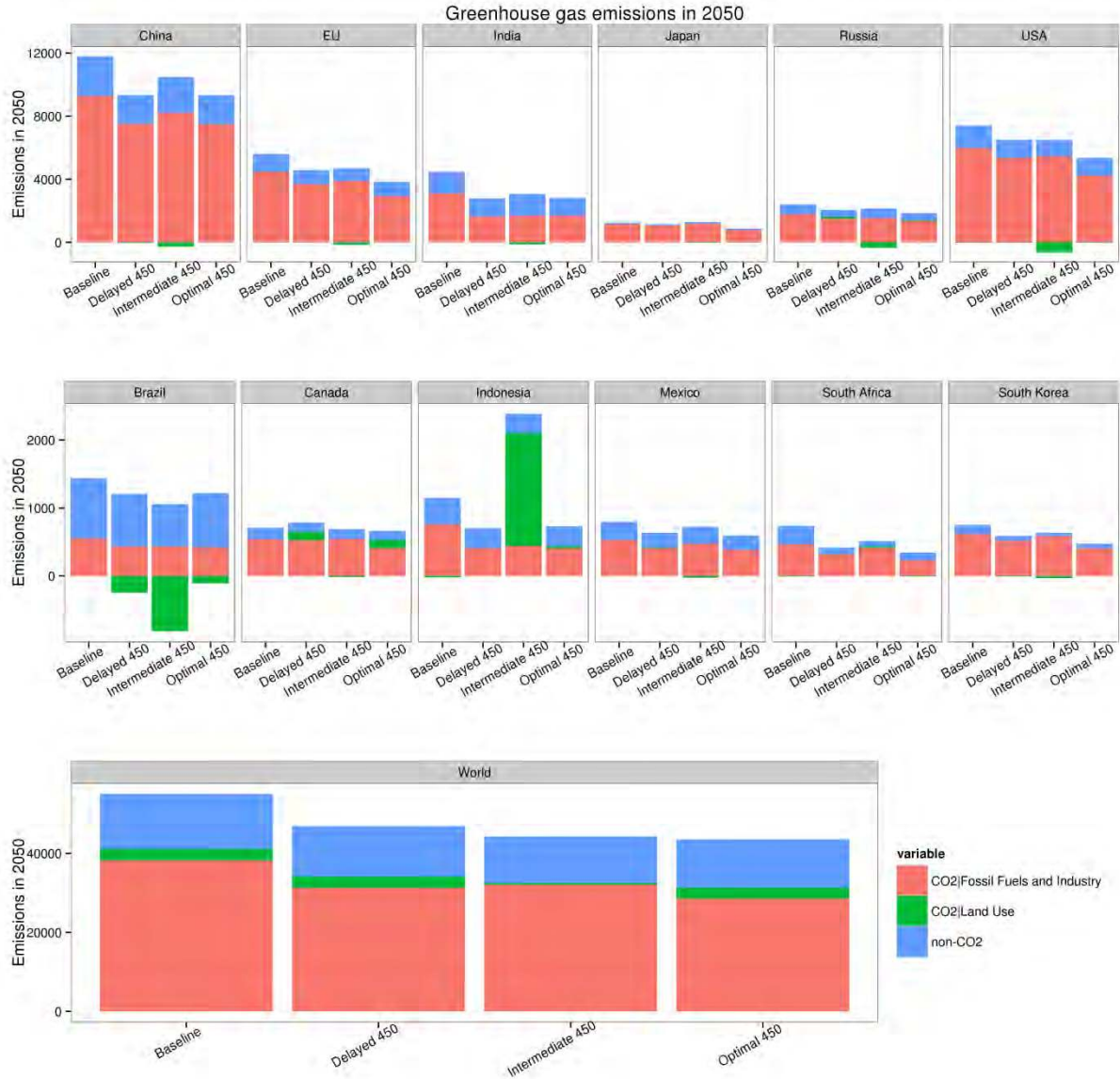




Figure 7: CO₂ emissions from energy supply and from land use, and non-CO₂ emissions in 2050 (upper graph: MtCO₂eq/year; lower graph: indexed to 2010) in baseline, delayed 450, intermediate 450 and optimal 450 scenarios.

Regional cumulative emissions

The scenarios can be used to calculate cumulative CO₂ emissions over a given period. These cumulative CO₂ emissions can be interpreted as regional emission constraints consistent with global climate policy targets assuming cost-efficient implementation across the regions. Note that the cumulative emissions linked to e.g. a <2°C temperature outcome need to be constantly updated to account for revised estimates of past, current and future emissions as well as developments in climate science. The regional cumulative emissions are presented in Figure 8

(median of all models). The difference in cumulative emissions between the baseline and the mitigation scenarios is especially pronounced in China and India.

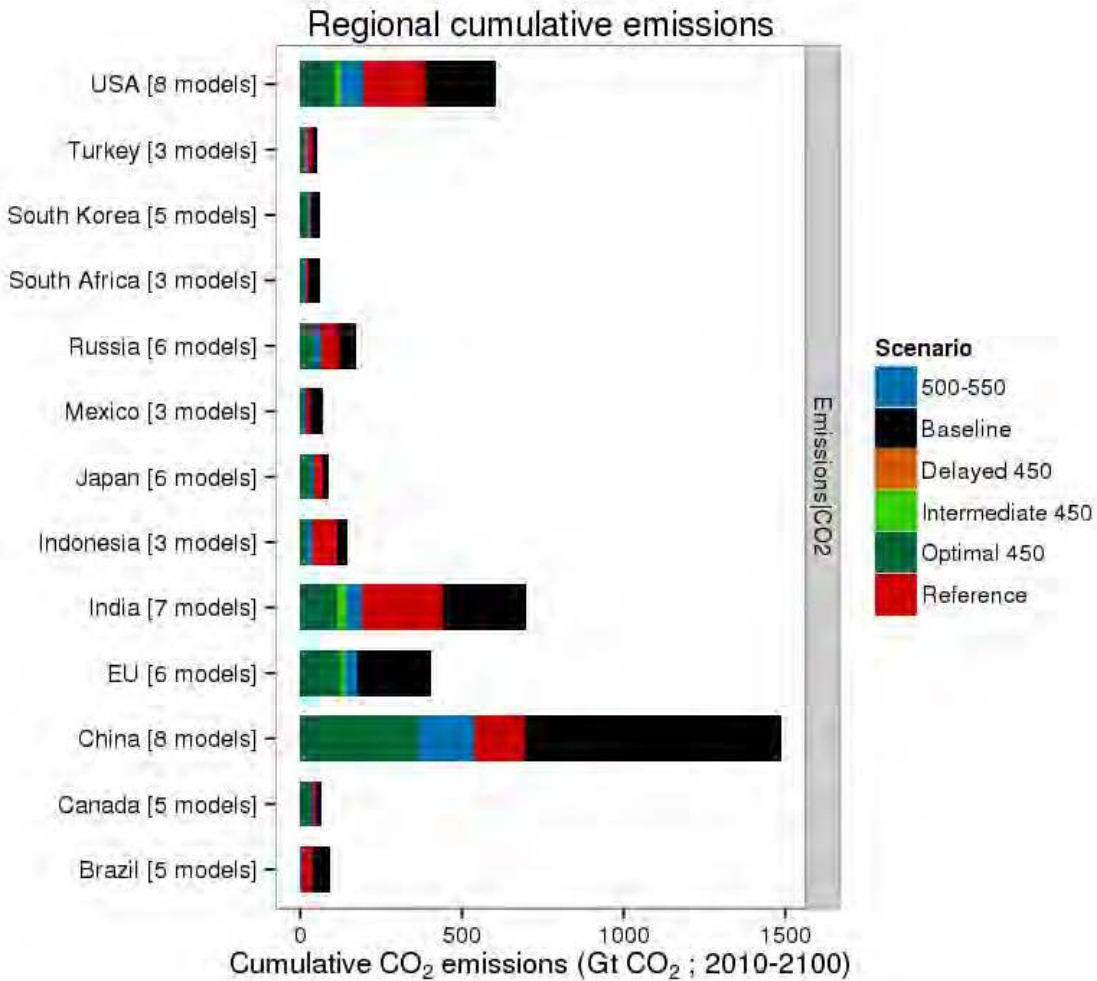


Figure 8: Cumulative CO₂ emissions (Gt CO₂) between 2010 and 2100 per country / region and scenario, based on the median of the model ensemble. The number of models per country is indicated. The coloured areas are indicative of the emission reductions going from one scenario category to another. For instance, the black area indicates the additional emissions in the baseline scenario compared to the current policy (reference) scenarios. The red area shows the additional emissions between current policies and 550 ppm CO₂.

Peak Year

Figure 9 presents the peak year in CO₂ emissions per region. Under the optimal 450 scenarios, most countries' CO₂ emissions peak before 2025 (except for India, which peaks around 2030). Under delayed 450 scenarios, this peak generally shifts to later in the century by construction, although not by much. The peak year is even later in 500-550 ppm scenarios, especially in India and Indonesia.

Comparison with the national model results

National scenarios for the European Union indicate that emissions have already peaked, which is not the case for some of the global model scenario results. For Brazil, the peak year of CO₂ emissions in the reference scenario is projected to be around 2060 (albeit with a large model spread), which is slightly later than found by Herreras Martínez et al. (2015), whose reference scenario shows a peak between 2045 and 2050. Peaking occurs considerably earlier in mitigation scenarios for Brazil, around 2015 under delayed 450 scenarios. The 450 ppm scenario by Herreras Martínez et al. (2015) peaks in 2020.

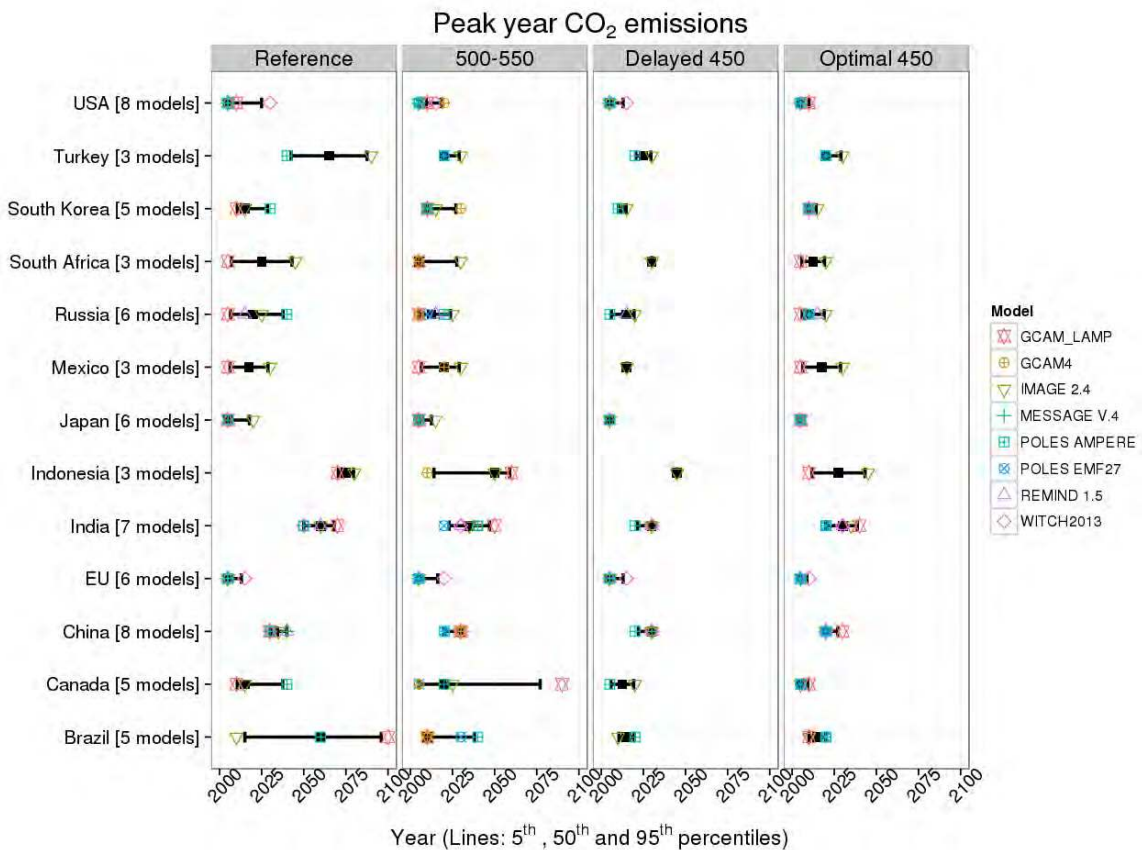


Figure 9: Peak year of CO₂ emissions per country, in reference, 500-550 ppm, delayed 450 and optimal 450 scenarios. Models are plotted individually (coloured shapes), lines show the 5th, 50th and 95th percentiles of the range of model results.

Low-carbon energy technology as a function of cumulative emissions

All countries show increasing deployment of low-carbon primary energy sources with respect to carbon-intensive energy sources as stringency in mitigation increases, i.e. lower cumulative emission scenarios, as shown in Figure 10. Low-carbon primary energy sources are all primary energy sources except coal, gas and oil without carbon capture and storage (CCS). For developed countries, this

generally means a substantial increase on 2010 levels. Some developing countries, such as Brazil, India and Indonesia, on the other hand, show 2010 shares of low-carbon primary energy sources that are already close to the range reached in mitigation scenarios (over 25% of total primary energy supply in these cases).

Figure 11 shows that the share of low-carbon energy sources in electricity generation increases substantially in mitigation scenarios, compared to baseline scenarios. In 2030, the global average share of low-carbon energy sources is roughly twice as high in mitigation scenarios as the share in baseline scenarios.

Comparison with the national model results

Mexico is projected to reach about a 65% – 100% share of low-carbon energy sources in the mitigation scenarios, which is confirmed by Veysey et al. (2015). They conclude that all models included in their study find a significant decarbonisation necessary to reach Mexico's greenhouse gas emission reduction target, with 'clean sources'³ reaching a share of 80% to 100% of electricity generation by 2050.

The Brazilian national modelling team created their own intermediate 450 scenario for comparison, in which they defined low-carbon sources in the same way as was used to produce Figure 11 (i.e. fossil fuels with CCS, nuclear, biomass with and without CCS, and non-biomass renewables). They find high shares of low-carbon sources in electricity generation, going from 79% in 2010 to 100% in 2050, mainly due to growth of non-biomass renewables (solar photovoltaic, solar CSP, distributed solar, wind, wind offshore, hydropower and ethanol). The global models project similar shares, reaching about 80%–100% by 2050.

³ Defined as in Mexico's Electricity Industry Law: non-biomass renewables, biomass, nuclear, and CCS technologies (Veysey et al., 2015).

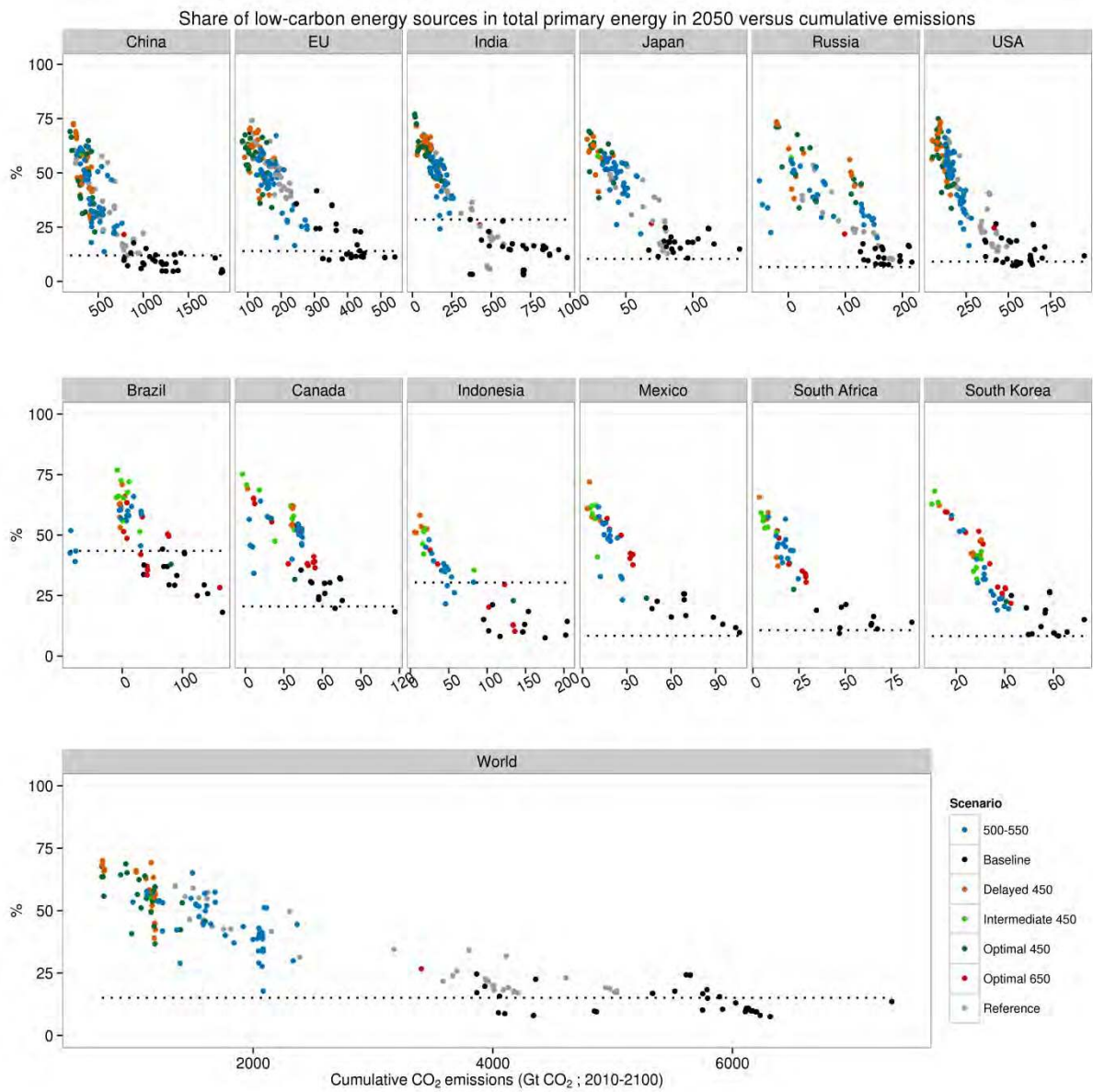


Figure 10: Share (%) of low-carbon primary energy sources (all sources except coal, gas and oil without carbon capture and storage, CCS) in total primary energy supply in 2050, versus cumulative CO₂ emissions (Gt CO₂) between 2010 and 2100. The scenario categories are shown as colour. 2010 values are indicated by black dotted lines.

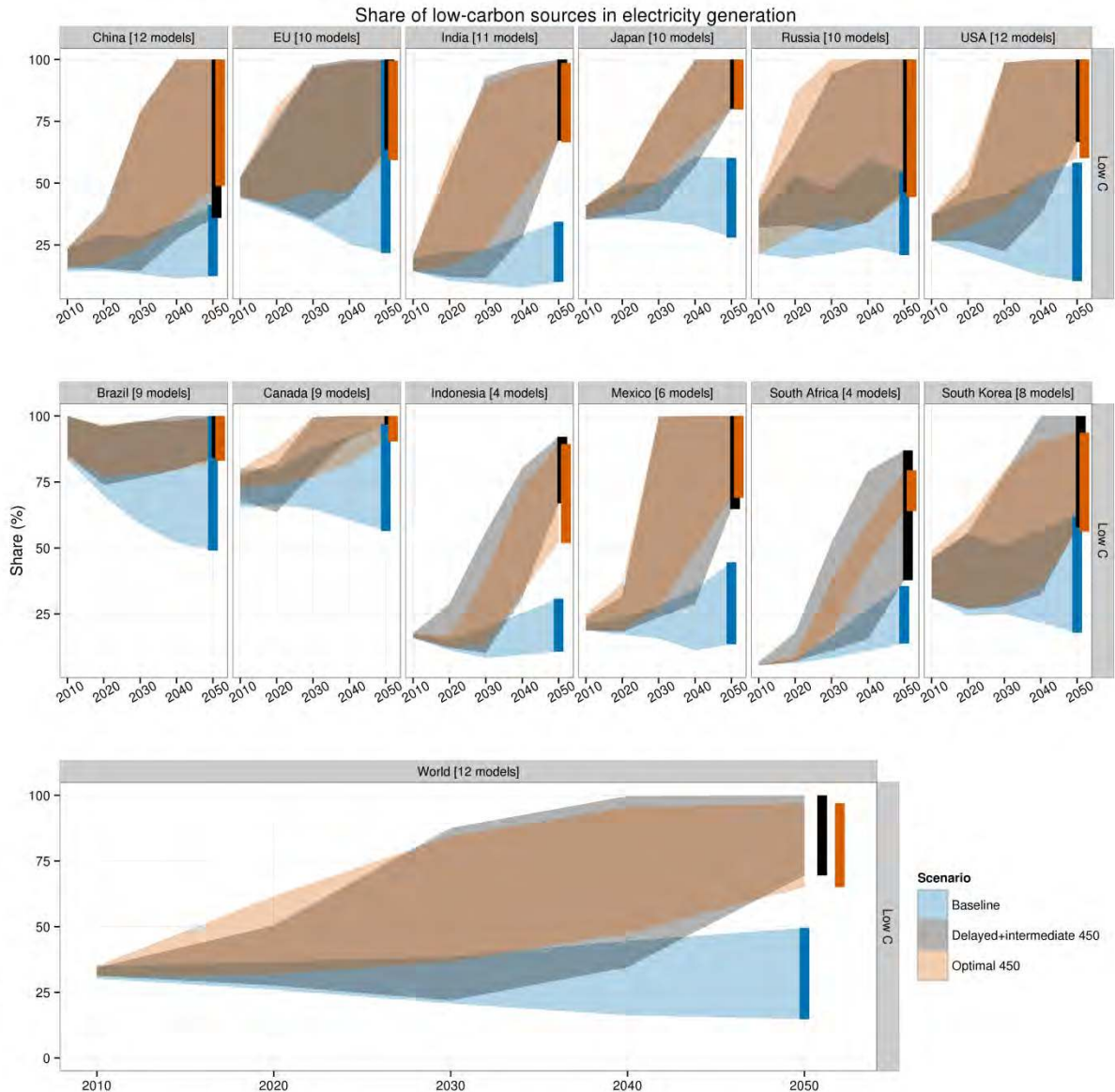


Figure 11: Share (%) of low-carbon energy sources in electricity generation (all sources except oil, gas and oil without carbon capture and storage, CCS). The number of models per country is indicated.

Policy Costs

By 2030, the median policy costs under optimal 450 scenarios are higher than those under delayed 450 scenarios for the world and for the region of China (Figure 12). However, the delayed 450 scenarios result in higher policy costs by 2050, compared to the optimal 450 scenarios. This can be explained by the steeper emission reductions needed in the longer term in the delayed 450 scenarios. To some extent, these policy costs may be compensated by avoided impacts of climate change, though economic modelling is beyond the scope of this paper.

Note that the regions are covered by less models than for other variables shown above, because models report different policy cost variables; here, consumption loss is shown.

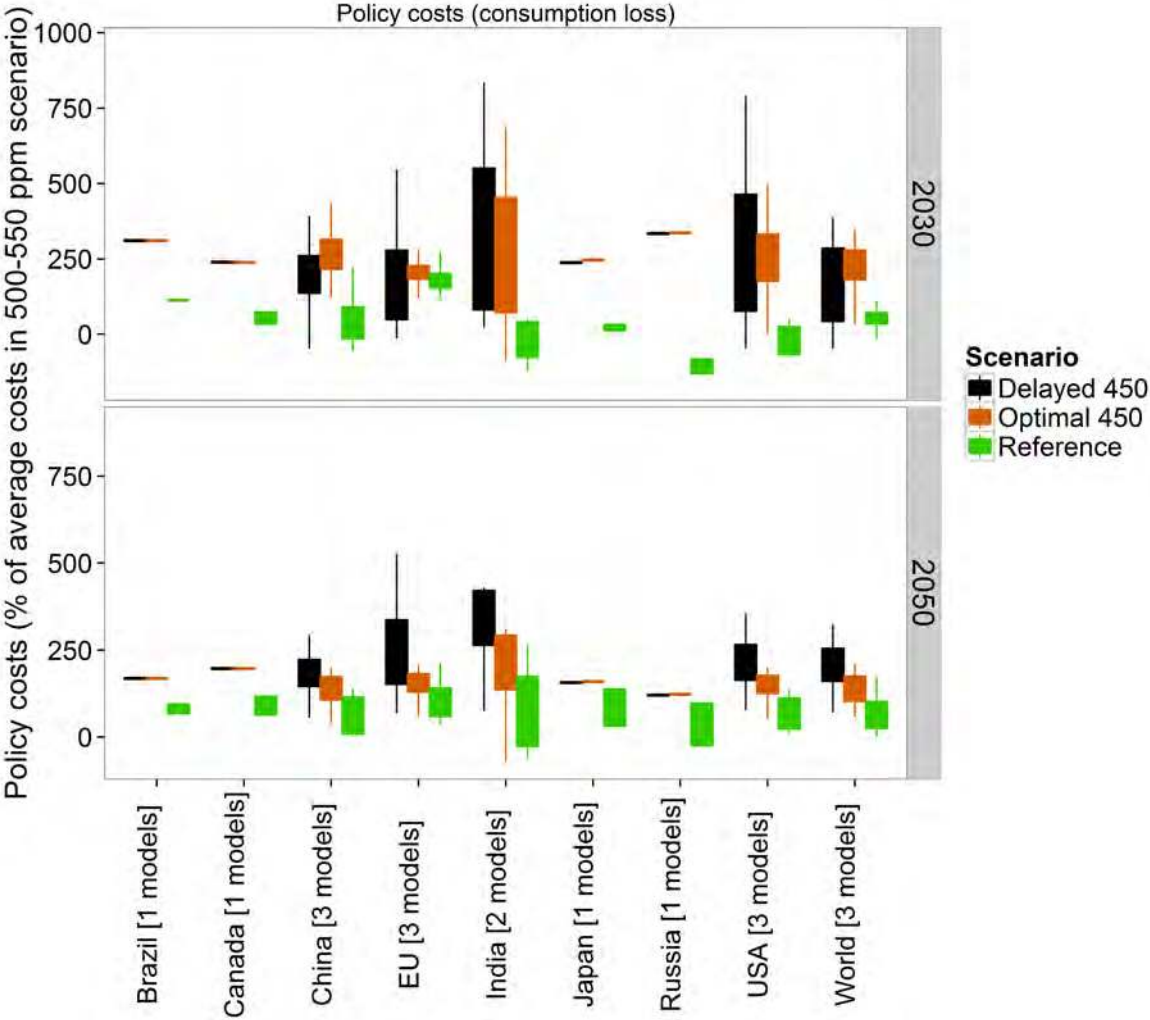


Figure 12: Policy costs (consumption loss), expressed as % of average costs in the 500-550 ppm scenarios of the same model, by 2030 and 2050, per country and scenario category. The number of models per country reporting this cost variable is indicated. Categories include the reference scenario (current climate policies), the cost-optimal implementation of a 450 ppm target and the delayed implementation of a 450 ppm target (see methods).

How do assumptions on the availability of different technologies influence these results?

Implications of Technology Availability Assumptions

The two modelling inter-comparison projects AMPERE and EMF27 have explored the implications of different technology assumptions on scenario results. Figure

13 shows the different primary energy mixes for five different technology assumptions as indicated in Table 5.

Table 5: Scenario categories used to evaluate technology availability implications (all scenario categories are variants of the AMPERE2-450-xxx-OPT scenario, thus assume an optimal 450 ppm pathway).

Scenario category	Description
FullTech	The default assumption of each model.
Low EI	Assuming lower energy intensity of the economy, which can be interpreted as a higher efficiency of end-use technologies, that are not explicitly represented in some of the models, or a less materialistic evolution of the economy with a strong focus on the service sector, or a combination of both.
noCCS	Assuming that carbon capture and storage will not be used (due to technology failures or as a political decision).
Conv	A conventional world, with only limited biomass use (100 EJ globally is available) and the share of variable power technologies (wind + solar) does not exceed 20% of electricity generation.
EERE	A world of high efficiency and with focus on renewable energies. This combines the assumption of LowEI and noCCS and additionally assumes a global phase-out of nuclear power after the end of the economic lifetime of all standing and currently planned nuclear reactors.

For this analysis, we have selected the REMIND model for illustration, which studied several variants of the AMPERE2-450-xxx-OPT scenario for the 6 regions shown in Figure 13. REMIND was the only model able to provide all scenarios for all 6 regions.

These different assumptions result in very strong differences in the deployment of different technologies, with generally more deployment of the unrestricted options, if one or several options are unavailable. Therefore, the extremes observed in technology-restricted scenarios tend to be higher than in the default scenario (FullTech). Moreover, the difference across scenarios is more important than variability across regions. The results imply a large deployment of CCS for India and Japan, which might raise feasibility problems. Furthermore, the high use of biomass for some regions is improbable unless regions can import biomass.

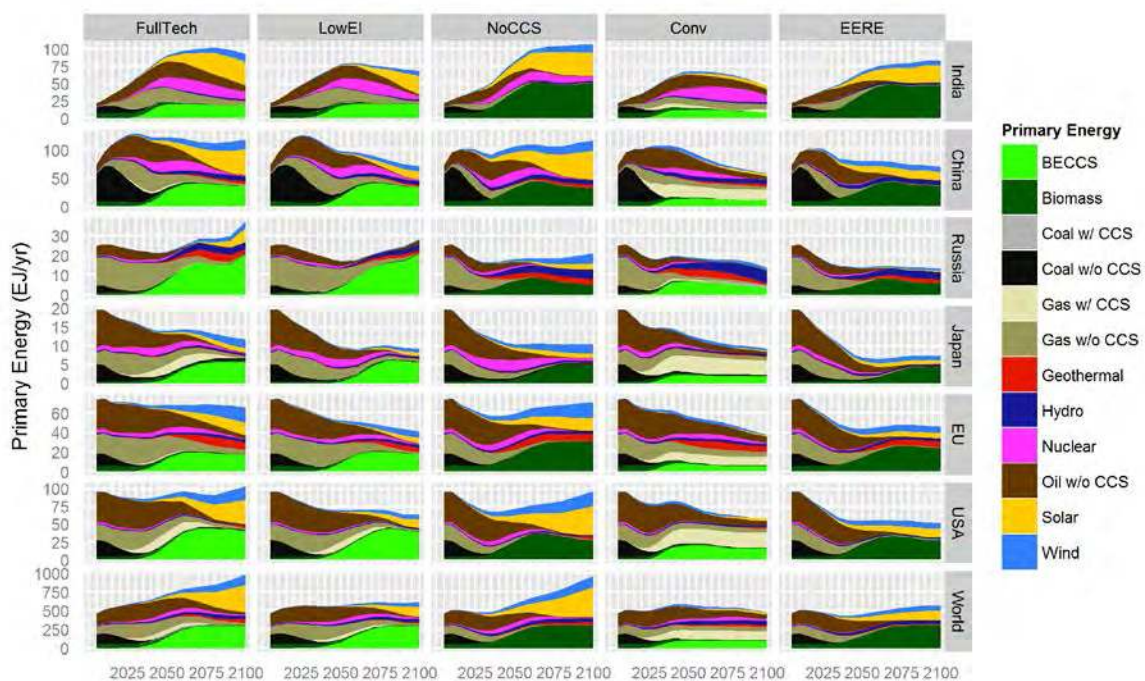


Figure 13: Primary energy mixes for 4 major economies + world under different assumptions on technology availability in the REMIND model.

What are important co-benefits at the national/ regional level of the different policies?

Co-benefits

Energy Security and Energy Independence Co-benefits of Mitigation

Climate policies (both existing pledges⁴ (see e.g. Den Elzen et al., 2015, Roelfsema et al., 2014) and 450 stabilization scenarios) globally lead to lower energy trade (Cherp et al., 2013, Jewell et al., 2014, Jewell et al., 2013), but both the uncertainty and the reduction in net-energy imports (or conversely reduction in net-exports) from the baseline varies between countries and over time. There are three types of national dynamics with respect to net-energy trade. Firstly, energy importers generally experience a decrease in net-energy imports in climate stabilization scenarios compared to the baseline development while, secondly, energy exporters experience a loss of energy export revenues from climate stabilization policies (Figure 14). However, the differences between the baseline and the climate stabilization scenario are relatively small, except for the Middle East and North Africa (MENA) region. The results for Canada are

⁴ The **Pledges** scenario is the so-called “Stringent Policy” scenario from the LIMITS exercise (Kriegler et al., 2014b).

influenced by one model showing a strong decrease in exports. Regional analyses for Europe and the 2030 framework study show that energy imports decrease with increasing ambition of climate policies, confirming the trends shown in Figure 14.

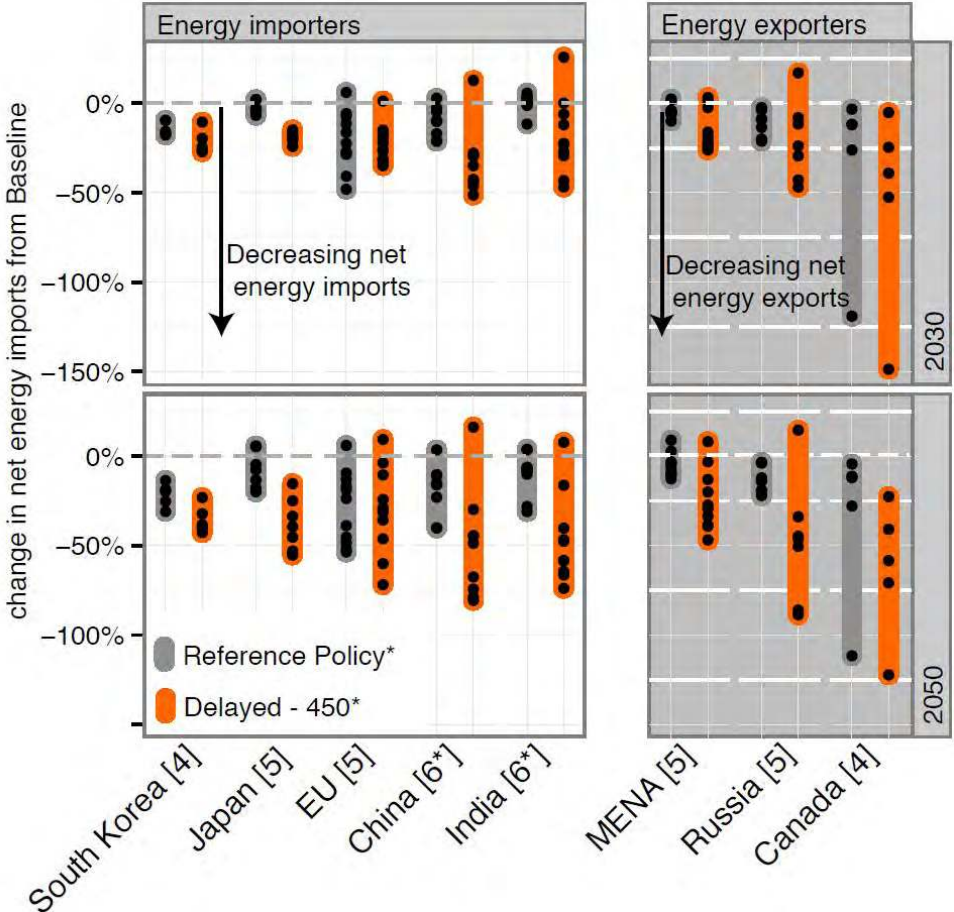


Figure 14: Change in net-energy imports (left) and net-energy exports (right) for major energy importers and exporters. The number for each country represents the number of models. * Note: Reference Policy includes LIMITS-RefPol and AMPERE3-RefPol. Delayed-450 includes LIMITS-RefPol-450 and AMPERE3-450. Models include IMAGE, MESSAGE, REMIND, TIAM-ECN, WITCH, DNE and POLES. For China and India, we excluded one model which diverges from the trend of all the other models. In both cases, all but one model depict them as energy importers.

Thirdly, there are countries that in the baseline experience changes in their net-energy trade (Table 6). For these countries, climate policies would likely not have the biggest impact on their net-energy trade in the short term, but rather the relative cost of extraction technologies and resource base development between different regions. This dynamic is most pronounced in the USA, which becomes a net energy exporter (primarily of coal) in most models between 2025 and 2060; climate stabilization does not reverse this trend but delays it and prevents the USA from developing significant energy export revenues in the latter half of the century. For Mexico, as the country’s oil reserves are depleted, the country

becomes a net energy importer around 2030, followed by growing energy imports. Climate stabilization curbs the growth of energy imports. Finally, Brazil is characterized by very low energy imports today, which grow but plateau around 2030 before becoming a net energy exporter around 2050.

Table 6: Countries with shifting net-energy dependence in the Baseline

	Baseline	Reference Policy	Delayed-450
USA	Becomes a net energy exporter in most models (5 out of 7) between 2025 and 2060.	Similar to Baseline but the shift is delayed and coal exports are lower.	Similar to Baseline but loses most energy exports post 2050.
Mexico	Oil reserves are depleted, and becomes energy importer ~ 2030 followed by growing imports.	Similar to Baseline	Similar to Baseline but lower imports.
Brazil	Very low energy imports today. In Baseline, modest growth in energy imports which plateau ~ 2030.	Similar to Baseline	Similar to Baseline

Air Pollution Co-benefits of Mitigation

Achieving a 450 ppm stabilization scenario implies a fundamental transformation of the global energy system. Such a transformation will not only result in the required greenhouse gas emissions reductions, but will also affect the abundance of air pollutants in the atmosphere. Greenhouse gas emissions, in particular CO₂, are reduced to a large degree by phasing out unabated fossil-fuel energy production, like coal, and replacing them with less carbon intensive alternatives like renewables or biomass energy. Because air pollutants are co-emitted with CO₂ during the combustion processes, changes in the energy system can result in less or more air pollutants emissions.

Figure 15 shows that, across the board, sulphur dioxide emissions are strongly reduced as a positive side-effect of greenhouse gas emission mitigation. This is the case for both developing and developed countries. The main reason for this reduction is that unabated coal combustion is a dominant source of sulphur dioxide emissions, and this source of energy production needs to be rapidly

replaced by less carbon-intensive alternatives in order to achieve a 450 stabilization scenario.

Significant reductions can also be found for emissions of black carbon (soot). However, because black carbon can be emitted during the combustion of fossil fuels as well as from much less carbon-intensive energy sources, like biomass (Bond et al., 2013), the effect can vary regionally. While, generally, black carbon emissions are reduced together with emissions of greenhouse gases in 450 scenarios, some estimates show increasing black carbon emissions in countries that strongly rely on bioenergy to achieve their greenhouse gas targets. In the latter cases, more complementary policies are required to specifically reduce air pollution from black carbon.

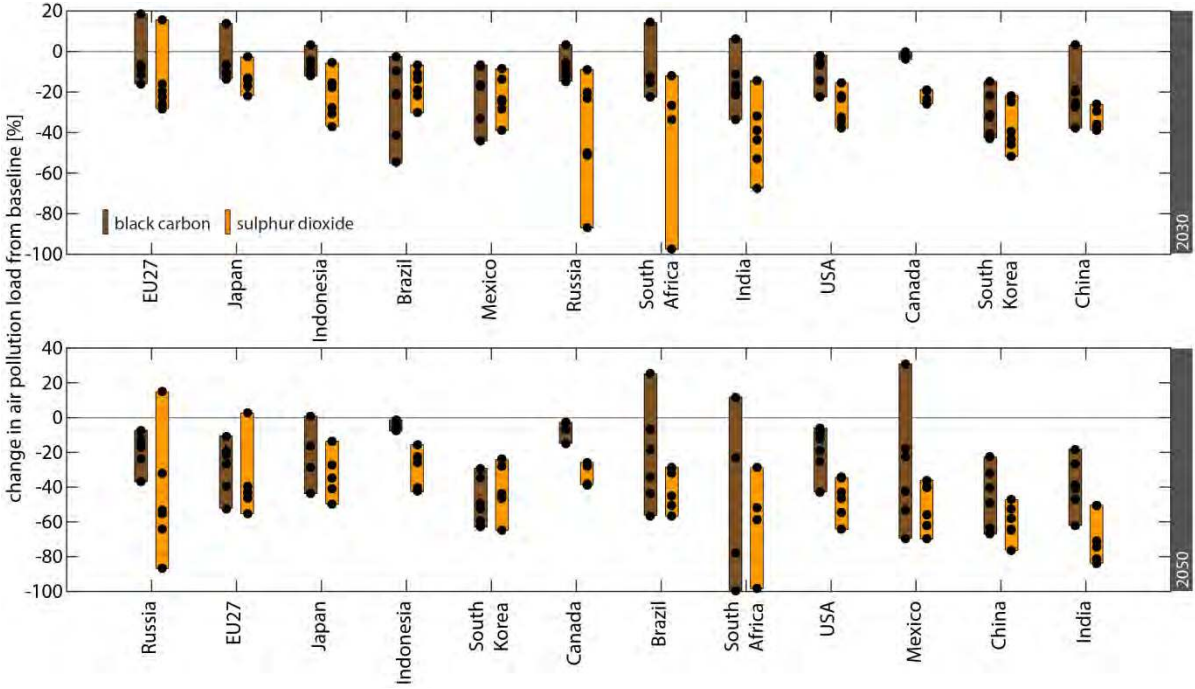


Figure 15: Changes in black carbon (brown) and sulphur dioxide (orange) emissions when moving from a baseline in absence of targeted new climate policies to a pathway in line with stabilizing atmospheric CO₂-equivalent concentrations at 450 ppm. Data is provided for 2030 (top) and 2050 (bottom). Dots show single model results, bars the full range. * Note: The LIMITS-Base (LIMITS1) scenario is taken as the baseline scenarios. LIMITS-RefPol-450 (LIMITS6) is taken as the 450 scenario. Models include IMAGE, MESSAGE, REMIND, GCAM, AIM, and WITCH. In case models did not report data at the national level, the reductions in air pollutants from the encompassing region were downscaled based on the shares found in the IMAGE model. Both the baseline and the 450 scenario assume a successful implementation of current air pollution legislation policies (CLE).

Conclusions

In this paper, we have looked into the regional results of a set of global models in order to derive policy-relevant indicators at the national level and to compare the insights of the global models with insights of national modelling teams.

General conclusions

- **The mitigation scenarios require major emission reductions in all countries. These can only be achieved by a considerable change in the energy supply of these countries.** Primary energy demand decreases strongly in the mitigation scenarios, compared to the baseline scenario, especially in developing countries. The 450 scenarios show a reduction in all countries of roughly 30-40% compared to the baseline. There are regional differences, with e.g. South Africa showing a stronger reduction in primary energy demand under mitigation scenarios.
- **Per capita CO₂ emissions are projected to decline in all countries under mitigation scenarios. Global average CO₂ emissions reach about 0.3 – 2 tCO₂/ capita under delayed 450 scenarios.** Total CO₂ emissions decrease in most countries under the mitigation scenarios, and even turn negative in Brazil (due to land use, acting as a sink). In terms of per capita emissions, developing countries generally remain below the global average, although the upper end of the ranges for China, Indonesia and South Africa are slightly above the global average. Most OECD countries show per capita emissions ranges similar to or higher than the global average. CO₂ emissions from fossil fuels and industry represent the majority of global total emissions in the baseline, while the mitigation scenarios result in about equal shares of non-CO₂ emissions and CO₂ emissions from fossil fuels and industry globally. There are, however, regional differences in the mitigation scenarios. In China, for example, CO₂ emissions from fossil fuels and industry remain the major contributor to total emissions, while in Indonesia, land use emissions represent the lion's share. The difference in cumulative emissions between the baseline and the mitigation scenarios is especially pronounced in China and India (assuming cost-efficient implementation across regions).
- **Under the optimal 450 scenarios, most countries' CO₂ emissions peak before 2025 (except for India) and a phase-out of CO₂ emission occurs around 2060.** Under delayed and intermediate 450 scenarios (taking into account 2020 pledges and introducing optimal policies between 2020 and 2025), this peak generally shifts to later in the century, although not by much. The peak year is even later in 500-550 ppm scenarios, especially in India and Indonesia.
- **All countries show increasing shares of low-carbon primary energy sources with lower cumulative emissions.** For developed countries,

this generally means a substantial increase on 2010 levels. Some developing countries, such as Brazil, India and Indonesia, on the other hand, show 2010 shares of low-carbon primary energy sources that are already close to the range reached in mitigation scenarios (over 25% of total primary energy supply in these cases).

- **There is a cost advantage to starting mitigation early.** Delayed 450 scenarios show lower median policy costs in the short term in some regions (China and the world), but higher policy costs in the long term in all regions, compared to the optimal 450 scenarios.

Comparison with national projections

- **In general the projections seem to be in line with those used at the national level, although the latter show somewhat higher growth rates in Brazil and India.**
- Primary energy intensity decreases strongly in all countries and all scenarios, including the baseline scenario, but especially in developing countries and the Russian Federation.

Co-benefits

- **Energy importing countries generally experience a decrease in net-energy imports in climate stabilization scenarios compared to the baseline development, while energy exporters experience a loss of energy export revenues from climate stabilization policies.** Countries that experience changes in net energy trade in the baseline, most notably the USA, are likely more affected by relative costs of extraction technologies and resource base developments than by climate policies.
- **Across the board, sulphur dioxide emissions are strongly reduced as a positive side-effect of greenhouse gas emission mitigation.** This is the case for both developing and developed countries. Significant reductions of black carbon emissions can also be found, albeit with regional differences. Countries that strongly rely on bioenergy to reach mitigation targets, for example, see increasing black carbon emissions, thus requiring additional policies to reduce air pollution from black carbon.

Acknowledgements

This publication has been prepared by PBL and FEEM/CMCC for the MILES project Consortium under contract to DG CLIMA (No. 21.0104/2014/684427/SER/CLIMA.A.4).

The MILES project

The MILES project (Modelling and Informing Low Emission Strategies) is an international cooperation project between 19 research teams from emerging countries like China, India and Brazil and research teams in developed countries from Europe, the US and Japan. Key objectives of the project are: 1) to explore different country-level strategies consistent with the 2°C target, 2) to increase understanding of differences between strategies in different parts of the world, and 3) to enhance in all participating countries the capacity to perform analysis of mitigation strategies. This is implemented by sharing experience on i) scenario definition to ensure the necessary level of detail in the definition of the low-carbon strategies for informing national and international policy discussions on decarbonisation, ii) model development to ensure the improvement of national modelling capacities permitting the elaboration of modelling frameworks able to represent a broad coverage of sectors, activities and GHG, and enable the representation of socio-economic implications of policy choices; iii) comparative and diagnostic model analysis to better understand the influence of model structure on model results and iv) policy analysis of model results to identify those trajectories that are relevant for the purpose of defining strategies and policies that are both consistent with climate and development objectives.

This project is funded by the European Union.



Disclaimer: This publication was written by a group of independent experts who have not been nominated by their governments. The contents of this publication are the sole responsibility of PBL and FEEM/CMCC and can in no way be taken to reflect the views of the European Union or any government, organization, etc.

References

- BOND, T. C., DOHERTY, S. J., FAHEY, D. W., FORSTER, P. M., BERNTSEN, T., DEANGELO, B. J., FLANNER, M. G., GHAN, S., KÄRCHER, B., KOCH, D., KINNE, S., KONDO, Y., QUINN, P. K., SAROFIM, M. C., SCHULTZ, M. G., SCHULZ, M., VENKATARAMAN, C., ZHANG, H., ZHANG, S., BELLOUIN, N., GUTTIKUNDA, S. K., HOPKE, P. K., JACOBSON, M. Z., KAISER, J. W., KLIMONT, Z., LOHMANN, U., SCHWARZ, J. P., SHINDELL, D., STORELVMO, T., WARREN, S. G. & ZENDER, C. S. 2013. Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres*, 118, 5380-5552.
- CHERP, A., JEWELL, J., VINICHENKO, V., BAUER, N. & DE CIAN, E. 2013. Global energy security under different climate policies, GDP growth rates and fossil resource availabilities. *Climatic Change*, 1-12.
- CLARKE, L., JIANG, K., AKIMOTO, K., BABIKER, M., BLANFORD, G., FISHER VANDEN, K., HOURCADE, J., KREY, V., KRIEGLER, E., LÖSCHEL, A., MCCOLLUM, D., PALTSEV, S., ROSE, S., R. SHUKLA, P., TAVONI, M., VAN DER ZWAAN, B. & VAN VUUREN, D. P. 2014. Assessing Transformation Pathways. In: EDENHOFER, O., PICHs-MADRUGA, R., SOKONA, Y., FARAHANI, E., KADNER, S., SEYBOTH, K., ADLER, A., BAUM, I., BRUNNER, S., EICKEMEIER, P., KRIEMANN, B., SAVOLAINEN, J., SCHLÖMER, S., VON STECHOW, C., ZWICKEL, T. & MINX, J. C. (eds.) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge, United Kingdom: Cambridge University Press.
- DEN ELZEN, M. G. J., FEKETE, H., ADMIRAAL, A., FORSELL, N., HÖHNE, N., KOROSUO, A., ROELFSEMA, M., VAN SOEST, H., WOUTERS, K., DAY, T., HAGEMANN, M., HOF, A. & MOSNIER, A. 2015. Enhanced Policy Scenarios for Major Emitting Countries. Analysis of Current and Planned Climate Policies, and Selected Enhanced Mitigation Measures. The Hague: PBL Netherlands Environmental Assessment Agency.
- HERRERAS MARTÍNEZ, S., KOBERLE, A., ROCHEDO, P., SCHAEFFER, R., LUCENA, A., SZKLO, A., ASHINA, S. & VAN VUUREN, D. P. 2015. Possible energy futures for Brazil and Latin America in conservative and stringent mitigation pathways up to 2050. *Technological Forecasting and Social Change*.
- JEWELL, J., CHERP, A. & RIAHI, K. 2014. Energy security under de-carbonization scenarios: An assessment framework and evaluation under different technology and policy choices. *Energy Policy*, 65, 743-760.
- JEWELL, J., CHERP, A., VINICHENKO, V., BAUER, N., KOBER, T., MCCOLLUM, D., VAN VUUREN, D. P. & VAN DER ZWAAN, B. 2013. Energy security of China, India, the E.U. and the U.S. under long-term scenarios: Results from six IAMs. *Climate Change Economics*, 04, 1340011.
- KRIEGLER, E., RIAHI, K., BAUER, N., SCHWANITZ, V. J., PETERMANN, N., BOSETTI, V., MARCUCCI, A., OTTO, S., PAROUSSOS, L., RAO, S., ARROYO CURRÁS, T., ASHINA, S., BOLLEN, J., EOM, J., HAMDY-CHERIF, M., LONGDEN, T., KITOUS, A., MÉJEAN, A., SANO, F., SCHAEFFER, M., WADA, K., CAPROS, P., VAN VUUREN, D. & EDENHOFER, O. 2014a. Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technological Forecasting and Social Change*.
- KRIEGLER, E., TAVONI, M., ABOUMAHBOUB, T., LUDERER, G., CALVIN, K., DE MAERE, G., KREY, V., RIAHI, K., ROSLER, H., SCHAEFFER, M. & VAN VUUREN, D. 2014b. What does the 2°C target imply for a global climate agreement in 2020? The LIMITS study on Durban Platform scenarios. *Climate Change Economics*, 4.
- KRIEGLER, E., WEYANT, J. P., BLANFORD, G. J., KREY, V., CLARKE, L., EDMONDS, J., FAWCETT, A., LUDERER, G., RIAHI, K., RICHEL, R., ROSE, S. K., TAVONI, M. & VAN VUUREN, D. P.

- 2014c. The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change*, 123, 353-367.
- RIAHI, K., KRIEGLER, E., JOHNSON, N., BERTRAM, C., DEN ELZEN, M., EOM, J., SCHAEFFER, M., EDMONDS, J., ISAAC, M., KREY, V., LONGDEN, T., LUDERER, G., MÉJEAN, A., MCCOLLUM, D. L., MIMA, S., TURTON, H., VAN VUUREN, D. P., WADA, K., BOSETTI, V., CAPROS, P., CRIQUI, P., HAMDI-CHERIF, M., KAINUMA, M. & EDENHOFER, O. 2014. Locked into Copenhagen pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change*.
- ROELFSEMA, M., DEN ELZEN, M. G. J., HÖHNE, N., HOF, A. F., BRAUN, N., FEKETE, H., BRANDSMA, R., LARKIN, J. & BÖTTCHER, H. 2014. Are major economies on track to achieve their pledges for 2020? An assessment of domestic climate and energy policies. *Energy Policy*.
- TAVONI, M., KRIEGLER, E., RIAHI, K., VAN VUUREN, D. P., ABOUMAHBOUB, T., BOWEN, A., CALVIN, K., KOBER, T., JEWELL, J., LUDERER, G., MARANGONI, G., MCCOLLUM, D., VAN SLUISVELD, M., ZIMMER, A. & VAN DER ZWAAN, B. 2014. Post-2020 climate agreements in the major economies assessed in the light of global models. *Nature Clim. Change*, Published on-line.
- UNFCCC 2010. Report of the Conference of the Parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010. Addendum. Part Two: Action taken by the Conference of the Parties at its sixteenth session. Decision 1/CP.16: The Cancun Agreements: Outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention. FCCC/CP/2010/7/Add.1.
- VAN SLUISVELD, M. A. E., GERNAAT, D. E. H. J., ASHINA, S., CALVIN, K. V., GARG, A., ISAAC, M., LUCAS, P. L., MOURATIADOU, I., OTTO, S. A. C., RAO, S., SHUKLA, P. R., VAN VLIET, J. & VAN VUUREN, D. P. 2013. A multi-model analysis of post-2020 mitigation efforts of five major economies. *Climate Change Economics*, 04, 1340012.
- VEYSEY, J., OCTAVIANO, C., CALVIN, K., MARTINEZ, S. H., KITOUS, A., MCFARLAND, J. & VAN DER ZWAAN, B. 2015. Pathways to Mexico's climate change mitigation targets: A multi-model analysis. *Energy Economics*.

NOTE DI LAVORO DELLA FONDAZIONE ENI ENRICO MATTEI

Fondazione Eni Enrico Mattei Working Paper Series

Our Note di Lavoro are available on the Internet at the following addresses:

<http://www.feem.it/getpage.aspx?id=73&sez=Publications&padre=20&tab=1>
http://papers.ssrn.com/sol3/JELJOUR_Results.cfm?form_name=journalbrowse&journal_id=266659
<http://ideas.repec.org/s/fem/femwpa.html>
<http://www.econis.eu/LNG=EN/FAM?PPN=505954494>
<http://ageconsearch.umn.edu/handle/35978>
<http://www.bepress.com/feem/>

NOTE DI LAVORO PUBLISHED IN 2015

ERM	1.2015	Elena Verdolini, Laura Diaz Anadon, Jiaqi Lu and Gregory F. Nemet: The Effects of Expert Selection, Elicitation Design, and R&D Assumptions on Experts' Estimates of the Future Costs of Photovoltaics
CCSD	2.2015	James Lennox and Ramiro Parrado: Capital-embodied Technologies in CGE Models
CCSD	3.2015	Claire Gavard and Djamel Kirat: Flexibility in the Market for International Carbon Credits and Price Dynamics Difference with European Allowances
CCSD	4.2015	Claire Gavard: Carbon Price and Wind Power Support in Denmark
CCSD	5.2015	Gunnar Luderer, Christoph Bertram, Katherine Calvin, Enrica De Cian and Elmar Kriegler: Implications of Weak Near-term Climate Policies on Long-term Mitigation Pathways
CCSD	6.2015	Francisco J. André and Luis M. de Castro: Incentives for Price Manipulation in Emission Permit Markets with Stackelberg Competition
CCSD	7.2015	C. Dionisio Pérez Blanco and Thomas Thaler: Water Flows in the Economy. An Input-output Framework to Assess Water Productivity in the Castile and León Region (Spain)
CCSD	8.2015	Carlos M. Gómez and C. Dionisio Pérez-Blanco: Simple Myths and Basic Maths about Greening Irrigation
CCSD	9.2015	Elorri Igos, Benedetto Rugani, Sameer Rege, Enrico Benetto, Laurent Drouet, Dan Zachary and Tom Haas: Integrated Environmental Assessment of Future Energy Scenarios Based on Economic Equilibrium Models
ERM	10.2015	Beatriz Martínez and Hipòlit Torró: European Natural Gas Seasonal Effects on Futures Hedging
CCSD	11.2015	Inge van den Bijgaart: The Unilateral Implementation of a Sustainable Growth Path with Directed Technical Change
CCSD	12.2015	Emanuele Massetti, Robert Mendelsohn and Shun Chonabayashi: Using Degree Days to Value Farmland
CCSD	13.2015	Stergios Athanassoglou: Revisiting Worst-case DEA for Composite Indicators
CCSD	14.2015	Francesco Silvestri and Stefano Ghinoi: Municipal Waste Selection and Disposal: Evidences from Lombardy
CCSD	15.2015	Loïc Berger: The Impact of Ambiguity Prudence on Insurance and Prevention
CCSD	16.2015	Vladimir Otrachshenko and Francesco Bosello: Identifying the Link Between Coastal Tourism and Marine Ecosystems in the Baltic, North Sea, and Mediterranean Countries
ERM	17.2015	Charles F. Mason, Lucija A. Muehlenbachs and Sheila M. Olmstead: The Economics of Shale Gas Development
ERM	18.2015	Anna Alberini and Charles Towe: Information v. Energy Efficiency Incentives: Evidence from Residential Electricity Consumption in Maryland
CCSD	19.2015	ZhongXiang Zhang: Crossing the River by Feeling the Stones: The Case of Carbon Trading in China
CCSD	20.2015	Petterson Molina Vale: The Conservation versus Production Trade-off: Does Livestock Intensification Increase Deforestation? The Case of the Brazilian Amazon
CCSD	21.2015	Valentina Bosetti, Melanie Heugues and Alessandro Tavoni: Luring Others into Climate Action: Coalition Formation Games with Threshold and Spillover Effects
CCSD	22.2015	Francesco Bosello, Elisa Delpiazzi, and Fabio Eboli: Macro-economic Impact Assessment of Future Changes in European Marine Ecosystem Services
CCSD	23.2015	Maryse Labriet, Laurent Drouet, Marc Vielle, Richard Loulou, Amit Kanudia and Alain Haurie: Assessment of the Effectiveness of Global Climate Policies Using Coupled Bottom-up and Top-down Models
CCSD	24.2015	Wei Jin and ZhongXiang Zhang: On the Mechanism of International Technology Diffusion for Energy Technological Progress
CCSD	25.2015	Benjamin Michallet, Giuseppe Lucio Gaeta and François Facchini: Greening Up or Not? The Determinants Political Parties' Environmental Concern: An Empirical Analysis Based on European Data (1970-2008)
CCSD	26.2015	Daniel Bodansky, Seth Hoedl, Gilbert Metcalf and Robert Stavins: Facilitating Linkage of Heterogeneous Regional, National, and Sub-National Climate Policies Through a Future International Agreement
CCSD	27.2015	Giannis Vardas and Anastasios Xepapadeas: Time Scale Externalities and the Management of Renewable Resources
CCSD	28.2015	Todd D. Gerarden, Richard G. Newell, Robert N. Stavins and Robert C. Stowe: An Assessment of the Energy-Efficiency Gap and Its Implications for Climate Change Policy
CCSD	29.2015	Cristina Cattaneo and Emanuele Massetti: Migration and Climate Change in Rural Africa
ERM	30.2015	Simone Tagliapietra: The Future of Renewable Energy in the Mediterranean. Translating Potential into Reality
CCSD	31.2015	Jan Siegmeier, Linus Mattauch, Max Franks, David Klenert, Anselm Schultes and Ottmar Edenhofer: A Public Finance Perspective on Climate Policy: Six Interactions That May Enhance Welfare
CCSD	32.2015	Reyer Gerlagh, Inge van den Bijgaart, Hans Nijland and Thomas Michielsen: Fiscal Policy and CO2 Emissions of New Passenger Cars in the EU
CCSD	33.2015	Marie-Laure Nauleau, Louis-Gaëtan Giraudet and Philippe Quirion: Energy Efficiency Policy with Price-quality Discrimination

CCSD	34.2015	Eftichios S. Sartzetakis, Anastasios Xepapadeas and Athanasios Yannacopoulos: Regulating the Environmental Consequences of Preferences for Social Status within an Evolutionary Framework
CCSD	35.2015	Todd D. Gerarden, Richard G. Newell and Robert N. Stavins: Assessing the Energy-efficiency Gap
CCSD	36.2015	Lorenza Campagnolo and Fabio Eboli: Implications of the 2030 EU Resource Efficiency Target on Sustainable Development
CCSD	37.2015	Max Franks, Ottmar Edenhofer and Kai Lessmann: Why Finance Ministers Favor Carbon Taxes, Even if They Do not Take Climate Change into Account
CCSD	38.2015	ZhongXiang Zhang: Carbon Emissions Trading in China: The Evolution from Pilots to a Nationwide Scheme
CCSD	39.2015	David García-León: Weather and Income: Lessons from the Main European Regions
CCSD	40.2015	Jaroslav Mysiak and C. D. Pérez-Blanco: Partnerships for Affordable and Equitable Disaster Insurance
CCSD	41.2015	S. Surminski, J.C.J.H. Aerts, W.J.W. Botzen, P. Hudson, J. Mysiak and C. D. Pérez-Blanco: Reflections on the Current Debate on How to Link Flood Insurance and Disaster Risk Reduction in the European Union
CCSD	42.2015	Erin Baker, Olaitan Olaleye and Lara Aleluia Reis: Decision Frameworks and the Investment in R&D
CCSD	43.2015	C. D. Pérez-Blanco and C. M. Gómez: Revealing the Willingness to Pay for Income Insurance in Agriculture
CCSD	44.2015	Banchongsan Charoensook: On the Interaction between Player Heterogeneity and Partner Heterogeneity in Two-way Flow Strict Nash Networks
CCSD	45.2015	Erin Baker, Valentina Bosetti, Laura Diaz Anadon, Max Henrion and Lara Aleluia Reis: Future Costs of Key Low-Carbon Energy Technologies: Harmonization and Aggregation of Energy Technology Expert Elicitation Data
CCSD	46.2015	Sushanta Kumar Mahapatra and Keshab Chandra Ratha: Sovereign States and Surging Water: Brahmaputra River between China and India
CCSD	47.2015	Thomas Longden: CO₂ Intensity and the Importance of Country Level Differences: An Analysis of the Relationship Between per Capita Emissions and Population Density
CCSD	48.2015	Jussi Lintunen and Olli-Pekka Kuusela: Optimal Management of Markets for Bankable Emission Permits
CCSD	49.2015	Johannes Emmerling: Uncertainty and Natural Resources - Prudence Facing Doomsday
ERM	50.2015	Manfred Hafner and Simone Tagliapietra: Turkish Stream: What Strategy for Europe?
ERM	51.2015	Thomas Sattich, Inga Ydersbond and Daniel Scholten: Can EU's Decarbonisation Agenda Break the State-Company Axis in the Power Sector?
ERM	52.2015	Alessandro Cologni, Elisa Scarpa and Francesco Giuseppe Sitzia: Big Fish: Oil Markets and Speculation
CCSD	53.2015	Joosung Lee: Multilateral Bargaining in Networks: On the Prevalence of Inefficiencies
CCSD	54.2015	P. Jean-Jacques Herings: Equilibrium and Matching under Price Controls
CCSD	55.2015	Nicole Tabasso: Diffusion of Multiple Information: On Information Resilience and the Power of Segregation
CCSD	56.2015	Diego Cerdeiro, Marcin Dziubinski and Sanjeev Goyal: Contagion Risk and Network Design
CCSD	57.2015	Yann Rébillé and Lionel Richafort: Networks of Many Public Goods with Non-Linear Best Replies
CCSD	58.2015	Achim Hagen and Klaus Eisenack: International Environmental Agreements with Asymmetric Countries: Climate Clubs vs. Global Cooperation
CCSD	59.2015	Ana Mauleon, Nils Roehl and Vincent Vannetelbosch: Constitutions and Social Networks
CCSD	60.2015	Adam N. Walker, Hans-Peter Weikard and Andries Richter: The Rise and Fall of the Great Fish Pact under Endogenous Risk of Stock Collapse
CCSD	61.2015	Fabio Grazi and Henri Waisman: Agglomeration, Urban Growth and Infrastructure in Global Climate Policy: A Dynamic CGE Approach
CCSD	62.2015	Elorri Igos, Benedetto Rugani, Sameer Rege, Enrico Benetto, Laurent Drouet and Dan Zachary: Combination of Equilibrium Models and Hybrid Life Cycle-Input-Output Analysis to Predict the Environmental Impacts of Energy Policy Scenarios
CCSD	63.2015	Delavane B. Diaz: Estimating Global Damages from Sea Level Rise with the Coastal Impact and Adaptation Model (CIAM)
CCSD	64.2015	Delavane B. Diaz: Integrated Assessment of Climate Catastrophes with Endogenous Uncertainty: Does the Risk of Ice Sheet Collapse Justify Precautionary Mitigation?
CCSD	65.2015	Jan Witajewski-Baltvilks, Elena Verdolini and Massimo Tavoni: Bending The Learning Curve
CCSD	66.2015	W. A. Brock and A. Xepapadeas: Modeling Coupled Climate, Ecosystems, and Economic Systems
CCSD	67.2015	Ricardo Nieva: The Coalitional Nash Bargaining Solution with Simultaneous Payoff Demands
CCSD	68.2015	Olivier Durand-Lasserve, Lorenza Campagnolo, Jean Chateau and Rob Dellink: Modelling of Distributional Impacts of Energy Subsidy Reforms: an Illustration with Indonesia
CCSD	69.2015	Simon Levin and Anastasios Xepapadeas: Transboundary Capital and Pollution Flows and the Emergence of Regional Inequalities
CCSD	70.2015	Jaroslav Mysiak, Swenja Surminski, Annegret Thieken, Reinhard Mechler and Jeroen Aerts: Sendai Framework for Disaster Risk Reduction – Success or Warning Sign for Paris?
CCSD	71.2015	Massimo Tavoni and Detlef van Vuuren: Regional Carbon Budgets: Do They Matter for Climate Policy?
CCSD	72.2015	Francesco Vona, Giovanni Marin, Davide Consoli and David Popp: Green Skills
CCSD	73.2015	Luca Lambertini, Joanna Poyago-Theotoky and Alessandro Tampieri: Cournot Competition and "Green" Innovation: An Inverted-U Relationship
ES	74.2015	Michele Raitano and Francesco Vona: From the Cradle to the Grave: the Effect of Family Background on the Career Path of Italian Men
ES	75.2015	Davide Carbonai and Carlo Drago: Positive Freedom in Networked Capitalism: An Empirical Analysis
CCSD	76.2015	Wei Jin and ZhongXiang Zhang: Levelling the Playing Field: On the Missing Role of Network Externality in Designing Renewable Energy Technology Deployment Policies
ERM	77.2015	Niaz Bashiri Behmiri and Matteo Manera: The Role of Outliers and Oil Price Shocks on Volatility of Metal Prices
CCSD	78.2015	Jan Witajewski-Baltvilks, Elena Verdolini and Massimo Tavoni: Directed Technological Change and Energy Efficiency Improvements

ES	79.2015	David Cuberes and Rafael González-Val: The Effect of the Spanish Reconquest on Iberian Cities
CCSD	80.2015	Isabella Alloisio, Alessandro Antimiani, Simone Borghesi, Enrica De Cian, Maria Gaeta, Chiara Martini, Ramiro Parrado, Maria Cristina Tommasino, Elena Verdolini and Maria Rosa Virdis: Pathways to Deep Carbonization in Italy
CCSD	81.2015	Yonky Indrajaya, Edwin van der Werf, Hans-Peter Weikard, Frits Mohren and Ekko C. van Ierland: The Potential of REDD+ for Carbon Sequestration in Tropical Forests: Supply Curves for carbon storage for Kalimantan, Indonesia
ES	82.2015	Carlo Drago, Roberto Ricciuti, Paolo Santella: An Attempt to Disperse the Italian Interlocking Directorship Network: Analyzing the Effects of the 2011 Reform
CCSD	83.2015	Joseph E. Aldy: Policy Surveillance in the G-20 Fossil Fuel Subsidies Agreement: Lessons for Climate Policy
CCSD	84.2015	Milan Ščasný, Emanuele Massetti, Jan Melichar and Samuel Carrara: Quantifying the Ancillary Benefits of the Representative Concentration Pathways on Air Quality in Europe
CCSD	85.2015	Frédéric Branger and Misato Sato: Solving the Clinker Dilemma with Hybrid Output-based Allocation
ERM	86.2015	Manfred Hafner and Simone Tagliapietra: The Role of Natural Gas in the EU Decarbonisation Path
CCSD	87.2015	Cristina Cattaneo and Giovanni Peri: The Migration Response to Increasing Temperatures
CCSD	88.2015	Maximilian Schumacher and Lion Hirth: How much Electricity do we Consume? A Guide to German and European Electricity Consumption and Generation Data
CCSD	89.2015	Lorenza Campagnolo, Carlo Carraro, Fabio Eboli, Luca Farnia: Assessing SDGs: A new methodology to measure sustainability
CCSD	90.2015	Carlo Reggiani, Francesco Silvestri: Municipal Waste Collection: Market Competition and the EU policy
ERM	91.2015	Maryam Ahmad, Matteo Manera, Mehdi Sadeghzadeh: Global Oil Market and the U.S. Stock Returns
CCSD	92.2015	Mattia Amadio, Jaroslav Mysiak, Lorenzo Carrera, Elco Koks: Improving Flood Damage Assessment Models in Italy
CCSD	93.2015	Sabine Fuss, Claudine Chen, Michael Jakob, Annika Marxen, Narasimha D. Rao, Ottmar Edenhofer: Could Resource Rents Finance Universal Access to Infrastructure? A First Exploration of Needs and Rents
CCSD	94.2015	Michael Jakob, Claudine Chen, Sabine Fuss, Annika Marxen, Narasimha Rao, Ottmar Edenhofer: Using Carbon Pricing Revenues to Finance Infrastructure Access
CCSD	95.2015	ZhongXiang Zhang: Making China the Transition to a Low-Carbon Economy: Key Challenges and Responses
CCSD	96.2015	Roberto Iacono: The Basilicata Wealth Fund: Resource Policy and Long-run Economic Development in Southern Italy
CCSD	97.2015	Francesco Bosello, Shouro Dasgupta: Development, Climate Change Adaptation, and Maladaptation: Some Econometric Evidence
CCSD	98.2015	Valentina Bosetti, Giacomo Marangoni, Emanuele Borgonovo, Laura Diaz Anadon, Robert Barron, Haewon C. McJeon, Savvas Politis, Paul Friley: Sensitivity to Energy Technology Costs: A Multi-model Comparison Analysis
ERM	99.2015	Andrea Bastianin, Francesca Conti, Matteo Manera: The Impacts of Oil Price Shocks on Stock Market Volatility: Evidence from the G7 Countries
ERM	100.2015	Andrea Bastianin, Marzio Galeotti, Matteo Manera: The Impacts of Exogenous Oil Supply Shocks on Mediterranean Economies
ERM	101.2015	Maryam Ahmadi, Niaz Bashiri Behmiri, Matteo Manera: How is Volatility in Commodity Markets Linked to Oil Price Shocks?
CCSD	102.2015	Margaretha Breil, Cristina Cattaneo, Katie Johnson: Qualitative Scenarios Building for Post-carbon Cities
CCSD	103.2015	Natasha Chichilnisky-Heal, Graciela Chichilnisky: Bargaining to Lose the Global Commons
ERM	104.2015	Giovanni Marin, Alessandro Palma: Technology Invention and Diffusion in Residential Energy Consumption. A Stochastic Frontier Approach
ES	105.2015	Jacopo Zotti: The Long Italian Stagnation and the Welfare Effects of Outsourcing
CCSD	106.2015	Michael Hübler, Oliver Schenker, Carolyn Fischer: Second-Best Analysis of European Energy Policy: Is One Bird in the Hand Worth Two in the Bush?
CCSD	107.2015	Richard Schmalensee, Robert N. Stavins: Lessons Learned from Three Decades of Experience with Cap-and-Trade
CCSD	108.2015	Giovanna d'Adda, Valerio Capraro, Massimo Tavoni: The not so Gentle Push: Behavioral Spillovers and Policy Instruments
CCSD	109.2015	Samuel Carrara, Giacomo Marangoni: Including System Integration of Variable Renewable Energies in a Constant Elasticity of Substitution Framework: the Case of the WITCH Model
CCSD	110.2015	Heleen van Soest, Lara Aleluia Reis, Detlef van Vuuren, Christoph Bertram, Laurent Drouet, Jessica Jewell, Elmar Kriegler, Gunnar Luderer, Keywan Riahi, Joeri Rogelj, Massimo Tavoni, Michel den Elzen, Aayushi Awasthy, Katherine Calvin, Pantelis Capros, Leon Clarke, Michel Colombier, Teng Fei, Amit Garg, Fernanda Guedes, Mariana Imperio, Mikiko Kainuma, Jiang Kejun, Alexandre C. Köberle, Peter Kolp, Volker Krey, Alban Kitous, Paroussos Leonidas, Andre Lucena, Toshihiko Masui, Larissa Nogueira, Roberta Pierfederici, Bert Saveyn, Roberto Schaeffer, Fu Sha, Bianka Shoai, P.R. Shukla, Thomas Spencer, Alexandre Szklo, Henri Waisman: Regional Low-Emission Pathways from Global Models

