Kiel

Working Papers

Kiel Institute for the World Economy

Multi-model analyses of the economic and energy implications for China and India in a post-Kyoto climate regime

by Daniel J.A. Johansson, Paul L. Lucas, Matthias Weitzel, Erik O. Ahlgren, A.B Bazaz, Wenying Chen, Michel G.J. den Elzen, Joydeep Ghosh, Maria Grahn, Qiao-Mei Liang, Sonja Peterson, Basanta K. Pradhan, Bas J. van Ruijven, P.R. Shukla, Detlef P. van Vuuren, Yi-Ming Wei

No. 1808 | November 2012

Web: www.ifw-kiel.de

Kiel Working Paper No.1808 | November 2012

Multi-model analyses of the economic and energy implications for China and India in a post-Kyoto climate regime

Daniel J.A. Johansson[a, 1], Paul L. Lucas[b], Matthias Weitzel[c], Erik O. Ahlgren[a], A.B Bazaz[d], Wenying Chen[e], Michel G.J. den Elzen[b], Joydeep Ghosh[f], Maria Grahn[a], Qiao-Mei Liang [g], Sonja Peterson[c], Basanta K. Pradhan[f], Bas J. van Ruijven[b,h], P.R. Shukla[d], Detlef P. van Vuuren[b,i], Yi-Ming Wei[g]

Abstract: This paper presents a modeling comparison project on how the 2°C climate target could affect economic and energy systems development in China and India. The analysis uses a framework that harmonizes baseline developments and soft-links seven national and global models being either economy wide (CGE models) or energy system models. The analysis is based on a global greenhouse gas emission pathway that aims at a radiative forcing of 2.9 W/m^2 in 2100 and with a policy regime based on convergence of per capita CO_2 emissions with emissions trading. Economic and energy implications for China and India vary across models. Decreased energy intensity is the most important abatement approach in the CGE models, while decreased carbon intensity is most important in the energy system models. Reliance on Coal without Carbon Capture and Storage (CCS) is significantly reduced in most models, while CCS is a central abatement technology in energy system models, as is renewable and nuclear energy. Concerning economic impacts China bears in general a higher cost than India, as China benefits less from emissions trading. Costs are also affected by changes in fossil fuel prices, currency depreciation from capital inflow from carbon trading and timing of emission reductions.

Keywords: Climate policy; China; India

[a] Department of Energy and Environment, Chalmers University of Technology, 412 96, Gothenburg Sweden

[b] PBL - Netherlands Environment Assessment Agency, PO Box 303, 3720 AH Bilthoven, The Netherlands

[c] Kiel Institute for the World Economy, Hindenburgufer 66, D-24105 Kiel, Germany

[d] Public Systems Group, Wing 3, Indian Institute of Management Ahmedabad, Vastrapur, Ahmedabad-380015, India

[e] Energy, Environment, and Economy (3E) Research Institute, Tsinghua University, Beijing 100084, China

[f] Institute of Economic Growth (IEG), University Of Delhi Enclave, North Campus, Delhi 110007, India

[g] Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, China

[h] National Center for Atmospheric Research (NCAR), PO Box 3000, Boulder, CO, 80305, USA

[i] Department of Geosciences, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

[1] Corresponding author: Daniel Johansson. E-mail: daniel.johansson@chalmers.se. Telephone: +46 (0) 31 772 31 25. Fax: +46 (0)31 772 31 50.

1. Introduction

In the Copenhagen Accord (UNFCCC, 2009) and the Cancún Agreements (UNFCCC, 2010), countries worldwide agreed on limiting global average temperature increase to maximum 2°C above pre-industrial levels. In order to reach the 2°C target with a probability of more than 50% global greenhouse gas emissions need be to be cut about 35-55% by 2050 compared to the emissions level in 1990 (Rogelj et al., 2011). By 2005, about 50% of the anthropogenic greenhouse gases accumulated in the atmosphere can be attributed to developed countries (Höhne et al., 2011a). However, the greater share of future emissions is expected to come from developing countries. Already, developing countries account for more than half of the global CO_2 emissions (Peters et al., 2012), while China is the largest global CO_2 emitter since 2006. China's average per capita CO_2 emissions have increased significantly over the last decade, reaching almost similar per capita emissions as those of the EU in 2011 (Olivier et al., 2012).The current size and expected growth of the Chinese and Indian population and economy imply that these countries will have an important role in shaping the dynamics of the future global energy system and related CO_2 emissions (IEA, 2011).

Thus, the mitigation efforts of China and India are increasingly important for meeting ambitious climate targets. In fact, emissions from developing countries alone will soon exceed the global emission trajectory for reaching a low concentration target (Metz et al., 2002; Blanford et al., 2009; Clarke et al., 2009). This implies that, even though universal participation in a climate regime is not necessary in the short-run, participation of rapidly developing countries in greenhouse gas abatement activities is essential. At the same time, however, per capita income levels in both China and India are still much lower than those of developed countries. For India, this also holds for per capita emissions. Consistent with Article 3.1 of the UNFCCC (1992) - indicating that countries have a "common but differentiated responsibility" to contribute to future reductions - China and India have so-far been reluctant to take on (ambitious) emission reduction targets. Still, they have adopted emission intensity targets (i.e. reduction in emissions per unit of GDP) as part of the Cancún Agreements, for which the impact of the emissions for 2020 is heavily dependent on GDP growth. In general as part of the Copenhagen Accord and Cancún Agreements, 42 developed countries have submitted quantified economy-wide emission reduction targets for 2020, and 43 developing countries submitted so-called nationally appropriate mitigation action plans (pledges) reaching until 2020. While these mitigation pledges are able to reduce emissions compared to baseline development, several papers concluded that these reductions are less than those that would be necessary to follow global emissions in the costs-effective pathways that aim to meet the 2 °C target (e.g. Fee et al., 2010; Rogelj et al., 2010; Den Elzen et al., 2011; Höhne et al., 2011b).

In addition, beyond 2020 deeper cuts beyond these pledges are required in order to achieve the 2°C target. Given the fact that both China and India have expressed support for this climate target during the UNFCCC climate negotiations and the earlier considerations on their contribution to global emissions, it seems logical to assume that deep emission reductions compatible with meeting these target will also be undertaken in these countries. Part of these reductions could be financed by multilateral public or international funding (including international carbon market). There are many post-2012 effort-sharing regime or emission allocation approaches discussed in the literature, each with different participation levels, timing of reductions, as well as stringency and type of commitments (See an overview of proposals in e.g. Bodansky, 2004; Kameyama, 2004; Philibert, 2005; Gupta et al., 2007; Den Elzen and Höhne, 2008). Furthermore, there is a broad literature on the economic impact of these different effort-sharing proposals, and many papers report how China and India would be affected (see Van Ruijven et al., 2012 and references therein). Regardless of the allocation approach, deep emission cuts in 2050 relative to the business-as-usual emission projections in the absence of climate policy are required especially for China, but also for India (Van Ruijven et al., 2012).

In this paper we analyze a climate policy scenario aiming at achieving the 2°C target for China and India, focusing on:

- the impact on their energy systems; and
- the direct mitigation costs and welfare implications.

We analyze these questions in a multi-model comparison approach involving six models, differing in geographic scale (China, India or global) and scope (economy wide or energy system). Furthermore, a seventh climate policy model is used that determines a global emission pathway compatibility with the 2°C target and the related national allocation of emission allowances based on the assumed effort-sharing approach. A sensitivity analysis is carried out with respect to economic growth, timing in global emission reductions and the effort-sharing approach. Given our modeling framework the paper also aims to contribute to the understanding of the major driving forces of different modeling approaches and the drivers of partly diverging model results.

The paper is structured as follows. Section 2 describes the modeling framework and gives a brief overview of the different models used in the analysis. Section 3 presents the baseline assumptions and the policy scenarios. Section 4 first shows the emissions and corresponding carbon tax found in the models. In Section 5 detailed results of the policy scenario are presented, which are subject to a sensitivity analysis in Section 6. Section 7 discusses the results and Section 8 concludes.

2. Modeling framework

The modeling framework applied in this paper, harmonizing and soft-linking national and global as well as economy wide or energy system models, is unique in the literature and aims to yield a consistent global and national perspective. Traditionally, assessment of climate policy impacts in India or China has either been carried out in national models (Shukla, 1996; Fisher-Vanden et al., 1997 for India; and ERI, 2009 for China; e.g. Shukla and Chaturvedi, 2012), or within global models (e.g. van Vuuren et al., 2003; Edenhofer et al., 2010; Luderer et al., 2012; Calvin et al., in press). Large differences in results have not only occurred due to differences in effort sharing approaches or prescribed emission mitigation scenarios, but also due to different assumptions on e.g. economic growth, energy prices or technology development. Comparison of the different studies is therefore not an easy task because differences in results cannot be clearly attributed to differences in effort sharing approaches, modeling approaches or underlying assumptions on the baseline (Van Ruijven et al., 2012). In addition, most studies that perform global analyses of effort-sharing approaches are carried out by scholars and institutes from developed countries. Consequently, analysis on a global scale made by scholars of the affected countries is relatively scarce. National analyses on the other hand often lack to place their findings into an international perspective. The modeling framework we apply here, by harmonizing and soft-linking national and global as well as economy wide or energy system models, aims to yield a more consistent perspective.

2.1 Description of the models

Central to the modeling framework is the climate policy model FAIR (den Elzen and Lucas, 2005; den Elzen et al., 2008). It is used to and to analyze regional emission reductions and abatement costs for different effort-sharing approaches and to construct long-term global greenhouse gas emission pathways consistent with the 2 ^{o}C target. Furthermore, six energy-economic models are used to determine changes to the energy system and national costs of climate policy. These models differ in two important dimensions: they are either global or national models and they are either energy system models or computable general equilibrium (CGE) models. While the global models can capture international linkages and feedbacks, the national models account better for country specifics and can analyze the national impacts of climate policy in more detail. While energy system models include technological details of energy production and consumption technologies, CGE models account for macro-economic feedbacks, changes in energy demand and shifts in trade. Central features of the models are presented in Table 1.

The **FAIR** model links long-term climate targets and global reduction objectives with regional emissions allowances and abatement costs (den Elzen and Lucas, 2005; den Elzen et al., 2008). The cost model uses a least-cost approach involving regional Marginal Abatement Cost (MAC) curves to distribute a global emission reduction effort over world regions, gases and sources, and allowing offsetting mechanisms such as emission trading and the Clean Development Mechanism (CDM). The MAC curves take into account all major emission abatement options for the energy- and industry-related greenhouse gasses, based on the TIMER energy model (see below), as well as non-CO_2 greenhouse gases (Lucas et al., 2007) and deforestation emission (Busch et al., 2009). The MAC curves account for technology change, inertia and removal of implementation barriers. FAIR includes the model FAIR–SiMCaP (Den Elzen et al., 2007) and the MAGICC 6 climate model (Meinshausen et al., 2011a) to calculate long-term cost-effective global greenhouse emission pathways, by minimizing cumulative discounted abatement costs under achieving long-term climate targets.

2.1.1 Energy-systems models

Three energy-system models are used, describing long-term dynamics of demand and supply of energy services based on large sets of existing and future technologies (that today are in demonstration phase) that can play a role in the future energy system. The technologies are linked together by energy (and/or material) flows. **TIMER**[1] is a recursive dynamic global energy-system model that describes the long-term dynamics of the production and consumption of energy for 26 world regions (van Vuuren et al., 2006; 2007). In addition, **China MARKAL** (Chen, 2005; Chen et al., 2007; Chen et al., 2010) and **MARKAL-India** (Shukla, 1997; Shukla et al., 2008) are national energy system optimization models based on the MARKAL modeling system (Fishbone and Abilock, 1981).

All models account for energy related CO_2 emissions from fossil fuels, while TIMER accounts for energy and industry related emissions of all Kyoto gases, BC/OC and major air pollutants. The models include most primary energy sources, including fossil fuels, biomass (TIMER also includes traditional biomass), nuclear energy and several renewables. A carbon tax can be used to induce a dynamic response such as increased use of low or zero-carbon technologies, energy efficiency improvement and end–of–pipe emission reduction technologies such as Carbon Capture and Storage (CCS).

In TIMER, model behavior is mainly determined by substitution processes of various technologies based on long-term prices and fuel preferences. These two factors drive multi-nomial logit models that describe investments in new energy production and consumption capacity. As capital is only replaced at the end of the technical lifetime demand for new capacity is limited. The long-term prices are

[1] TIMER is part of the IMAGE integrated assessment model (Bouwman et al., 2006), but is here used as a stand-alone energy model.

determined by resource depletion (fossil and renewable) and technology development. Technology development is determined by endogenous learning curves or through exogenous assumptions. The MARKAL models are dynamic linear programming energy system optimization models, encompassing extraction, transformation and end-use of energy. The models are driven by a set of demands for energy services and the objective function is the long-term discounted energy system cost. Investment decisions are taken on the basis of least-cost optimization of the energy system, taking into account learning and depletion or resources. The optimizing feature ensures that the model computes a partial economic equilibrium of the energy system (Loulou et al., 1997).

2.1.2 Computable General Equilibrium (CGE) models

Three multi-sectoral, recursive-dynamic computable general equilibrium (CGE) models are used in this model exercise, describing the behavior of economic agents and their interactions in the macroeconomic system. **DART** is a global model calibrated to the data set of the Global Trade Analysis Project (Narayanan and Walmsley, 2008) and aggregated to 13 regions (Klepper et al., 2003; Kretschmer et al., 2009). In addition, two single-country CGE models are applied: **CEEPA** describes the Chinese economy (Liang et al., 2007; Liang and Wei, 2012), based on input-output data of the National Bureau of Statistics PR China (2009). **IEG-CGE** describes the Indian economy (Pradhan and Ghosh, 2012b, a) and is based on a social accounting matrix (Pradhan et al., 2006; Ojha et al., 2009) . The single country models capture characteristics of the labor and energy markets of the respective countries. For international trade, all models make use of the Armington assumption.

DART uses one representative agent for each region that comprises private households and the government sector, and receives all income generated by providing sectorally mobile but regionally immobile primary factors (capital, labor, land and natural resources) to the production process. In CEEPA, consumers are divided into households, enterprises and government. Considering the current energy- and emission-intensive international trade structure of China, a foreign account was included. IEG-CGE divides consumers into nine household groups (based on socioeconomic characteristics) enterprises and government. DART and IEG-CGE model consumption as a linear expenditure system (LES).

All models account for energy related CO_2 emissions from fossil fuels. In all cases, the policies were introduced by exposing a carbon price. Finally, all models have introduced low carbon electricity generation technologies such as renewables or CCS. In the DART model, making used of information provided by the TIMER model, the electricity sector was split into conventional generation and new generation technologies from four renewable sources; additionally gas and coal generation with CCS is introduced as a latent technology (Weitzel, 2010). Different electricity generation technologies are assumed to be perfect substitutes, each technology has a convex cost function and exhibits learning-by-doing. In IEG-CGE and CEEPA, different electricity generation options are non-perfect substitutes. Alternative energy carriers in the transport sector are not explicitly modeled in either of the three models.

Table 1: Characteristics of the models

	FAIR	TIMER	DART	CEEPA	China MARKAL	IEG-CGE	MARKAL-India
Institute	Netherlands Environmental Assessment Agency (PBL)	Netherlands Environmental Assessment Agency (PBL)	Kiel Institute for the World Economy (IfW)	Beijing Institute of Technology (BIT)	Tsinghua University (TU)	Institute of Economic Growth (IEG)	Indian Institute of Management (IIM-A)
Model class	Climate policy model	Recursive dynamic energy system model	Recursive dynamic computable general equilibrium model (CGE)	Recursive dynamic computable general equilibrium model (CGE)	Energy system model with perfect foresight	Recursive dynamic computable general equilibrium model (CGE)	Energy system model with perfect foresight
Regional coverage	Global (26 regions)	Global (26 regions)	Global (13 regions)	China	China	India	India
Household groups	NA	10 (urban and rural quintiles)	1representative agent per region	2 (urban and rural)	2 (urban and rural)	9	1
Sectors	NA	5 sectors (industry, transport, residential, services and other)	12	24	5 sectors (agriculture, industry, commercial, residential and transport) and 32 sub-sectors	18	5 Sectors (agriculture, industry, commercial, residential and transport) 46 end-use sectors
Energy carriers	NA	Coal, oil, natural gas, modern biofuels, traditional biofuels, nuclear, solar, wind and hydro	Coal, natural gas, oil, bio-energy, wind and hydro	Coal, natural gas, oil, bio-energy, nuclear, wind and hydro	Coal, natural gas, oil, bio-energy, nuclear, wind and hydro	Coal, natural gas, oil, bio-energy, nuclear, wind/solar and hydro	Coal, natural gas, oil, bio-energy, nuclear, solar, wind and hydro, hydrogen
Technology dynamics	Based on marginal abatement cost curves from TIMER and other models	Capital stocks, Penetration rate constraints, Learning by Doing	Capital stocks, Learning by doing, Autonomous energy efficiency improvement	Capital stocks, Autonomous energy efficiency improvement	Capital stocks, penetration rate constraints	Capital stocks, Energy efficiency improvement, Total factor productivity growth, Efficiency improvement in renewables	Capital stocks, Penetration rate constraint, Energy Infrastructure
CCS	NA	Yes	Yes	No	Yes	Yes	Yes
Substitutes to petroleum as transport fuel	NA	Electricity, modern biomass, hydrogen	Not explicitly modeled	Not explicitly modeled	Yes	No	Electricity, modern biomass, hydrogen

NA = not applicable

2.2 Description of the model framework

In order to exploit the advantages of all seven models, central features have been harmonized among the models. The models are also linked in the sense that the outputs from some models are used as input to other models. In this linking the FAIR model provides a bridge function, see Figure 1.

The harmonization and linking between the models can be summarized as follows:

1. All models are harmonized to a common baseline scenario
2. FAIR calculates the CO_2-equivalent emissions[2] pathway, a globally uniform carbon price and regional emission allowances based on the energy-related CO_2 part of the pathway and an effort-sharing approach
3. DART determines the globally uniform carbon price based on the global energy-related CO_2 pathway and the regional emission allowances from FAIR
4. The national CGE models use the emission allowance from FAIR and the carbon price from DART to determine changes to the energy system and total climate policy cost
5. The national MARKAL models use the emission allowances and carbon price from FAIR to determine changes to energy system and total climate policy cost
6. TIMER uses the emission allowances from FAIR to determine changes to energy system. Total climate policy cost is determined by FAIR.

The reason for letting the national CGE models using CO_2 prices from DART and the national MARKAL model using prices from FAIR (based on cost-curves from TIMER) is that the models in each respective model class (CGE models vs Energy System models) have many common features. The CGE models also have a similar theoretical underpinning.

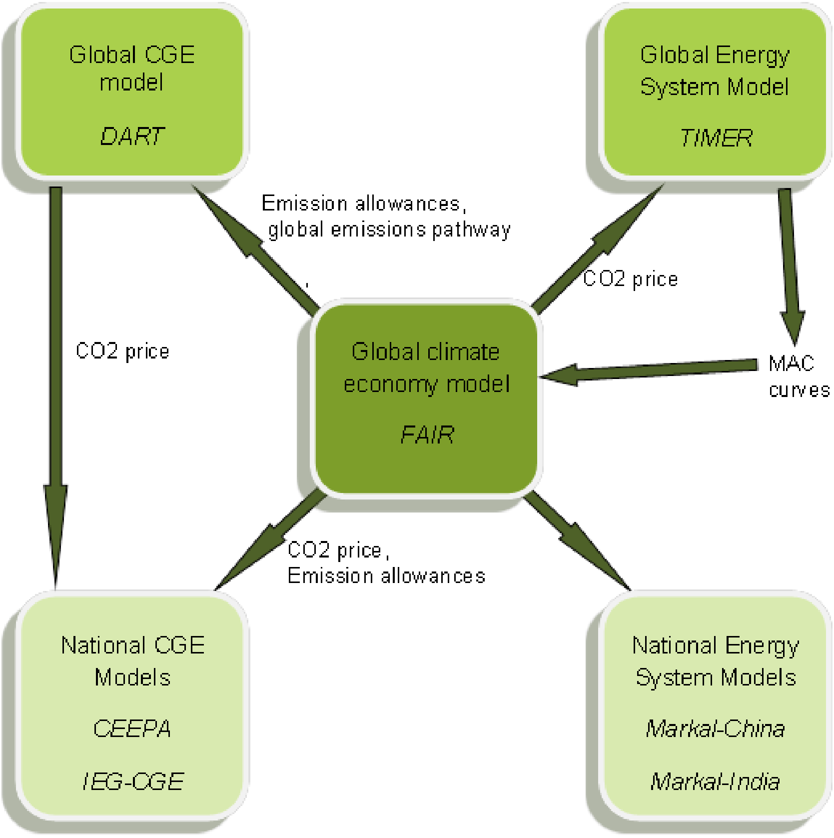

Figure 1. Schematic overview of model linkages.

[2] All greenhouse gas emissions refer to all emissions relevant under the Kyoto Protocol (Annex A) including the land-use related CO_2 emissions, i.e. the global warming potential-weighted sum of six Kyoto greenhouse gas emissions (CO_2 equivalent emissions).

3. Basic modeling assumptions

3.1 Baseline assumptions and model harmonization

The models are harmonized with respect to discount rate, population growth, GDP growth and fossil fuel prices. The discount rate is set at 5% as in GEA (2012). The population projections are in line with the medium variant of UN World Population Prospects (UNDESA, 2011). Globally, the population is projected to increase to about 9.1 billion people in 2050, 1.6 billion people in India and 1.5 billion people in China. The GDP growth scenario is based on the reference scenario of the OECD Environmental Outlook (OECD, 2012). In this scenario, the global economy is projected to grow with a factor of about 4 between 2010 and 2050, China's economy with a factor of about 7 and India's economy with a factor of about 14. Finally, developments in international fossil fuel prices towards 2035 are taken from the "current policy scenario" of the World Energy Outlook 2010 (IEA, 2010). Prices are kept constant between 2035 and 2050.The baseline does not in general include current climate policies after 2010 (like the 12th five year plan for China). Although China MARKAL and MARKAL India consider some planned policies in the reference scenario. The reference scenario for China include the targets set for the National 12th five-year plan, the new and renewable energy development goal for the year 2020, and the target of 40%-45% reduction of carbon intensity from 2005 to 2020. The baseline assumptions for India include the targets set for the country as detailed in the National Action Plan on Climate Change (which technically overlaps with the end of the 13th five-year plan i.e. 2022). Table 2 summarizes the key baseline assumptions. The Indian analysis includes the mitigation targets committed under the national missions proposed by the India's National Action Plan on Climate Change (NAPCC) communicated to the UNFCCC. The targets set in the NAPCC and other government policy targets (e.g. grid-connected solar power capacity o of 20 GW by 2022) are included as firm commitments in the base case scenario

Table 2: Key-assumptions in the baseline scenarios on population and GDP per capita.

		World	India	China
Population	2010	6927	1214	1388
(million persons)	2020	7691	1367	1467
	2050	9154	1614	1454
GDP per Capita	2010	7268	965	3278
(MER, USD_{2005} /yr)	2020	9375	1975	7186
	2050	19836	9944	22841

Different models do to some extent assume different energy conversion efficiency for different technologies. However, when presenting results on primary energy supply from non-combustible and non-fossil energy (wind, hydro, other renewable and nuclear) we convert the electricity production from these sources by using a direct equivalent method, assuming a conversion efficiency of 35% as in GEA (GEA, 2012)

3.2 Global emission pathway

The FAIR-SIMCAP model is used to create a global emission pathway that aims for a total radiative forcing of 2.9 W/m^2 in 2100. This forcing level results, according to (Meinshausen et al., 2006), in at least 50% chance to stay within 2°C temperature increase by 2100. The pathway implements the conditional, more ambitious Copenhagen pledges for 2020 (Den Elzen et al., 2011).[3] Between 2020 and 2025 global emissions gradually reduce, while between 2025 and 2050 a constant reduction rate is assumed. This reduction rate is chosen such that the global cumulative 2010 – 2050 emissions are equal to a so-called cost-optimal pathway derived from the FAIR–SiMCaP model that aims for a total radiative forcing of 2.9 W/m^2 in 2100, i.e. a cost-optimal allocation of the emission reductions across regions, gases and sources by minimizing cumulative discounted abatement costs for the 2010-2100 period (Van Vliet et al., 2012). For this study only the energy-related CO_2 emissions from the CO_2-equivalent pathway are used (see Figure 2). Figure 3 presents the global CO_2-tax required in FAIR and DART to reach the pathway.

3.3 Effort-sharing approach

An effort-sharing approach is used to determine which part of the required global emission reductions is allocated to China and India, and other world regions. Here, we apply the so-called common-but-differentiated convergence (CDC) approach, a simple allocation scheme that takes into account "common but differentiated responsibilities" (Höhne et al., 2006). It assumes – similar as the widely known contraction and convergence (C&C) regime (Meyer, 2000) - that per capita emission allowances of all countries converge over time. Different from C&C, in the CDC approach developing countries have to start their convergence trajectory only after reaching a certain threshold of per capita emissions. A similar differentiated per capita emissions convergence approach is discussed by Chinese researchers (He et al., 2009). Furthermore, the principle of long-term per capita emission convergence is also noted by the EU (Council of the European Union, 2009).

Important parameters for the CDC approach are the long-term per capita emissions convergence level and the threshold that requires countries to enter the regime and start converging. Here, instead of a threshold, we define different country groupings according to their current income levels, i.e. developed countries, Advanced Developing Countries (ADCs) and Other Developing Countries (ODCs), that take on different reduction objectives in terms of start year for convergence, convergence level and convergence year.

The developing countries are divided according to 2009 GNI per capita, calculated using the World Bank Atlas method (World Bank, 2011). High and upper middle income regions are classified as ADCs and low and lower middle income regions as ODCs. China and India are both categorized by the World Bank as lower middle income regions and could therefore be classified as ODCs. However, China's per capita income in 2009 is almost reaching the threshold to become an ADC. Therefore, China starts reducing emissions earlier than the other ODCs, but later than the ADCs. Also India starts converging earlier than the other ODCs, but later than China.

We assume that all countries that made a reduction pledge under Cancún Agreements meet their conditional, more ambitious one in 2020 (Den Elzen et al., 2011). Here, only energy-related CO_2 emission pledges are considered. Pledges addressing land-use emissions or other non-energy related source are not taken into account given the scope of this analysis, although these reductions are included in the global 2.9 W/m^2 greenhouse gas emission pathway. After 2020, the developed countries and ADCs start instantly following the per capita emission convergence trajectories of the

[3]The emission resulting from pledges for the developing countries – including China and India – has been revised in this study due to a different baseline assumptions (OECD, 2012), but keeping the same reduction below baseline from den Elzen et al. (2011).

CDC approach; developed countries converging in 2040 and the ADC in 2050. China and India start in 2025 and 2030, respectively. The other ODCs start in 2035. Between 2020 and the start of convergence countries follow their baseline trend. Therefore, countries that made a 2020 pledge (including China and India) have similar reductions compared to their baseline emissions as in 2020 until they start converging. China, India and the other ODCs take 30 years to converge.

In our 2.9 W/m^2 stabilization profile the global 2050 CO_2-equivalent emissions are 37% below 2000 levels. This is below the reduction range for the 2.5-3.0 W/m^2 category of 50-85% reduction below 2000 emission levels that the IPCC reports, but within the reduction range for the 3.0-3.5 W/m^2 category of 30-60% (IPCC, 2007). Therefore, in other to be consistent, we use the lower bound of the

IPCC 80%-95% reduction range in 2050 related to the 2.5-3.0 W/m^2 category for the group of aggregated developed countries. As a result, all countries converge to a level of 1.7 tCO_2/capita in their respective convergence year.

4. CO_2 emissions, emission allowances and global carbon taxes

4.1 Global results

The global greenhouse gas emissions, including all Kyoto gasses, and the corresponding energy related CO_2 emissions, are shown in Figure 2. Without any mitigation policies global greenhouse gas emissions and energy related CO_2 emissions continue to increase towards 2050, with more than 50% and 80% compared to 2010 levels, respectively. The dotted lines represent the 2.9W/m^2stabilization emissions pathway. Where global greenhouse gas emissions peak before 2020, energy-related CO_2 emission peak slightly later as in the short-term non-CO_2 emission reductions are more cost-effective than energy-related CO_2 emission reductions (Lucas et al., 2007). After peaking, emissions decrease gradually to 37% below 1990 levels for all greenhouse gases and 17% for the energy-related CO_2 emissions, respectively.

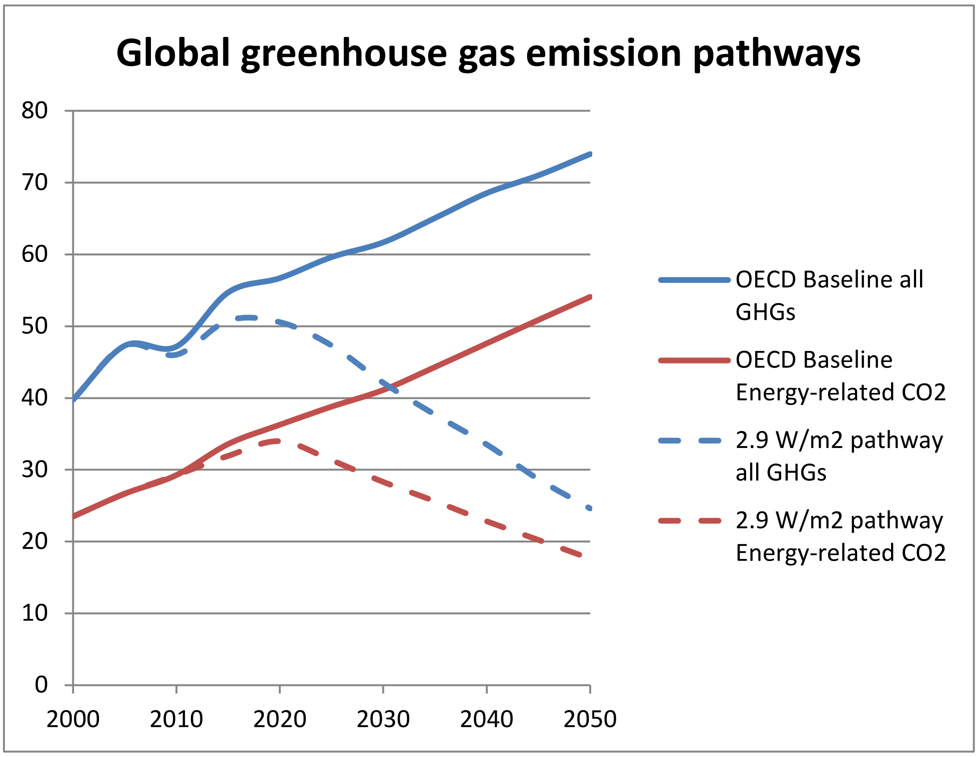

Figure 2. Global CO_2-equivalent emissions (Kyoto gases including land-use CO_2) and energy-related CO_2 emissions for the OECD baseline (OECD, 2012) and the 2.9 W/m^2 pathway generated by FAIR.

In DART and FAIR the transition from the baseline emissions to the 2.9 W/m^2pathway is achieved via a carbon tax on emissions (see Figure 3). These taxes are very similar up to 2045, beyond that the tax in DART rises further, as mitigation options in DART are limited after certain abatement levels, while FAIR allows for more radical technology changes that are especially available in the long run..

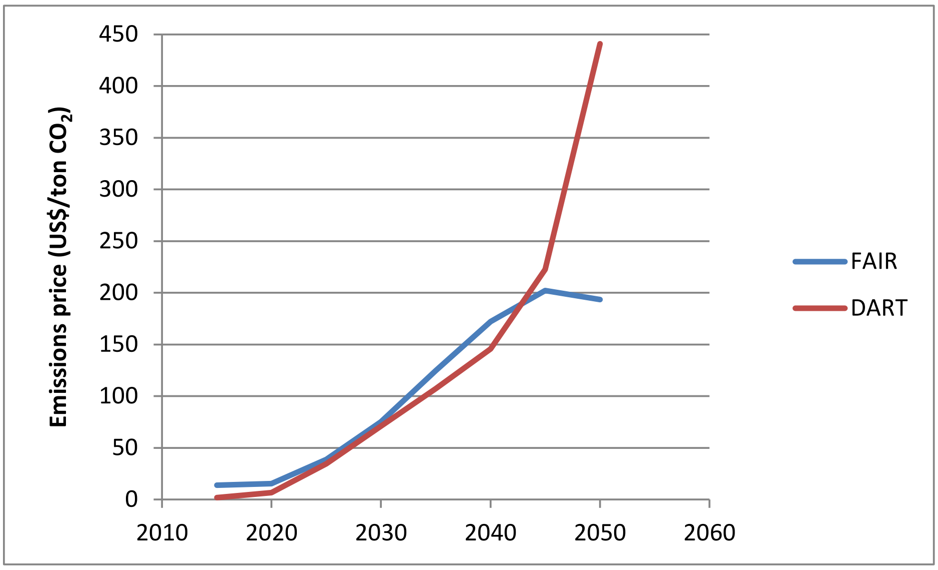

Figure 3. Carbon taxes compatible with the global emissions pathway leading to a stabilization of 2.9 W/m^2 in 2100 in FAIR and DART. These taxes consider only the energy-related CO_2 emissions.

4.2 Results for China

In the baseline scenario (without any international climate policies) CO_2 emissions for China continue to increase in all models (Figure 4). After 2030, a decrease in the growth rate can be observed even leading to a small decrease in absolute emissions in the CEEPA model. Since emissions were not harmonized, there is a spread. Interestingly, national models show considerably higher emissions in 2030. This implies that the 2020 Copenhagen pledge is much more challenging under these assumptions than in the global models. It should also be noted that China MARKAL do consider some planned climate policies in the baseline scenario - such as the renewable energy development goal for the year 2020, the reduction of 40%-45% carbon intensity during 2005 to 2020. The inclusion of these policies in the baseline in China MARKAL is one cause for the relatively low baseline emissions in that particular model towards the end of the time horizon. Furthermore, the final emissions according to the CDC regime – taking into account international emission trading – linger for most models and before 2035 slightly below the emission allowances, implying relative small revenues from international emissions trading. Only China MARKAL generates emissions under the CDC regime that are higher than the emission allowances for the whole time period, implying that, under our cost-optimal calculations, China is a net buyer of credits on the international carbon market. For the other three models China changes from being a seller to a buyer beyond 2035.

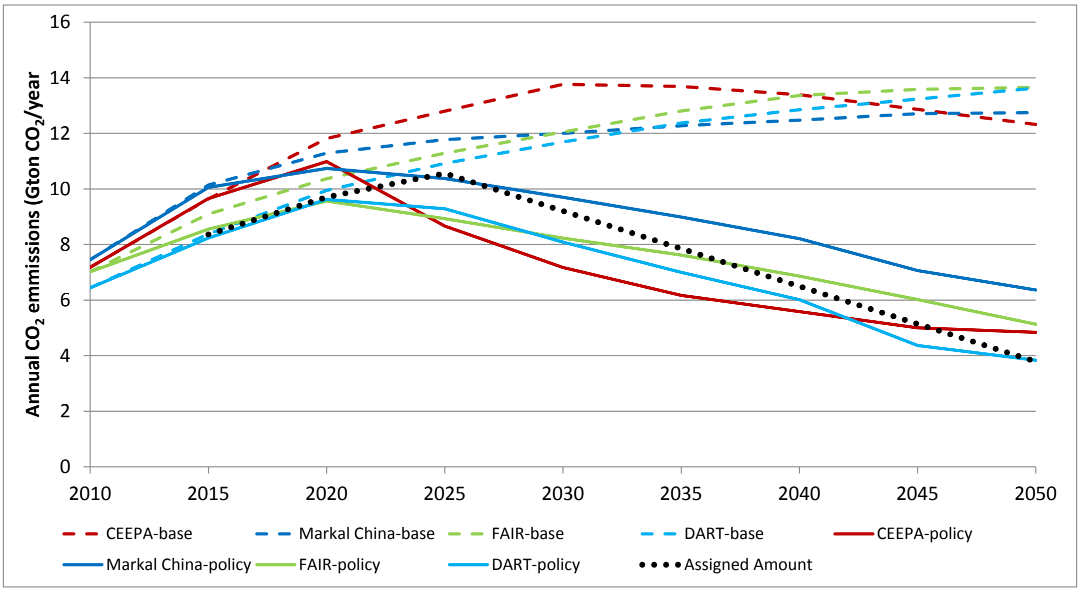

Figure 4. Baseline emissions, emission allowances and emissions (CO_2 only) in the policy scenario for China.

4.3 Results for India

In the baseline scenario CO_2 emissions in India will continue to increase with almost a constant growth rate over the coming decades (Figure 5). The 2020 Copenhagen pledge is almost identical or even slightly higher than baseline emissions in the different models. It should also be noted that MARKAL India does consider some planned climate policies in the baseline scenario. The final emissions according to the CDC regime – taking into account international emission trading – remain considerably below the emission allowances in all models for the whole 2020-2050 period. This implies that India is a net seller of credits on the international carbon market.

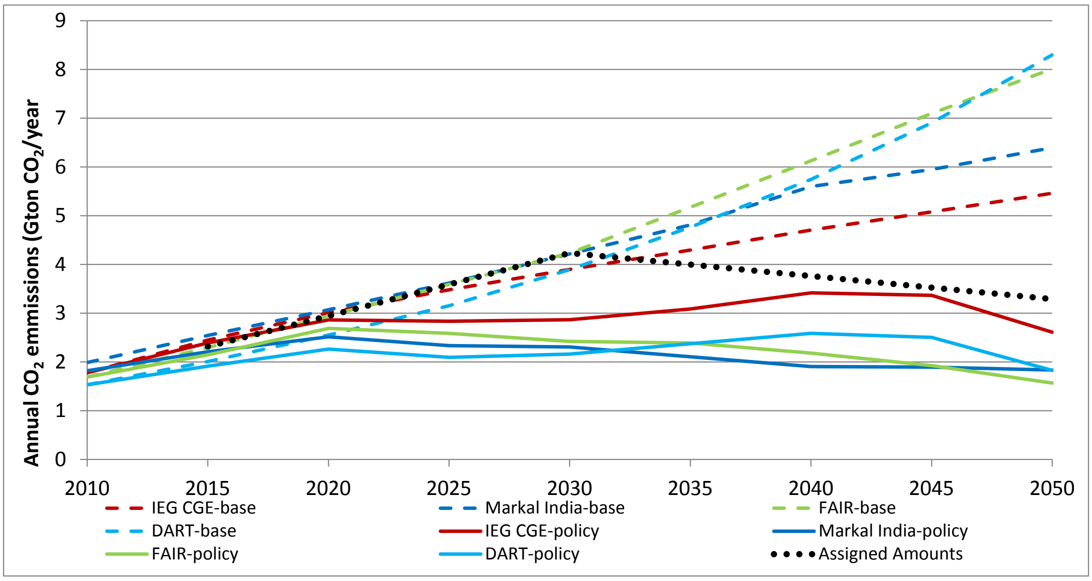

Figure 5. Baseline emissions, emission allowances and emissions (CO_2 only) in the policy scenario for India.

5. Energy system change and climate policy costs

5.1 Changes in fuel mix

5.1.1 China

Figure 6 presents the Chinese primary energy supply in the baseline and the climate policy scenario. Currently, the energy system is dominated by coal followed by oil. Other fuels such as natural gas and biomass play a less important role. The primary energy supply grows rapidly between 2010 and 2020, implying a decadal growth rate between 43 and 56 EJ in the baseline, and 34 to 55 EJ in the policy scenario. Between 2020 and 2050 primary energy supply grows at a slower speed with an additional 20-56 EJ. Notable is that CEEPA shows a peak in primary energy supply by 2030 in the baseline, while the other models show continued growth. The peak in CEEPA is caused by a decline in the supply of domestic fossils due to resource scarcity. This together with the imperfect substitution between domestic fuels and imported fuels (due to the Armington assumption) implies that domestic energy price increases and causes a decrease in energy demand.

In all models, coal remains the most important fuel in the baseline scenario; in 2050 it still contributes more than 50% of the primary energy supply. Oil remains the next most important fuel up to 2050 in all models. Finally, natural gas consumption is projected to grow rapidly in all models, especially in TIMER.

In the climate policy scenario, a reduction of energy use stands out as the most central mitigation option (Figure 6; see also Figure 8 for a decomposition analysis of abatement activities). As a result, in some models primary energy use even peaks around 2020-2030. Reductions in primary energy use are stronger in the CGE models than in the energy system models. In CEEPA one reason for the reduction in energy demand under climate policy is that economic activity declines, while it increases in DART. Changes in economic activity are not considered in China MARKAL and TIMER (see Section 5.2.1). Other important abatement options are CCS (except for CEEPA) and increased use of biomass (primarily in TIMER) and nuclear energy (MARKAL and TIMER).

A large difference across models is the degree to which low carbon technologies are deployed. The energy system models show higher shares than the CGE models, especially in the policy scenarios. In these models, high carbon prices imply that the system starts investing mainly in low carbon technologies. It also means that less energy efficiency improvements are required to achieve the same level of emission reduction the CGE models (see Section 5.2). In addition, reduced fossil fuel demand seems to lead to a more rapid fall in international fossil fuel prices in DART than in the energy system models, leading to a negative feedback for the expansion of low carbon technologies.

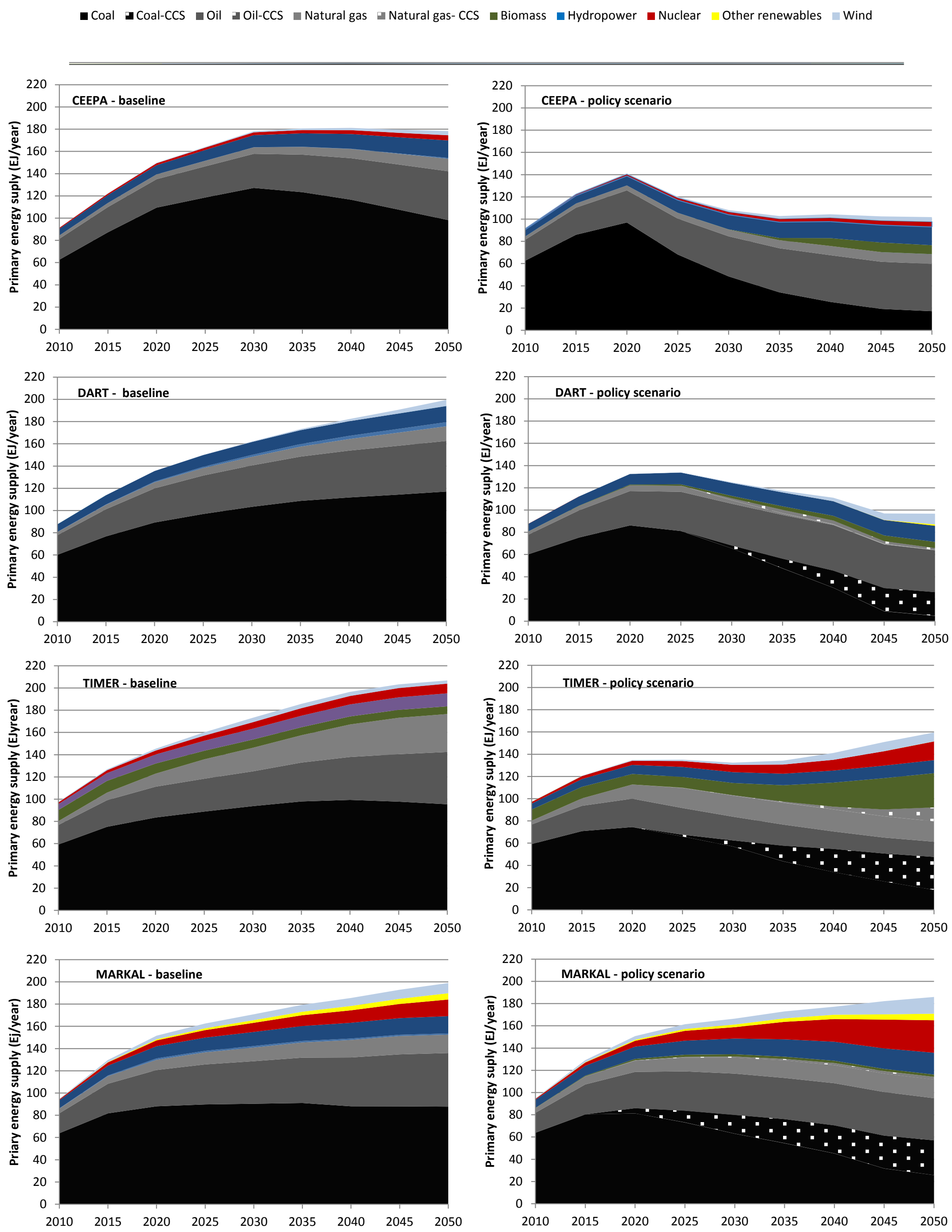

Figure 6. Primary energy supply in China for the baseline scenario and the climate policy scenario.

5.1.2 India

The primary energy supply scenarios for India diverge in the different models (Figure 7). It should be noted that quite a large range of different energy demand levels are projected already for 2020: the lowest demand amount to 20 EJ in the IEG-CGE model while the highest amount to 50 EJ (MARKAL-India model (one reason is that IEG-CGE does not include traditional biofuels, but this only explains a minor fraction of the e difference). More importantly, IEG-CGE shows a very high decoupling between energy and economic growth.

Similar as for China, it is projected that coal remains the most important fuel in the baseline scenario, followed by oil. In DART and TIMER, natural gas increases most rapidly. While natural gas also increases fast in MARKAL-India, it is outrun by nuclear power by 2050. This is attributed to the positive policy outlook towards building nuclear capacity in the country. Nuclear build-up starts around 2030, signifying new expected power plants around that time, as well as the diffusion of policy inertia within the country. This is not accounted for in DART and TIMER.

Again, the CGE models project a much larger role for the reduction in energy consumption in climate policy in the CGE models than in the energy system models. Other important abatement options are CCS (all models except IEG-CGE), increased use of biomass (primarily in TIMER) and other renewables (mainly being different forms of solar energy in MARKAL-India; particularly Solar PV). Due to the focus on enhancing energy efficiency measures, it is expected that there will be strong institutional support to promote use of solar PV, particularly in conjunction with the National Mission on Sustainable Habitat (use of enhanced energy efficiency measures in existing and new building stock). Similar to the results for China, the abatement in the energy system models depends to a stronger degree on biomass and other renewables than in the CGE models.

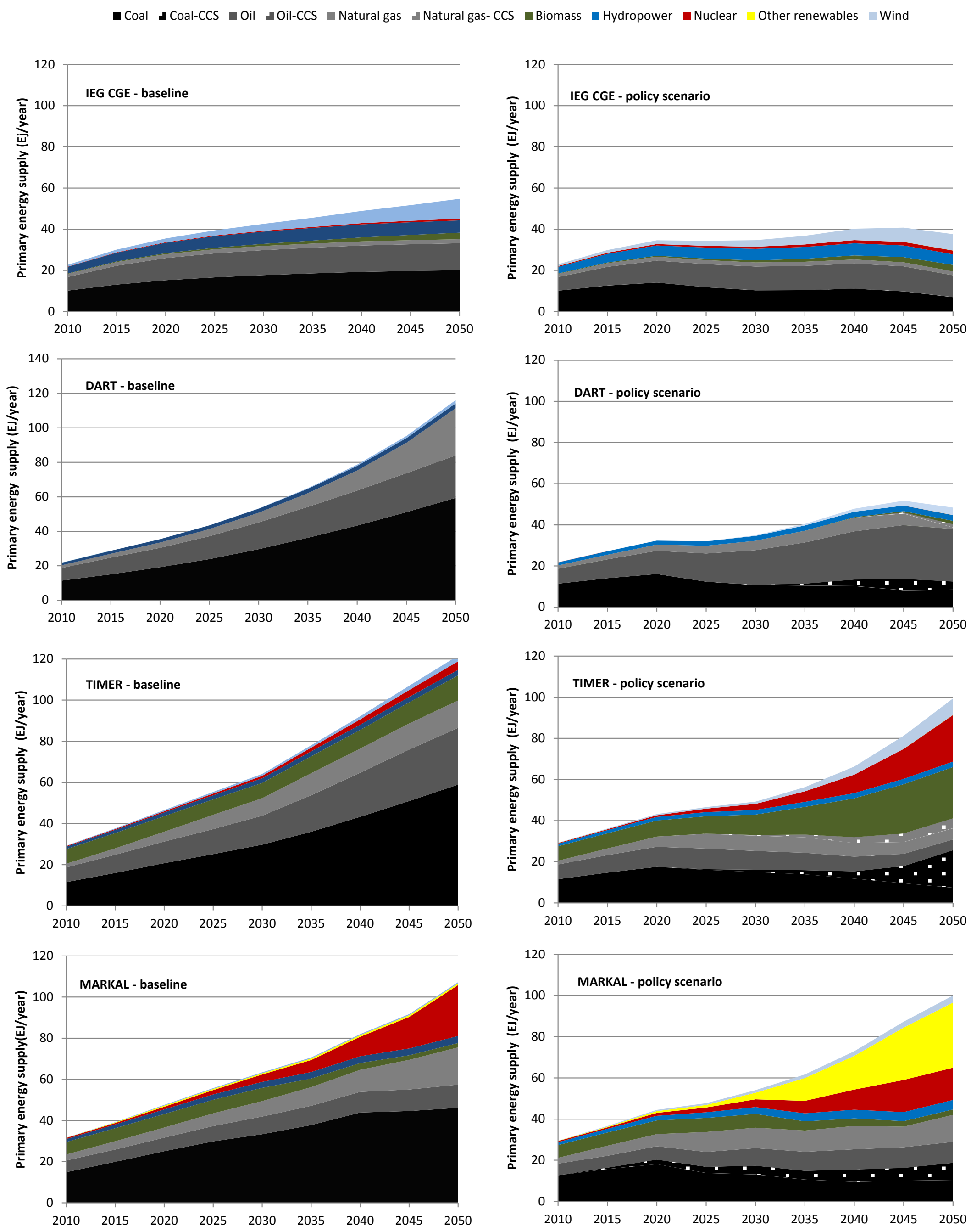

Figure 7. Primary energy supply in India for the baseline scenario and the climate policy scenario

5.2 Decomposition of abatement

A decomposition analysis can help to visualize the differences in abatement strategies across the models. Here we analyze the results from the models using the Kaya identity (Kaya, 1990):

$$E_{CO2}=GDP*EI*CI \quad (1)$$

Where E_{CO2} is annual CO_2 emissions, *GDP* the annual Grosss Domestic Product,*ei* annual average energy intensity (i.e., unit primary energy per unit GDP) and *ci* annual average CO_2 intensity (i.e., unit CO_2 emissions per unit primary energy). Based on additive decomposition techniques (Marshall-Edgeworth index) the Kaya identity can be approximated by an additive form and the contribution of

GDP, *ei* and *ci* changes to total cumulative emissions reductions can be analyzed (Hoekstra and van den Bergh, 2003).

5.2.1 China

There are large differences in cumulative abatement and in how abatement occurs across the different models (Figure 8). The total level of abatement in China is smaller in the energy-systems models compared to the CGE models (see Figures 6 and 8).

One striking difference between the models is how much of the abatement is related to a decline in energy intensity versus carbon intensity. A reduction in energy intensity is the main abatement approach in TIMER, DART and CEEPA, while a large share of emission reductions in China MARKAL comes from a reduction in carbon intensity. The overall large decline in energy intensity in three of the four models indicates that efficiency improvements and structural changes within the economy are central for abatement in China. Although, the decline in energy intensity does not only reflect end use efficiency improvements but rather total system efficiency improvements. Since there is a loss of conversion efficiency when using CCS one observes smaller energy intensity reductions when CCS is an important technology. Hence, it is possible that there are larger energy end use efficiency improvements than what is reflected in energy intensity contribution to emissions reductions for those models in which CCS expands significantly. In addition, in China MARKAL, energy conservation and efficiency improvements as are considered in the baseline scenario leaving only a smaller room for efficiency improvements in the climate policy scenarios compared to other models which do not consider this in the baseline. Finally, by its construction, being a technology focused model, China MARKAL do not consider the option for energy service demand changes when relative prices changes in the model. This is taken into account in the other three models. All these aspects contribute to the lower contribution from energy intensity reduction in China MARKAL. Therefore, the use of renewable fuels, nuclear and CCS is considerably more important than energy efficiency measures for reducing emissions. These results are in line with the fact that renewables, nuclear and CCS (and thus reductions in the carbon intensity) play a more important role in energy system models and in particular in MARKAL-China as seen in Figure 6.

In the two CGE models GDP is affected by climate policies. CEEPA shows a loss in GDP in the climate policy scenarios as compared to the baseline scenario and for this reason the reduction in GDP contributes to abatement. DART shows an increase in GDP due to climate policies partly due to emissions trading, and partly due to a decline in fossil fuel prices and this contributes to increasing the emissions. In general, the contribution of GDP is small compared to the contributions of reductions in energy and carbon intensity.

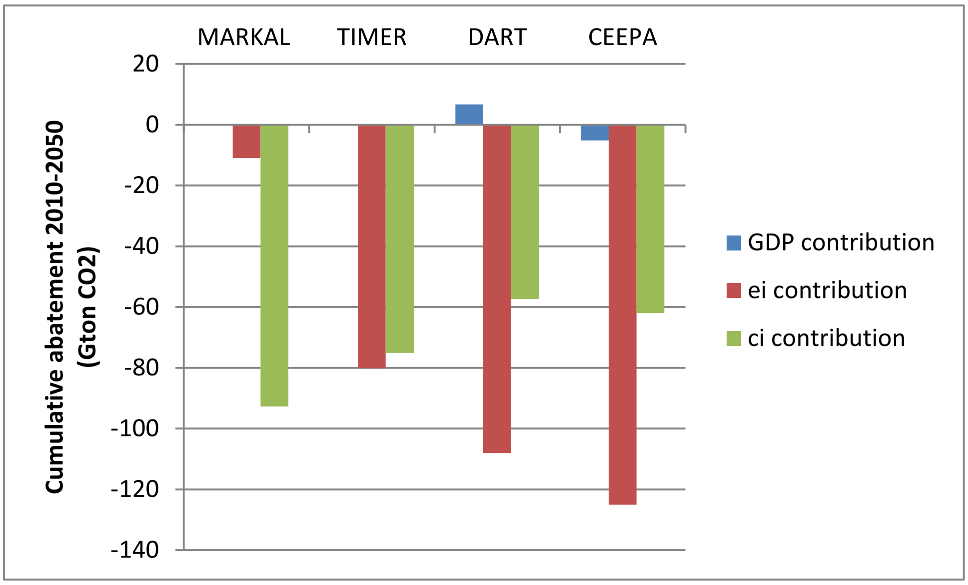

Figure 8. Decomposition analysis of cumulative abatement (2010-2050) in models used for analyzing climate policies in China.

5.2.2 India

Similar to China there are large differences in how abatement occurs in India in the different models (Figure 9). The total level of abatement is smallest in IEG-CGE model. The main reasons are that the baseline emissions in this model are considerably lower than in the other three models (but very close to the projections of the National Council of Applied Economic Research (Ministry of Environment and Forests and Government of India, 2009) till 2030), and that reducing emissions in this model is relatively costly (see Figure 9).

Also similar to the case for China, both CGE models (DART and IEG-CGE) mainly abate through a decrease in energy intensity (see Figure 9). This fact indicates, again, that efficiency improvements and structural changes within the economy are central for abatement in these models. On the other hand, the MARKAL-India obtains only a small reduction in emissions from decreased energy intensity. For TIMER, decreased energy intensity is important for abatement but not as important as a reduction in carbon intensity (this is different from the situation in China where a reduction in investment needs limited the ability to replace existing capital in TIMER – see also van Ruijven et al., 2012). A reduction in carbon intensity can be achieved via the use of CCS and renewable energy, and a switch from carbon intensive coal to less carbon intensive natural gas. In MARKAL-India virtually all abatement occurs through decreased carbon intensity. It is expected that this trend continues, since a substantial energy intensity improvements have already been achieved in various sectors. The reasons why MARKAL-India is showing only a small reduction in energy intensity in comparison to the other three models are virtually identical to those for China MARKAL as discussed in section 5.2.1.

In the two CGE models GDP is again affected by climate policies. GDP decreases in IEG-CGE due to climate policies and for this reason the reduction in GDP contributes to abatement. For DART the GDP increases due to climate policy contributing to increasing emissions. As in the case of China the overall contribution of GDP to total cumulative abatement is relatively small.

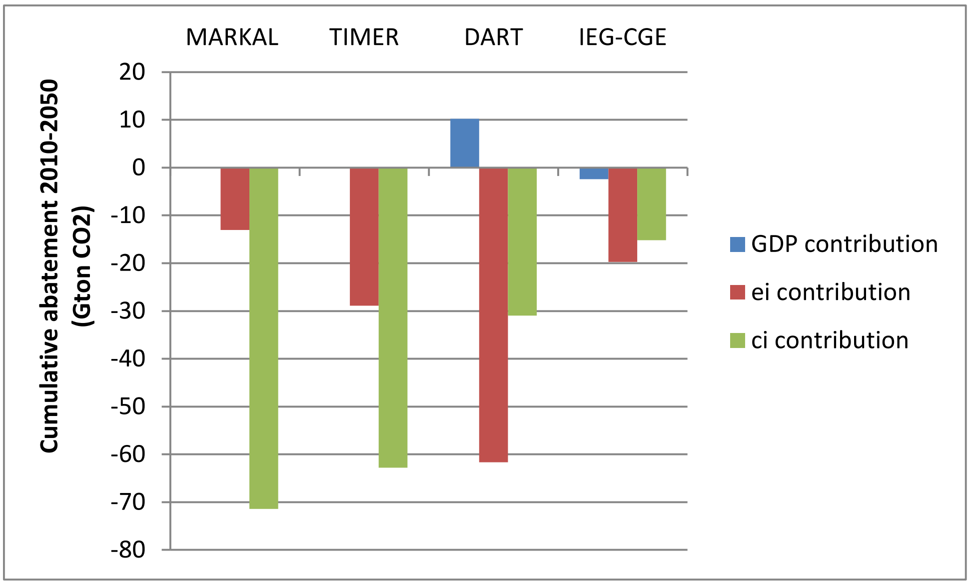

Figure 9. Decomposition analysis of cumulative abatement (2010-2050) in models used for analyzing climate policies in India.

5.3 Direct and macro-economic costs of climate policy

The cost of climate policy is measured as abatement cost relative to baseline GDP levels in the energy system models (including FAIR) and as welfare changes (Hicks equivalent variation) relative to the baseline for the CGE models. The estimates for economic impacts between model classes are therefore not directly comparable. Furthermore, since the models include different technologies, sectors and energy sources it can be expected that abatement costs differ. Energy systems models focus on the competition between different technologies for meeting the demand for goods and services and derive cost estimates from detailed descriptions of the energy systems. In contrast, CGE models focus on the economy as a whole and include the interactions between the various sectors. They do not focus on direct costs, but on changes in economic production and consumption levels or welfare, which better captures the implications overall structural changes and economy wide effects.

Both types of models have their strengths and weaknesses. The direct emission reduction costs calculated by the energy systems models neglect the fact that, by changing prices, indirect effects may occur within the economy. For instance, reducing emissions is likely to lead to a shift in consumption and production from carbon-intensive goods and services to those that are less carbon-intensive. Welfare changes will also result from redistribution of financial flows, changes in fossil-fuel trade (e.g. losses in export revenues from fossil-fuel exporters) and trade on international carbon markets. Market failures (e.g. existing taxes on energy use) may also cause a difference between direct cost and macroeconomic cost

The economic impacts of the climate policy scenario for China and India are depicted in Figure 10 and 11, respectively. The figures also show the global average effects from FAIR and DART to put regional effects into perspective (for the economic burden of India and China relative to the global average (Hof et al., 2009; Van Ruijven et al., 2012).

5.3.1 China

While in all models (except CEEPA), costs are increasing over time there are large differences between the models. While the CGE models show moderate costs for a longer period, in the case of DART for the whole model period, costs increase to 2.5 or even 5% relative to GDP in the energy system models by 2040.

One explanation for modest cost estimate in DART is that in DART the repercussions on the international fuel market are relatively large. The world (as a whole) consumes less fossil fuels in the climate policy scenario as compared to the baseline scenario, so that the (global) fossil fuel price declines. China, an importer of fossil fuels, can profit from this, while energy exporting countries such as Russia lose export revenue. In CEEPA, this effect is not present (assumption of a small open economy with world prices fixed between the two scenarios). Also neither FAIR nor MARKAL-China capture this effect. Further, China is a net seller of credits up to 2050 in DART, while in CEEPA and FAIR China is a seller the initial decades but becomes a net buyer later (see Figure 4). In MARKAL-China China is a net buyer of credits over the whole time period considered.

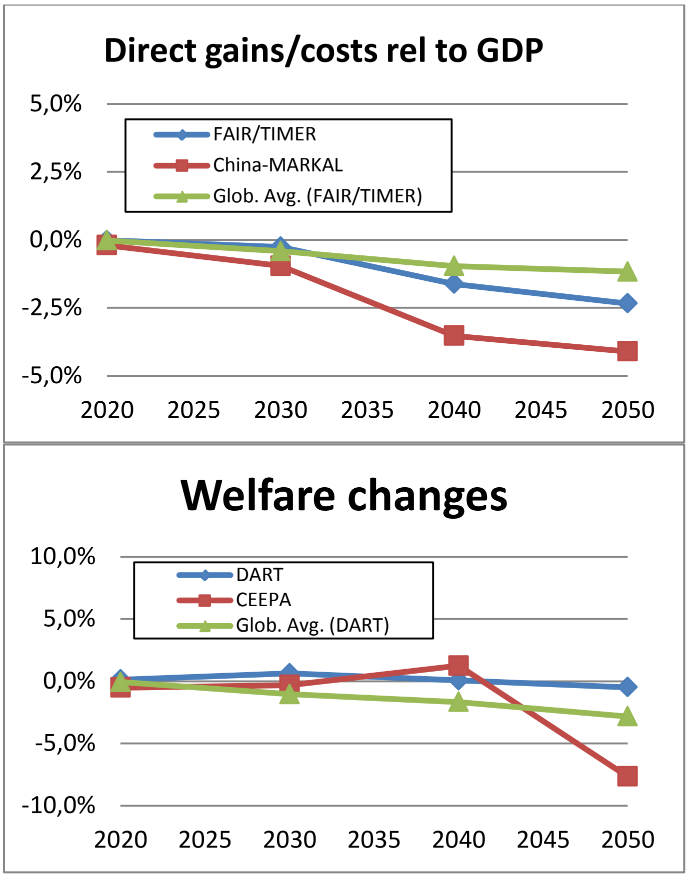

Figure 10. Economic impacts of climate policy in China for selected years). For FAIR and China-MARKAL gains or costs are reported as abatement cost relative to GDP (top) for the CGE models DART and CEEPA welfare changes (Hicks equivalent variation) are reported (bottom).

5.3.2 India

As expected, the climate policy scenario also affects India differently in the different models. The global models, DART and FAIR, show an economic gain from international climate policies throughout the simulation period. The main explanation for the economic gain is that Indian per capita emissions are lower than those in China. As a consequence, India can sell more allowances on the international allowance market than China (see Figures 4 and 5). In addition, the Indian economy is smaller than the Chinese and for this reason an equal net export of carbon allowances has a larger impact on India. FAIR shows a small benefit in 2020, a somewhat larger gain in 2030 and 2040, and a close to zero gain in 2050.The latter is caused by a reduction of export of allowances.

For the DART results it is again important that international fuels prices decline considerably benefitting net importers of fossil fuels such as India. This effect is again non-existing in FAIR, MARKAL-India and IEG-CGE.

IEG-CGE shows a loss in welfare that grows over time, due to an increase in carbon prices. This is in stark contrast to the results found in DART. In the IEG-CGE model capital inflows (from selling allowances) lead to an appreciation of the Indian currency which lowers international competitiveness, but at the same time result in lower prices and welfare loss relative to the carbon tax scenario. This is modeled differently in DART and not at all considered in MARKAL-India and FAIR.

The result for MARKAL-India is also different. One cause is the inter-temporal optimization as the knowledge of future high CO_2 prices causes investments and national fuel prices to decline early on in the model leading to a gain initially. Later, costly investments in abatement technologies are needed and the benefit of climate policies found at earlier decades turns to a loss.

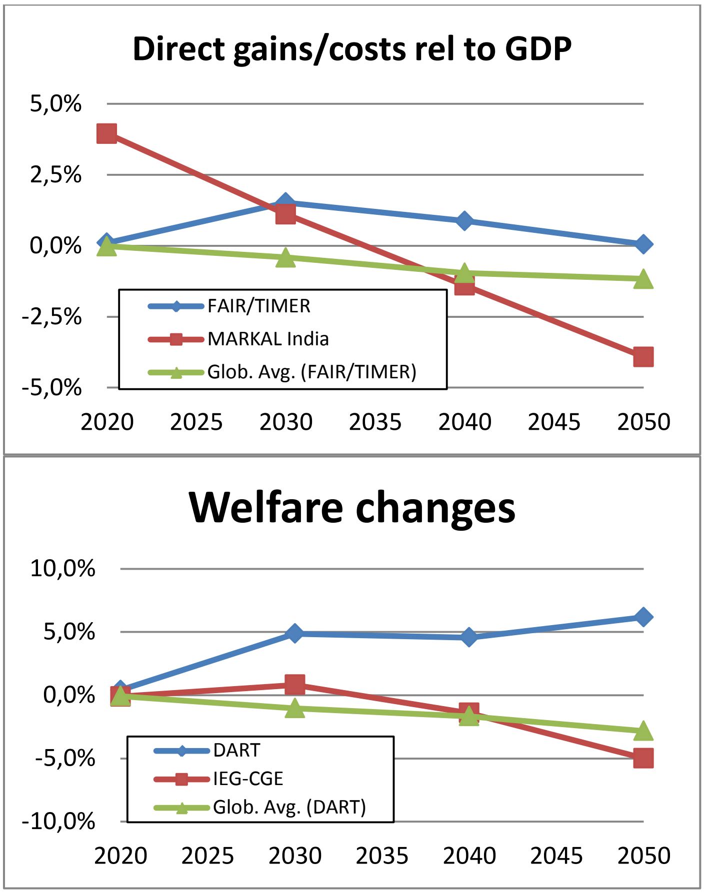

Figure 11. Economic impacts of climate policy in India for selected years. For FAIR and India-MARKAL gains or costs are reported as abatement cost relative to GDP (top) for the CGE models DART and CEEPA welfare changes (Hicks equivalent variation) are reported (bottom).

6 Sensitivity analysis

In the sensitivity analysis we test if the model results are sensitive to alternative assumptions in GDP growth, the timing of emissions reductions, and to choices in the effort-sharing approach. We focus on the economic implications, since the qualitative nature of the energy results turn out to be relatively robust to changes in these assumptions. Furthermore, the energy implications of some of these assumptions are analyzed in detail in Lucas et al.(in prep.).

6.1 Different assumptions tested

6.1.1 Alternative GDP assumption: higher GDP growth

The GDP assumptions we used throughout the main part of the analysis are based on OECD (2012). However, international studies in the past tended to underestimate economic and emission growth in the emerging economies in Asia, particularly in the case of China (Van Ruijven et al., 2012). We thus run the models with a higher GDP growth scenario for China and India, while the rest of the world still follows the OECD baseline scenario. For China, the national projection is based on Goldman Sachs (2010), IEA(2010), NBS Research Group(2011) and Li (2010). For India, we assume the high growth scenario of the Government of India (GOI, 2006) extrapolated to 2050 by assuming declining growth rates after 2032 where the GOI study ends. In this case China's economy is projected to grow on average about 6.2% per year between 2010 and 2050 compared to about5% per year in our base case, while India's economy to grow on average about 7.9 % per year instead of about 6.8% per year. The altered growth assumption also leads to increases in CO_2 emissions in the baseline.

6.1.2 Alternative global emission pathways: early action

In the climate policy case assumed throughout the main part of the analysis countries implements their high Copenhagen Accord pledge for 2020, after which global emissions gradually decrease. Resulting global 2020 emissions compared to 1990 are higher than in the cost-optimal pathway generated in FAIR–SiMCaP (Van Vliet et al., 2012). We consider such a cost-optimal pathway here. As a consequence of larger short-term reductions (31.7 Gton CO_2 globally in 2020 in the cost-optimal pathway versus 34.0 Gton CO_2 globally in 2020 in the Copenhagen pathway), while still aiming for the same 2.9 W/m^2radiative forcing target in 2100, the mid- and long-term emissions levels (2025-2050) can be slightly higher.

6.1.3 Alternative effort-sharing approaches: uniform carbon tax and CDC with delayed participation

As alternatives to the CDC base case, we consider two alternative regimes: a global uniform carbon tax approach and an alternative CDC approach.

One of the most straightforward proposals is a globally uniform carbon tax, i.e. carbon tax is the same across all regions. Through the global equalization of marginal abatement costs this approach would ensure cost-effectiveness. However, a uniform carbon tax does not distinguish between developed and developing countries, hence leading to no compensation to developing countries. Furthermore, under an uniform carbon tax studies generally find higher abatement costs as percentage of GDP for developing countries than for developed countries (Hof et al., 2009; van Vuuren et al., 2009), so that this approach is not in line with "common but differentiated responsibilities".

In the alternative CDC case, further referred to as CDC with delayed participation, China and India start converging 5 years later than in the base case. To stay within the global emission pathway, developed countries have thus to reduce more and converge to 0.6 tCO_2/cap - instead of 1.7 tCO_2/cap in the base case. This results in a 90% emission reduction for developed countries in 2050 compared to 1990; the upper level of the 80%-95% range of the IPCC (2007). The developing countries still converge to 1.7 tCO_2/cap.

Note that global carbon taxes calculated in FAIR and DART change for the new assumptions on GDP growth and timing of emissions reductions. In DART the carbon tax is also affected by the details of the effort-sharing approaches due to repercussions of carbon trade revenues on GDP and energy demand.

The impact of these different assumptions on the global carbon price is presented in Figure 12. It shows that the impact is relatively small in DART, while especially after 2030 it is much larger in FAIR. Impacts on the costs of climate policy for China and India are presented in Figure 13 and 14, respectively. To capture cost differences across the entire period considered, the cost of climate policy are measured as Net Present Value (NPV) welfare relative to the respective baseline for the CGE models, while for the energy system models costs are measured as the abatement cost including emissions trading compared to baseline GDP, both measured in NPV terms over the period 2010-2050. These results are discussed in the following two subsections.

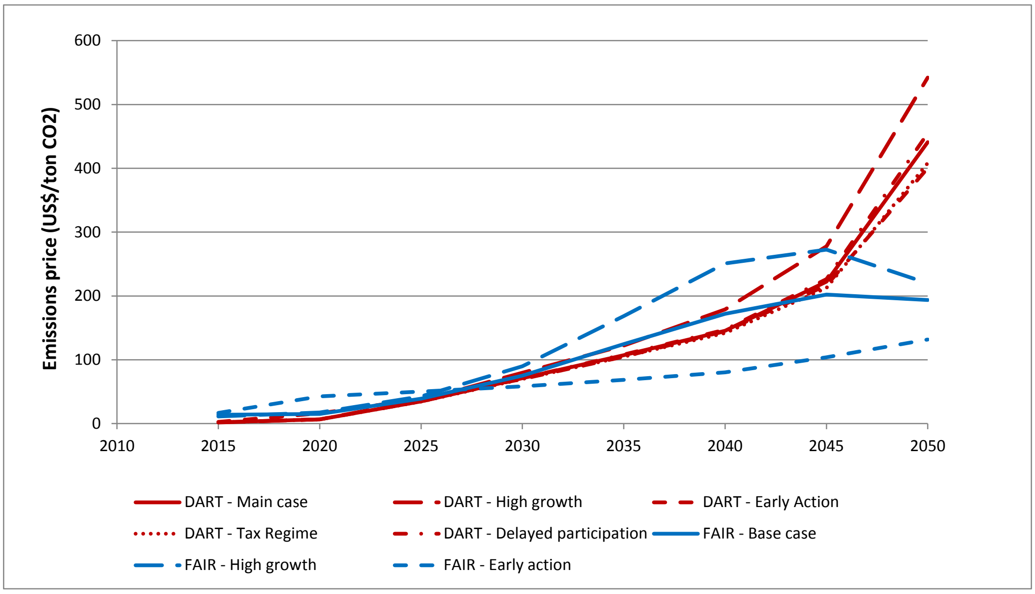

Figure 12. Carbon tax in the sensitivity analysis in FAIR and DART .Prices generated by FAIR for the tax regime and the delayed participation regime is equal to those generated in the Main case.

6.2 China

The overall climate policy costs for China are more sensitive to the assumptions on the effort-sharing approaches than to assumptions for economic growth and the global emission pathway.

Higher economic growth increases the cost of climate policy compared to the base case for all models, although considerably more for China-MARKAL and CEEPA than for FAIR and DART. The reason for this increase in cost is due to the fact that emission allowances are only slightly changed compared to the base case, but emissions under the high growth baseline deviate more substantially from the original baseline. This leads to more abatement and therefore larger abatement cost.

Early action - more global abatement in the short run - has a mixed impact on climate policy costs in the different models. The NPV cost decreases in the energy system models FAIR (based on cost-curves from TIMER) and China MARKAL, while NPV costs increase in the CGE models CEEPA and DART. One explanation for the differences is that TIMER and China-MARKAL capture capital stocks in a more detailed way and in the case of TIMER also learning by doing. A later adoption of reduction targets implies a larger built up of fossil fuel based technology without CCS. Assuming that technologies are only replaced after their normal lifetime, the expected decreased growth in demand in China implies that there are limits to the potential to reduce emissions, as there will be little demand for new facilities (see also van Ruijven et al., in press). Therefore the delay is more costly. In addition there is in TIMER also impact of less room for learning by doing of other less CO_2 emitting technologies and therefor larger NPV abatement cost. Abatement costs thus decrease more gradually in the early action case causing NPV abatement costs to be smaller.

Finally, an effort-sharing approach with a uniform carbon taxes tends to be most detrimental for China in most models, except China-MARKAL. The reason for this is that in the base case in China-MARKAL China is a net buyer of emissions credits, while in the other models China becomes a net buyer only beyond 2035 (Figure 4). Also, the magnitude of the economic impact of a tax policy is very different across models. CEEPA shows a significant increase in costs, while the increase in other models is much smaller. In the CDC with delayed participation, China does not adopt an emission cap in the context of the international climate negotiations until 2030 and for this reason costs are lower in all models compared to the base case. Besides DART, now also CEEPA shows a net benefit from such an effort-sharing approach.

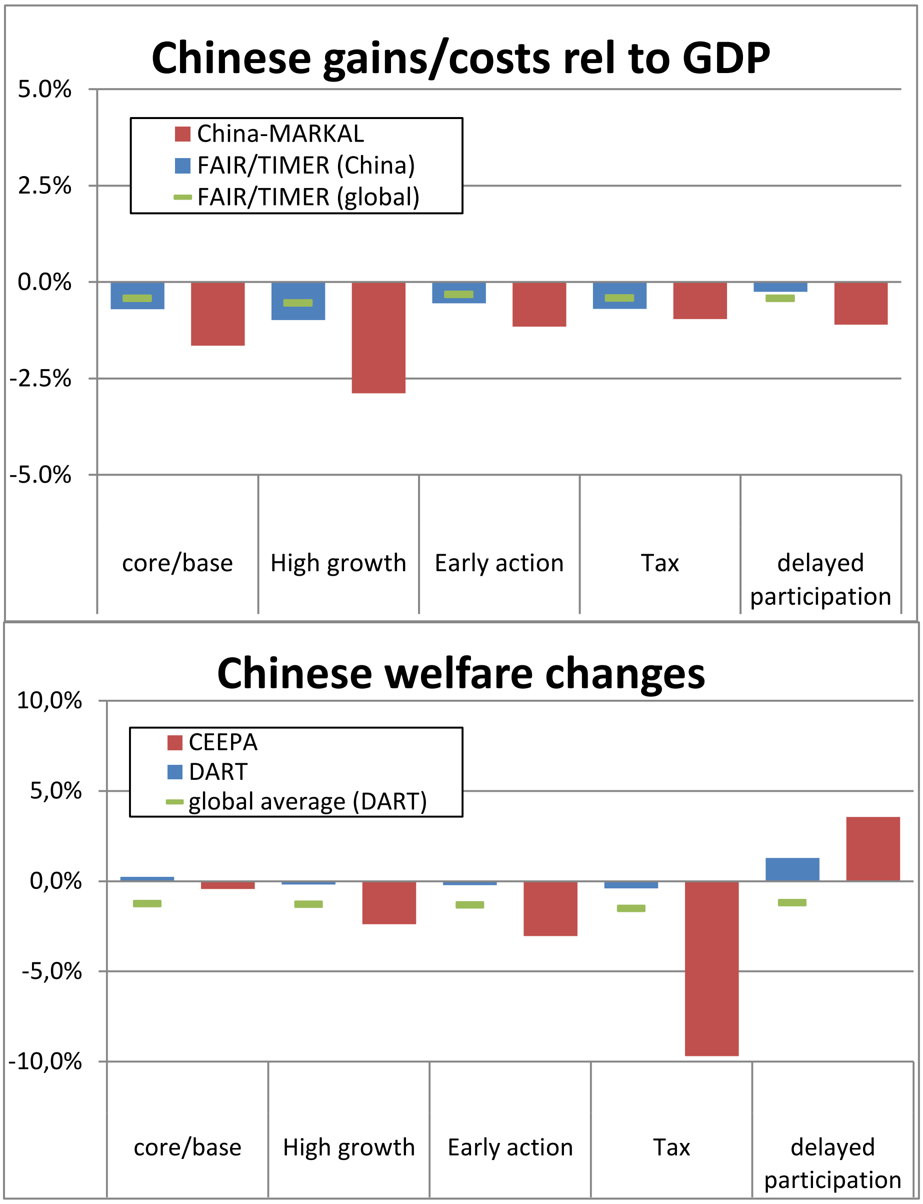

Figure13. Impact of key assumptions on cumulative discounted costs of climate policy in China.

6.3 India

For India, overall economic impacts are more sensitive to assumptions on the effort-sharing approaches than to different economic growth and global emission pathways in all models except for MARKAL-INDIA in which the results are most sensitive to the GDP growth assumption.

Under higher economic growth the cost of climate policy (in relative terms) increases slightly as compared to the base case for IEG-CGE, the benefits in DART and FAIR are almost similar and the benefit found in MARKAL-India is turned to a substantial loss. With higher growth, global emissions are higher in the baseline. Because the policy target is unchanged, the effort-sharing approaches become relatively more ambitious and carbon prices rise. Since India remains a net seller of credits it continues to benefits from higher carbon taxes. In sum, these two contradicting effects lead to similar costs for India under higher growth in both the DART and the FAIR model. MARKAL-India is negatively affected by the considerably higher CO_2 price and the larger demand in this scenario which results in that investment in relatively costly abatement technology is necessary. IEG-CGE shows an increase in welfare loss because in this model India benefits less from higher CO_2 prices as e.g. DART because increased capital inflows lead to an appreciation in IEG but not in DART.

Early action – more global abatement in the short run - has a negative impact on India in all models, i.e. the benefits either drops or the costs increases. The benefits decreases in FAIR and DART due to a higher reduction objective in 2020 leading to higher costs, which are not fully compensated through higher gains from selling of credits against a higher carbon price. Based on similar principles the cost increases in IEG-CGE and the benefit found in MARKAL-India is turned to a loss.

Concerning the effort-sharing approaches, a uniform carbon tax would on average be most detrimental for India. In all models the CDC with delayed participation results in the highest gains or lowest costs, respectively. In IEG-CGE emissions in the policy scenario are higher than in other models, resulting in less surplus allowances. Furthermore, selling carbon permits leads to an appreciation. Hence gains from emissions trading are not sufficient to completely offset the negative impact of higher carbon prices. While this affects the level of the welfare impacts in all scenarios similarly, the ranking between alternative scenarios in IEG-CGE is identical to DART and TIMER. All models show that the CDC approach with delayed participation results in the lowest costs or highest gains, while a global, uniform carbon tax shows the highest costs or lowest gains. This result is driven by the capital inflow from emissions trading, which is especially large in the CDC approach with delayed participation

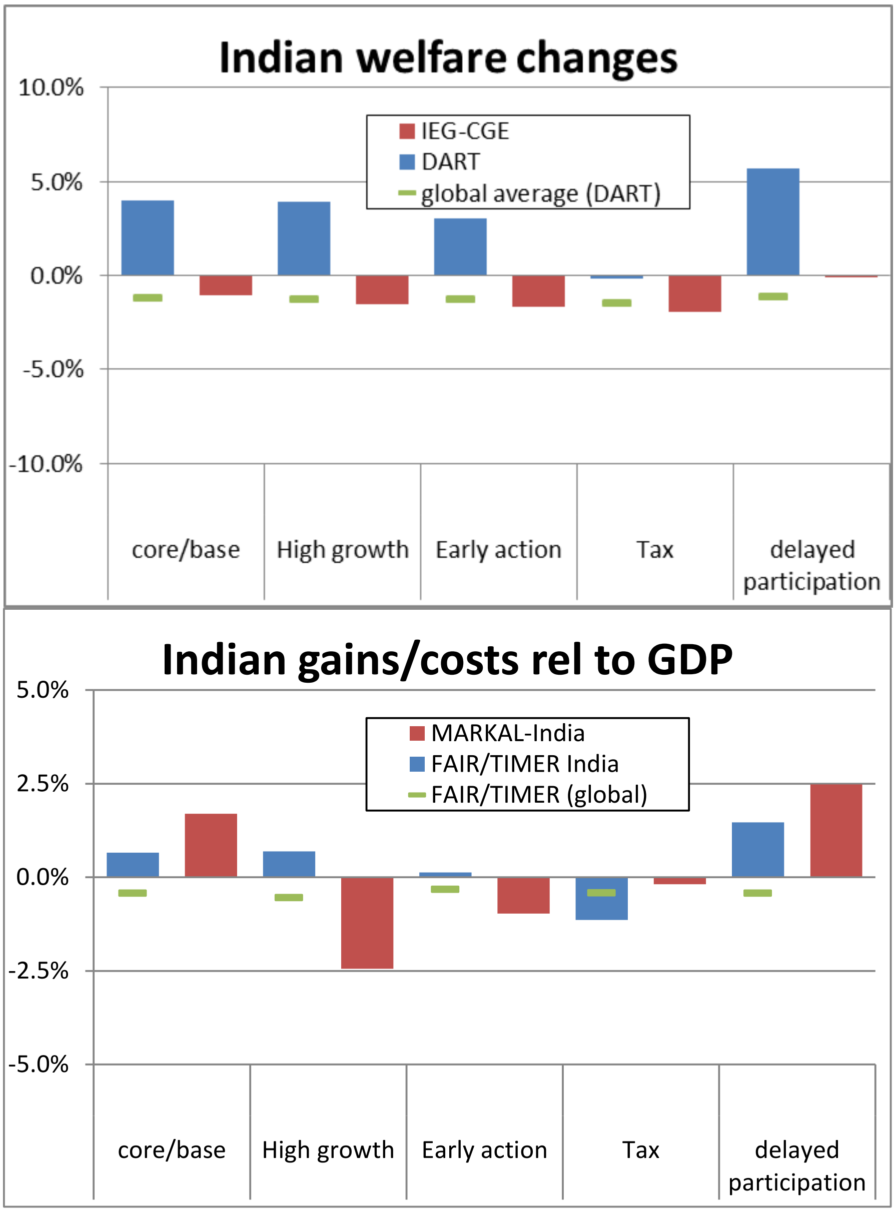

Figure 14. Impact of assumptions on cumulative discounted costs of climate policy in India.

7 Discussion

Energy system change and cost estimations of climate regimes in the literature are often not directly comparable and differences in result are not always easy to explain (Van Ruijven et al., 2012). The harmonization of the baseline and policy scenarios in this study improves the ability to understand the substantial differences in cost estimations across different model types and individual models. The analysis shows in particular that models with a similar structure (CGE vs. Energy system) lead to comparable results. Differences in model results can thus be explained in part by the general underlying assumptions of CGE versus energy system models.

CGE models are top-down models based on the economic structure and technologies of a reference year. Deviating from this equilibrium is possible through substituting energy inputs by additional capital inputs (technique effect) or by shifting demand to less carbon intensive sectors (composition effect), causing that a drop in energy intensity is important for abatement in these models, see Figure 8 and 9. Both effects are driven by changes in relative prices. Furthermore, while substitution possibilities in the vicinity of the initial equilibrium are easy to achieve and therefore relatively cheap, deviating further from the initial situation is increasingly costly. Only explicit modeling of alternative technologies makes it possible to change specific sectors more fundamentally. In our analysis, not all CGE models include low carbon technologies to the same extent (see Table 1) and thus react differently to climate policy. We identify in particular a lack of technology alternatives for oil consuming sectors, most important the transport sector. Concerning cost estimates, CGE models take into account different kind of repercussions on other markets. Differences between the national CGE models and the global CGE model include modeling differences in representing repercussion on international fossil fuel markets and the impact of capital transfers on the exchange rate. For details see Weitzel et al. (In prep.)

Generally, energy system models have more options for meeting energy demand than CGE models and more abatement takes place via carbon intensity reductions, i.e., through changes in the energy supply mix, see Figure 8 and 9. Also, the inertia in the capital stock imply that small carbon taxes lead to little change in the short run in the energy system models. The timing of emission reductions is therefore more important for energy system models and leads – compared to CGE models - to higher carbon taxes in the short run, see Figure 3 and 12. For a more detailed discussion of this issue see Lucas et al. (in prep.). In the longer run, carbon taxes are lower than in the CGE models due to learning and explicit modeling of more abatement options – a sharp increase would only be observable when the potential of relatively low cost abatement options is completely exhausted, which is not the case in our analysis. Concerning cost estimates energy system models are able to give only the direct cost of energy system changes.

For MARKAL models, the importance of energy efficiency improvements vis-à-vis carbon intensity improvements is about the same in relative terms for both countries. Also in TIMER, the carbon intensity improvement plays a major role – but here the contribution is even more important in India than in China. For the reduction in carbon intensity, CCS stands out as the most important options across models. In addition, solar energy and small hydro are important in MARKAL-India, CCS is important in China MARKAL and modern biomass in TIMER.

In the main climate policy case assuming a least-cost implementation of international climate policy, CO_2 emission levels for the different models in the year 2050 are in the range of -20% to +25% compared to 2005 emission levels in China and between +20 and +130% compared to 2005 emission levels in India. In 2010 China's CO_2 emissions are almost three times higher than the Indian emissions, while in the baseline and policy scenarios in 2050 the CO_2 emissions in China are about twice those in India. Demand for new capacity in India remains high towards 2050, while in China this demand levels off after 2030. As especially the energy-system models take account of the capital stock, this has a limiting effect on mitigation potential in China compared to India.

In our main policy case the costs of climate policy are larger for China than for India. In the energy system models the cumulative discounted costs as fraction of GDP are in the order of +0.4 to +1.8% for China and -0.7% to -1.7% for India, with positive numbers representing losses and negative numbers gains. In the CGE models welfare losses range from +0.4% to -0.2% for China and from +1.1% to -4% for India. The main reason for these differences is that per capita emissions for China are already around the world average, while for India they are substantially lower. As the CDC approach implies a convergence of global per capita emissions, India is confronted with a lower reduction objective, and, as a result has a higher potential of selling reductions on the international carbon market generating revenues.

In general China is a seller on the short term, but becomes buyer on the long-term, while India is a seller over the whole 2010-2050 period, see figure 4 and 5. Only DART finds that China can benefit from international climate policy, mainly due to reduced costs of fossil fuels, although gains are small. For India, on the other hand, most models show an economic benefit of climate policies up to 2030/2040, mainly due to benefits from international emissions trading. For both India and China the models with a national focus tend to show more negative economic implications of climate policies than the global models. The reason for this is not trivial. For the CGE models, it can be explained in part by repercussions on international fuels market taken into account by the international DART model.

The sensitivity analyses reveal that both China and India benefit from delayed participation and both countries are more negatively affected by climate policies if a uniform carbon tax is assumed instead of a CDC approach. Although, China MARKAL is an exception here, showing that a uniform carbon tax approach results in the lowest costs. The reason behind this result is that in China MARKAL China is a net buyer of permits in the main CDC case. Finally, if higher economic growth rates for China and India are assumed, the model results point towards smaller benefits or larger costs (relative to GDP) of climate policies for both countries.

8 Conclusions

This paper presents an overview of an international modeling comparison project, focused on how achieving the 2°C climate target could affect economic and energy systems development in China and India. The multi-model analysis concludes that, compatible with the 2°C target and global convergence of per capita CO_2 emissions, significant reductions are required in both China and India, implying huge changes in their energy systems.

There are large differences in the size of the energy system and the related CO_2 emissions between China and India today, pertinent to the differences in economic activity. In the baseline scenario, the differences will decrease over time primarily due to higher economic growth in India. The current situation and the assumed future developments imply that there are differences as well as similarities in how India and China may be affected by climate policies on an aggregated national level.

In the main climate policy case Indian emissions are allowed to grow more than the Chinese emissions and still stay below their assigned amount, due to the per capita convergence rule and the higher population growth in India. Clear differences and similarities with respect to the actual consequences for the energy system of climate policy can be observed, not only among the two countries, but also among the two model types - CGE vs. energy system model. Energy efficiency improvements are important in the CGE models, while improvements in the carbon intensity, primarily through expansion of CCS and renewables, are more important for the energy system models. With respect to the carbon intensity improvements, CCS is more important in China, while renewables (including biomass) is more important in India.

The economic impacts of international climate policy – either measured as direct mitigation costs in the energy system models or as welfare losses relative to baseline GDP in the CGE models - are generally larger in China than in India, while India can even gain. This is primarily the result of India benefiting more from international emissions trading. In general China is a seller on the short term, but becomes a buyer on the long-term, while India is a seller over the whole 2010-2050 period. Dependent on the model, costs are also affected by decreasing global fossil fuel prices, currency depreciation resulting from a net capital inflow from international carbon trading and timing of emission reductions. Furthermore, China and India benefit from delayed participation and both countries are more negatively affected by climate policies if a uniform carbon tax is assumed (no international emissions trading) instead of a CDC approach.

Acknowledgement

The work presented is based on research within the POEM (Policy Options to engage EMerging Asian economies in a post-Kyoto regime) project funded by the European Commission's 7th Framework Programme under contract 226282. The authors wish to thank partners of the POEM project for their contributions.

References

Blanford, G.J., Richels, R., Rutherford, T.F., 2009. Revised Emissions Growth Projections for China: Why Post-Kyoto Climate Policy Must Look East, in: Stavins, R., Aldy, J.E. (Eds.), Forthcoming in: Implementing Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World. Cambridge University Press, Cambridge.

Bodansky, D., 2004. International climate efforts beyond 2012: A survey of approaches. . Pew Climate Center, Washington, DC.

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

Busch, J., Strassburg, B., Cattaneo, A., Lubowski, R., Bruner, A., Rice, R., Creed, A., Ashton, R., Boltz, F., 2009. Comparing climate and cost impacts of reference levels for reducing emissions from deforestation. Environmental Research Letters 4.

Calvin, K., Fawcett, A., Kejun, J., in press. Comparing model results to national climate policy goals: Results from the Asia modeling exercise. Energy Economics.

Chen, W., 2005. The costs of mitigating carbon emissions in China: findings from China MARKAL-MACRO modeling. Energy Policy 33, 885-896.

Chen, W., Wu, Z., He, J., Gao, P., Xu, S., 2007. Carbon emission control strategies for China: A comparative study with partial and general equilibrium versions of the China MARKAL model. Energy 32, 59-72.

Chen, W., Li, H., Wu, Z., 2010. Western China energy development and west to east energy transfer: Application of the Western China Sustainable Energy Development Model. Energy Policy 38, 7106-7120.

Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., Tavoni, M., 2009. International climate policy architectures: Overview of the EMF 22 International Scenarios. Energy Economics 31, S64-S81.

Council of the European Union, 2009. Presidency Conclusions, 15265/1/09, Brussels.

den Elzen, M.G.J., Lucas, P.L., 2005. The FAIR model: A tool to analyse environmental and costs implications of regimes of future commitments. Environmental Modeling and Assessment 10, 115-134.

Den Elzen, M.G.J., Meinshausen, M., van Vuuren, D.P., 2007. Multi-gas emission envelopes to meet greenhouse gas concentration targets: Costs versus certainty of limiting temperature increase. Global Environmental Change 17, 260-280.

Den Elzen, M.G.J., Höhne, N., 2008. Reductions of greenhouse gas emissions in Annex I and non-Annex I countries for meeting concentration stabilisation targets. An editorial comment. Climatic Change 91, 249-274.

den Elzen, M.G.J., Lucas, P.L., van Vuuren, D.P., 2008. Regional abatement action and costs under allocation schemes for emission allowances for achieving low CO2-equivalent concentrations. Climatic Change 90, 243-268.

Den Elzen, M.G.J., Hof, A.F., Roelfsema, M., 2011. The emissions gap between the Copenhagen pledges and the 2C climate goal: Options for closing and risks that could wident he gap. Global Environmental Change 21, 733-743.

Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Chateau, B., Criqui, P., Isaac, M., Kitous, A., Kypreos, S., Leimbach, M., Lessmann, K., Magne, B., Scrieciu, S., Turton, H., Van Vuuren, D.P., 2010. The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs. Energy Journal 31, 11-48.

ERI, 2009. The Road of China’s 2050 Low Carbon Development. Energy Research Institute of the National Development and Reform Commission, Beijing,China.

Fee, E., Johansson, D.J.A., Lowe, J., Marbaix, P., Meinshausen, M., Smith, B., 2010. Scientific perspectives after Copenhagen, Information reference document, EU EG Science.

Fishbone, L.G., Abilock, H., 1981. Markal, a linear-programming model for energy systems analysis: Technical description of the bnl version. International Journal of Energy Research 5, 353-375.

Fisher-Vanden, K.A., Shukla, P.R., Edmonds, J.A., Kim, S.H., Pitcher, H.M., 1997. Carbon taxes and India. Energy Economics 19, 289-325.

GEA, 2012. Global Energy Assessment – Towards a Sustainable Future. Cambridge University Press, Cambridge UK and New York, NY, USA and the International Institute of Applied Systems Analysis, Laxenburg, Austria.

GOI, 2006. Integrated Energy Policy-Report of the Expert Committee. Government of India, Planning Commision.

Goldman Sachs, 2010. EM Equity in Two Decades: A Changing Landscape, Global Economics Paper No. 204.

Gupta, S., Tirpak, D.A., Burger, N., Gupta, J., Höhne, N., Boncheva, A.I., Kanoan, G.M., Kolstad, C., Kruger, J.A., Michaelowa, A., Murase, S., Pershing, J., Saijo, T., Sari, A.P., 2007. Policies, Instruments and Co-operative Arrangements. , in: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

He, J., Chen, W., Teng, F., Liu, B., 2009. Long-Term Climate Change Mitigation Target and Carbon Permit Allocation. Advances in Climate Change Research 5, 78-85.

Hoekstra, R., van den Bergh, J.C.J.M., 2003. Comparing structural decomposition analysis and index. Energy Economics 25, 39-64.

Hof, A., den Elzen, M., van Vuuren, D., 2009. Environmental effectiveness and economic consequences of fragmented versus universal regimes: what can we learn from model studies? International Environmental Agreements: Politics, Law and Economics 9, 39-62.

Höhne, N., den Elzen, M.G.J., Weiss, M., 2006. Common but differentiated convergence (CDC), a new conceptual approach to long-term climate policy. Climate Policy 6, 181-199.

Höhne, N., Blum, H., Fuglestvedt, J., Skeie, R.B., Kurosawa, A., Hu, G., Lowe, J., Gohar, L., Matthews, B., de Salles, A., Ellermann, C., 2011a. Contributions of individual countries' emissions to climate change and their uncertainty. Climatic Change 106, 359-391.

Höhne, N., Taylor, C., Elias, R., Den Elzen, M., Riahi, K., Chen, C., Rogelj, J., Grassi, G., Wagner, F., Levin, K., Massetti, E., Xiusheng, Z., 2011b. National GHG emissions reduction pledges and 2°C: comparison of studies. Climate Policy 12, 356-377.

IEA, 2010. World Energy Outlook 2010. International Energy Agency, Paris.

IEA, 2011. World Energy Outlook 2011. International Energy Agency, Paris.

IPCC, 2007. Climate Change 2007 - Synthesis Report. Cambridge University Press, Cambrige.

Kameyama, Y., 2004. The future climate regime: a regional comparison of proposals. . International Environmental Agreements: Politics, Law and Economics 4, 307-326.

Kaya, Y., 1990. Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios, Paper presented at the IPCC Energy and Industry Subgroup, Response Strategies Working Group, Paris, France.

Klepper, G., Peterson, S., Springer, K., 2003. DART97: A Description of the Multi-regional, Multi-sectoral Trade Model for the Analysis of Climate Policies, Kiel Working Paper No. 1149.

Kretschmer, B., Narita, D., Peterson, S., 2009. The economic effects of the EU biofuel target. Energy Economics 31, Supplement 2, S285-S294.

Li, S., 2010. China's Economic Prospect for the 12th Five-Year Plan Period and 2030. Review of Economic Research (Chinese) 43, 2-27.

Liang, Q.-M., Fan, Y., Wei, Y.-M., 2007. Carbon taxation policy in China: How to protect energy- and trade-intensive sectors? Journal of Policy Modeling 29, 311-333.

Liang, Q.-M., Wei, Y.-M., 2012. Distributional impacts of taxing carbon in China: Results from the CEEPA model. Applied Energy 92, 545-551.

Loulou, R.L., Shukla, P.R., Kanudia, A., 1997. Energy Strategies and Greenhouse Gas Mitigation: Models and Policy Analysis for India. Allied Publishers, New Delhi, India.

Lucas, P.L., van Vuuren, D.P., Olivier, J.G.J., den Elzen, M.G.J., 2007. Long-term reduction potential of non-CO2 greenhouse gases. Environmental Science and Policy 10, 85-103.

Lucas, P.L., Wenying, C., Shukla, P.R., Bazaz, A., van Ruijven, B., den Elzen, M.G.J., van Vuuren, D.P., in prep. Energy system changes for China and India under different climate stabilization pathways.

Luderer, G., DeCian, E., Hourcade, J.-C., Leimbach, M., Waisman, H., Edenhofer, O., 2012. On the regional distribution of mitigation costs in a global cap-and-trade regime. Climatic Change 114, 59-78.

Meinshausen, M., Hare, B., Wigley, T.M.L., Van Vuuren, D., Den Elzen, M.G.J., Swart, R., 2006. Multi-gas emissions pathways to meet climate targets. Climatic Change 75, 151-194.

Metz, B., Berk, M., Den Elzen, M., De Vries, B., Van Vuuren, D., 2002. Towards an equitable global climate change regime: Compatibility with Article 2 of the Climate Change Convention and the link with sustainable development. Climate Policy 2, 211-230.

Meyer, A., 2000. Contraction and Convergence. The Global Solution to Climate Change. Green Books Ltd., Devon.

Ministry of Environment and Forests, Government of India, 2009. India's GHG Emissions Profile: Results of Five Climate Modelling Studies.

Narayanan, B., Walmsley, T., 2008. Global trade, assistance, and production: the GTAP 7 data base. Center for Global Trade Analysis Purdue University.

National Bureau of Statistics PR China, 2009. Input–output table of China 2007. China Statistics Press, Beijing.

NBS Research Group, 2011. Input-Output Table of China, 2011, China's Economic Prospect for the 12th Five-Year Plan Period and 2030. Statistical Research (Chinese) 28, 5-10.

OECD, 2012. OECD Environmental outlook to 2050. Organisation for Economic Co-operation and Development, OECD Publishing.

Ojha, V.P., Pal, B.D., Pohit, S., Roy, J., 2009. Social Accounting Matrix for India (url: http://ssrn.com/abstract=1457628).

Olivier, J.G.J., Janssens-Maenhout, G., Peters, J.A.H.W., 2012. Trends in global CO2 emissions: 2012 report. PBL Netherlands Environmental Assessment Agency and Institute for Environment and Sustainability (IES) of the European Commission's Joint Research Centre (JRC), PBL publication number 500114022.

Peters, G.P., Marland, G., Le Quere, C., Boden, T., Canadell, J.G., Raupach, M.R., 2012. Rapid growth in CO2 emissions after the 2008-2009 global financial crisis. Nature Clim. Change 2, 2-4.

Philibert, C., 2005. Climate mitigation: Integrating approaches for future international co-operation. OECD/IEA Annex I Expert Group, Paris.

Pradhan, B.K., Saluja, M.R., Singh, S.K., 2006. Social Accounting Matrix for India: Concepts, Construction and Applications. Sage Publications, New Delhi, India.

Pradhan, B.K., Ghosh, J., 2012a. Carbon Taxes vs Productivity Shocks: A Comparative Analysis of the Costs in a CGE Framework for India, (forthcoming as an IEG Working Paper; paper presented at the POEM Workshop, organized by Institute of Economic Growth (IEG), Delhi, held at the India International Center (IIC), New Delhi, on Sep.6, 2012).

Pradhan, B.K., Ghosh, J., 2012b. The impact of carbon taxes on growth, emissions and welfare in India, (forthcoming as an IEG Working Paper; paper presented at the biennial International Society for Ecological Economics (ISEE) Conference, June 16-19, 2012, Rio de Janeiro, Brazil and at International Workshop on "Towards Greening the Economy" held at the Institute of Economic Growth (IEG), Delhi, on Feb 22, 2012).

Rogelj, J., Nabel, J., Chen, C., Hare, W., Markmann, K., Meinshausen, M., Schaeffer, M., Macey, K., Hohne, N., 2010. Copenhagen Accord pledges are paltry. Nature 464, 1126-1128.

Rogelj, J., Hare, W., Lowe, J., van Vuuren, D.P., Riahi, K., Matthews, B., Hanaoka, T., Jiang, K., Meinshausen, M., 2011. Emission pathways consistent with a 2 ˚C global temper Nature climate change 1, 413–418.

Shukla, P.R., 1996. The Modelling of Policy Options for Greenhouse Gas Mitigation in India. AMBIO XXV, 240-248.

Shukla, P.R. (Ed.), 1997. Energy and Environment Strategies for a Sustainable Future: Analysis with the Indian MARKAL Model. Allied Publishers, New Delhi, India.

Shukla, P.R., Dhar, S., Mahapatra, D., 2008. Low-carbon society scenarios for India. Climate Policy 8, S156-S176.

Shukla, P.R., Chaturvedi, V., 2012. Low carbon and clean energy scenarios for India: Analysis of targets approach. Energy Economics.

UNDESA, 2011. World Population Prospects: The 2010 Revision. Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat.

UNFCCC, 1992. United Nations Framework Convention on Climate Change, http://www.unfccc.int/resources.

UNFCCC, 2009. Copenhagen Accord. Proposal by the President. United Nations Framework Convention on Climate Change (UNFCCC), document FCCC/CP/2009/L.7.

UNFCCC, 2010. 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. United Nations Framework Convention on Climate Change (UNFCCC), UNFCCC document FCCC/CP/2010/7/Add.1.

Van Ruijven, B.J., Weitzel, M., den Elzen, M.G.J., Hof, A.F., van Vuuren, D.P., Peterson, S., Narita, D., 2012. Emission allowances and mitigation costs of China and India resulting from different effort-sharing approaches. Energy Policy 46, 116-134.

van Ruijven, B.J., van Vuuren, D.P., van Vliet, J., Mendoza Beltran, A., Deetman, S., den Elzen, M.G.J., in press. Implications of greenhouse gas emission mitigation scenarios for the main Asian regions. Energy Economics.

Van Vliet, J., van den Berg, M., Schaeffer, M., van Vuuren, D.P., den Elzen, M.G.J., Hof, A.F., Mendoza Bertrand, A., Meinshausen, M., 2012. Copenhagen Accord Pledges imply higher costs for staying below 2°C warming. Climatic Change 113, 551-561.

van Vuuren, D., Fengqi, Z., Vries, B.d., Kejun, J., Graveland, C., Yun, L., 2003. Energy and emission scenarios for China in the 21st century—exploration of baseline development and mitigation options. Energy Policy 31, 369-387.

van Vuuren, D.P., van Ruijven, B., Hoogwijk, M., Isaac, M., de Vries, H.J.M., 2006. TIMER 2: Model description and application, in: Bouwman, A.F., Kram, T., Klein Goldewijk, K. (Eds.), Integrated modelling of global environmental change. An overview of IMAGE 2.4. Netherlands Environmental Assessment Agency (MNP), Bilthoven, the Netherlands.

van Vuuren, D.P., den Elzen, M.G.J., Lucas, P.L., Eickhout, B., Strengers, B., van Ruijven, B., Wonink, S.J., van den Houdt, R., 2007. Stabilizing Greenhouse Gas Concentrations at Low Levels: An Assessment of Reduction Strategies and Costs. Climatic Change 81, 119-159.

van Vuuren, D.P., den Elzen, M.G.J., van Vliet, J., Kram, T., Lucas, P., Isaac, M., 2009. Comparison of different climate regimes: the impact of broadening participation. Energy Policy 37, 5351-5362.

Weitzel, M., 2010. Including renewable electricity generation and CCS into the DART model, Available at http://www.ifw-members.ifw-kiel.de/publications/including-renewable-electricity-generation-and-ccs-into-the-dart-model.

Weitzel, M., Peterson, S., Pradhan, B., Ghosh, J., In prep. Effects of a global climate regime for India: Evidence from a national and global CGE model.

World Bank, 2011. World Development Indicators. World Bank, Washington DC.